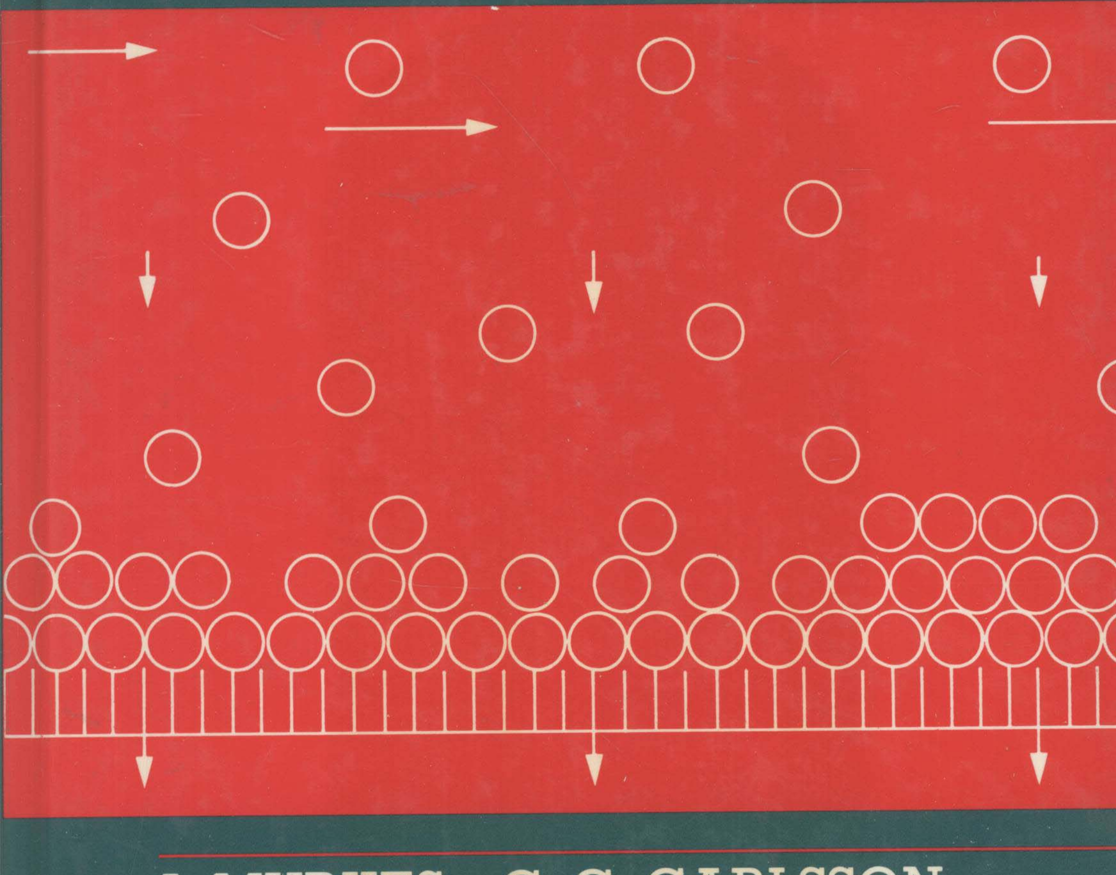
CROSSFLOW FILTRATION



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Crossflow Filtration

Theory and Practice

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Crossflow Filtration

General Remarks

We wish to give a few comments concerning the terminology. The term *flow* refers to the volume of liquid to be filtered flowing in the filter channel on its pressure side per unit of time, m^3/h.

The term *flux* refers to the volume of filtrate or permeate flowing through the filter medium per unit of time and per unit of filter area, m^3/m^2h. The physical meaning of the flux is the filtrate velocity, m/h. It is often practically convenient to express the flux in litre/m^2h or cm/h.

The term *permeate* is used in membrane technology instead of *filtrate*, a usual term in filtration technology. In crossflow filtration it is difficult to distinguish between these terms simply because both denominations can be used depending on whether the filter is equipped with a semipermeable or with a microporous membrane. These two terms are therefore interchangeable in this technology.

By retention or rejection we mean, just as in membrane technology, the ability of a medium to stop species in solution or in suspension from passing through it depending on their size. Retention depends—but far from unambiguously—on the nominal pore size of microporous media, on the so-called cut-off of semipermeable membranes and on the size and shape of particles or molecules in the liquid filtered.

Very often crossflow filtration is called more accurately 'crossflow microfiltration'. This is quite right, especially if the word 'micro' refers to the filter medium used. By using microporous media we extend the traditional crossflow ultrafiltration, in which only the anisotropic, 'skinned' membranes are used. Crossflow filtration with microporous media makes it possible to retain solids in suspension while letting the species in solution pass through (as we will see the things are in reality more complicated).

The term 'microfiltration' narrows unjustly, however, the real scope of crossflow filtration. This technique encompasses, as a matter of fact, several possible objectives:

—Clarification, if we define it as 'removal of small concentrations of suspended solids from liquids. Particle size can vary down to colloidal' (J. Wakeman, *Filtration Dictionary and Glossary*). (Crossflow filtration allows much higher concentrations than traditional filtration.)

—Purification, if we define it as 'separation of two liquid phases and a solid phase' (*Technical Glossary*, Alfa-Laval, 1982).

—Thickening of suspended solids

—Dewatering of suspensions and emulsions

—Concentration of macrosolutes (to certain extent).

Finally, we wish to point out that the low-shear and the high-shear crossflow filtration techniques are—in spite of their common denominator—two quite different techniques using totally different hardware.

Preface

Crossflow filtration is a relatively new technique, until now applied mainly to solute separation (ultrafiltration, reverse osmosis) processes. This technique is also now used for particulate separation.

In the traditional field of separation of particulate matter, the so-called 'dead-end' filtration is predominant. The no man's land between solute and particulate filtration always caused serious filtration problems. These problems were usually circumvented by relatively expensive and not always fully efficient methods (if applicable), such as addition of filter aids or flocculants.

Crossflow microfiltration constitutes a bridge between the crossflow solute separation and dead-end cake filtration. This technique is very recent, perhaps owing to educational factors as well as to the lack of adequate commercial hardware on the market. Only a few years ago hardware for crossflow microfiltration became very slowly available. There is really no justified reason to single out crossflow microfiltration as a separate technique. By means of microporous media micro- and submicroscopic particulates can be separated along with a large part of macromolecules. Conversely, micro- and submicroscopic particles can be efficiently separated together with macromolecules by means of ultrafiltration membranes.

Whether microporous or ultrafiltration membranes are used, the hardware and the processes are very similar. In both cases the process is influenced by the formation of the so-called dynamic or secondary membranes, tailored or natural. This is why crossflow filtration must always be regarded in interaction with the formation process of secondary membranes. A very important task is to devise optimal 'artificial' secondary membranes (sometimes also called 'microprecoat' because of similarities with the conventional precoat).

Crossflow filtration is a general method of cake-free clarification of liquids from any particulate matter, especially when recovery of this matter as a cake is not required. It solves most filtration problems when the traditional dead-end filtration offers difficulties. Sometimes crossflow filtration can also be used for very moderate concentration of suspension.

Just as in its special case, ultra- and hyperfiltration, the crossflow technique is characterized by bottlenecks preventing a faster development of its application. The most serious bottleneck is the decline of the filtrate flux owing to the fouling of the medium.

The only significant improvement in this respect has been brought about very recently: that is the high-shear filtration (as opposite to the low shear-force filtration discussed above). This very recent technique, requiring a new and totally different hardware, was until now almost uniquely applied to thickening of difficult suspensions. A very recent process and hardware development resulted in a novel concept of a multipurpose filter having numerous advantages as compared with existing low-shear filters. This new filter can be applied to ultra- and microfiltration, to clarification as well as concentration of suspensions and solutions. This filter represents a very significant breakthrough in the field of mechanical separation and seems to promise a lot for the future.

The aim of this book is to deepen the proper understanding of this new technique, which is a necessary step on the way to promoting its broader practical application.

Only the most characteristic examples of application are reported on here and only theories having a practical relevance are discussed. The reader, anxious to learn more details, is referred to the references in which the titles of the publications will facilitate the selection and the study.

The examples of application of low-shear crossflow filtration are partly from our own laboratories and partly taken from the literature, whereas the examples of application of the high-shear technique are taken from the authors' own experience: there are not yet any reports available on results from industrial applications.

To the memory
of my loving wife, Felicia

Jakob

Contents

CHAPTER 1

Crossflow Filtration. General Background

1.1 THE MARKET

The economic importance of crossflow filtration is not easy to evaluate today since this is a new technology, not yet well known and not yet established in the industry. The market assessment is based on microfiltration, but not necessarily crossflow microfiltration. Taking into consideration that crossflow can potentially 'take over' the traditional microfiltration, it is justified to quote some data given by Crull:[1]

The microfiltration market in the US was valued at US$ 116 million in 1983 and at US$ 155 million in 1985. The estimated sales in 1995 are $344 million. Thus, it is a rapidly growing market. But this is not the whole story. Crossflow filtration can also be expected to replace progressively a large part of traditional ultrafiltration (this refers especially to high-shear crossflow filtration).

The importance of the market can be easily explained by the fact that there is virtually no industrial field which could not be considered as a potential market for crossflow filtration: food and pharmaceutical industry, chemical and metallurgical industry, environmental protection, dyestuffs, electronics and nuclear industry, water supply, etc. Some of these applications will be reported in this book, many others are to be found in literature.

Thus, it is obvious that this new technology is not to be regarded as an academic curiosity but as an important commercial issue.

1.2 CROSSFLOW FILTRATION—ITS OBJECTIVES AND FEATURES

Nothing is absolutely pure in nature. All streams of liquids contain dispersed particles and droplets of other liquids. To get each one of the mixture constituents free from the other species is an imperative task of direct importance to human and industrial consumption.

There are two basic methods to separate continuous liquids from particulate inclusions. Either to let the liquid move while retaining the particles on a collecting and permeable barrier—this is what filtration is about—or to accelerate the particles towards a collecting surface while preventing the liquid flowing in the same direction. This is sedimentation in a gravitational or centrifugal field.

The simplest and most generally applied method of filtration is consequently to collect the particles on a permeable barrier. The deposited particles form what is called a 'cake', the liquid flows at right angles to the barrier and to the cake and emerges behind this barrier as a more or less pure filtrate. This is the so-called 'dead-end' filtration. The vast majority of filtration procedures and of filter hardware works according to this principle. Dead-end filtration is certainly the most adequate solution to a great many practical separation problems.

It is evident that this kind of filtration yields a deposit of the suspended material on the filter medium, a cake which grows in proportion to the quantity of suspension filtered and to the solids concentration. As long as the main objective of filtration is to recover the suspended solids, the dead-end filtration is the obvious method to use. The cake grows continuously bringing about an increasing pressure drop and/or a decreasing filtrate flux. When the pressure drop becomes prohibitively high and when the flux becomes too low the cake must be removed and the process begins again with the cake-free medium. The filter medium must be regenerated at intervals in order to remove the solids which clog the medium internally and thus make it less and less permeable. The regeneration can be more or less difficult, more or less complete, it is time consuming and it consists usually of one or several washing procedures. In the ideal case the permeability of the medium is restored completely to its initial value.

It is easy to understand that the inherent filtration properties of the medium (permeability, filtration fineness) are of secondary importance. These properties influence the filtration result only in the very beginning, since already the first monolayer of solid particles alters the filtration properties of the medium. In fact, it is the cake that takes over the responsibility for the filtration result. The really relevant properties of the medium are in the first place mechanical and chemical resistance and chemical compatibility, rather than the filtration properties. Pore openings must not, of course, be too large since this would make the cake formation difficult or impossible. Otherwise the inherent filtration properties of the medium are of little relevance. This point is seldom emphasized.

Another general characteristic of the dead-end filtration is its suitability for rather concentrated suspensions. In many cases it may be advantageous to preconcentrate the dilute suspension before dead-end filtration.[2] Filtration of dilute suspension is uneconomic.

Still another feature of dead-end filtration is that a thin cake and a more open medium give a higher capacity, which is quite obvious. On the other hand such media bring about some losses of fine solids fractions in the filtrate.

Dead-end filtration is in general not appropriate for filtration of very fine suspensions, nor for the production of a very pure filtrate. Suspensions entailing formation of a compressible impermeable cake are a real problem.

This is why two costly processes are usually applied for these purposes: the use of filter aids and the use of flocculants. Both these methods have also other disadvantages apart from the costs: they complicate the filtration process, they require space for storage and, as far as filter aids are concerned, they pose problems of disposal and they contaminate the solids recovered.

Crossflow filtration is a complementary technique (of rapidly increasing importance) suitable in those fields of application where dead-end filtration is not appropriate: for filtration of very fine and very dilute suspensions without the addition of flocculants and filter aids, in cases of very exacting demand for purity of the filtrate, and when the solids recovery is of secondary importance. The process is quasi-continuous, and the inherent properties of the filter medium are more relevant to filtration than in the dead-end process. Furthermore, crossflow filtration has opened new fields of application: separation of colloids, molecules and ions, as well as stable emulsions, depending on the nature of the filtering barrier.

'Crossflow' is perhaps not a sufficiently illustrative term. It should describe a process where the liquid to be treated flows parallel (and not at right angles) to the filter medium (see Fig. 1.1). Perhaps a better term would have been 'parallel filtration'. This method is basically a cake-free method (or intended to be such). Its purpose is to prevent the formation of the cake. Particles deposited on the filter medium are swept away by the feed flow. The clean-keeping efficiency of the flowing liquid increases with its velocity. Thus, the particle and solute concentration polarization is controlled by the flow velocity.

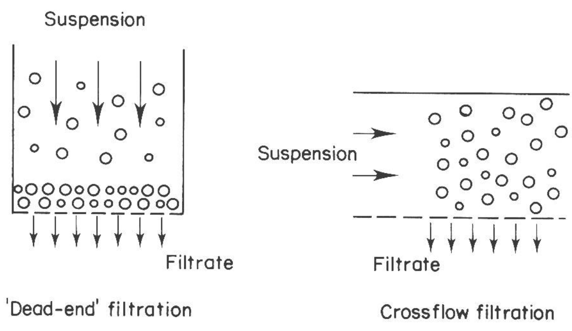

Figure 1.1 Dead-end filtration with cake formation and crossflow cake-free filtration.

In crossflow filtration one can use a multitude of types of media: very tight anisotropic membranes for reverse osmosis and for ultrafiltration, microporous membranes for microfiltration and, finally, tight-woven media for thickening of suspensions. Crossflow is predominant in hyper- and ultrafiltration. It is astonishing that for many years this method has not been extended to microfiltration, which would have been logical and natural. It is indeed somewhat difficult to explain why it took so many years until the first commercial hardware for crossflow microfiltration appeared on the market. This technique is now at an early stage of its industrial application. Now, when very efficient crossflow filters are available, this technique holds a great promise. We would like to quote Dr L. Svarovsky who says: 'In conclusion to the crossflow filtration as a unit operation, it is probably the most exciting development in solids–liquid separation yet to be fully explored'.[3] His opinion is still much more justified if applied to the high-shear crossflow technique.

Crossflow filtration and membrane filtration became nearly synonymous.[4] In principle they are not, since the term 'membrane filtration' refers to the type of filter medium and does not presuppose anything about the flow pattern. (Membrane filtration can be subdivided into hyper-, ultra- and microfiltration, in which corresponding media are used.) The term 'crossflow' refers on the other hand to the flow pattern and does not presuppose anything about the type of medium. In practice, however, crossflow filtration overlaps almost completely, with a few marginal exceptions, membrane filtration. An example of exceptions is a so-called stirred cell equipped with a membrane, but with a perpendicular flow; there are, on the other hand, coarse screens for dewatering of very coarse suspensions, where the flow is parallel to the screen surface. The continuous screw press is another example.

In other words, membrane filtration is almost always carried out by crossflow, whereas crossflow can basically be carried out with any filter medium, but this would not be very practical.

There are cases reported in the literature where woven hoses are used for crossflow filtration of effluents.[5] In these cases, however, filter aids have to be used in order to prevent a rapid dewatering of the suspension and a subsequent plugging of the filter channel.

On the other hand, carrying out the dead-end filtration through a membrane would be quite pointless since the filtration would end very rapidly in total clogging.

How dead-end and membrane filtration overlap is shown in Fig. 1.2. The principles of dead-end and crossflow filtration are shown in Fig. 1.1.

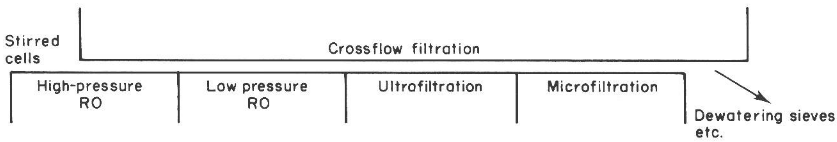

Figure 1.2 Crossflow filtration versus membrane filtration.

The use of the crossflow technique in ultrafiltration and reverse osmosis is well known and well covered in the literature. This subject is therefore beyond the scope of this book. What is relatively new is the use of crossflow for microfiltration and for deliquoring of suspensions having poor filtrability properties and the application of secondary, so-called dynamic membranes (microporous and ultrafiltration membranes). What is new as well, is the application of what we call high-shear crossflow to ultrafiltration.

There are two kinds of crossflow filtration: low-shear and high-shear crossflow filtration. Until now we have been talking about the relatively well known and applied low-shear crossflow technique.

However advantageous the low-shear technique may be, the cleaning efficiency of the sweeping liquid flow is rather limited, which causes filter clogging problems in many practical applications. The problem of unavoidable fouling of media has been recognized as one of the most serious bottlenecks of the low-shear crossflow technique. Many attempts to alleviate this crucial problem did not result in a sufficiently satisfactory practical solution.

This difficulty can to a very large extent be overcome by creating a sufficiently large shear force close to the filter medium. Such force keeps the medium virtually free from deposits.

The way of generating an adequate shear force was indicated in an old, forgotten American patent.[6] Its author, C. D. Morton, expressed in his application in 1927 a wish that is nourished by most people concerned with mechanical separation. He wrote the following: 'The main purpose and accomplishment of this apparatus is to maintain an indefinitely unclogged filtering medium with a constant rate of filtering flow'. This could be accomplished, he wrote further, by means of a rotary filter. Thus, he applied for a patent on a filter with a 'continuously rotating filtering medium'. His application was granted in 1930 (see Fig. 1.3).

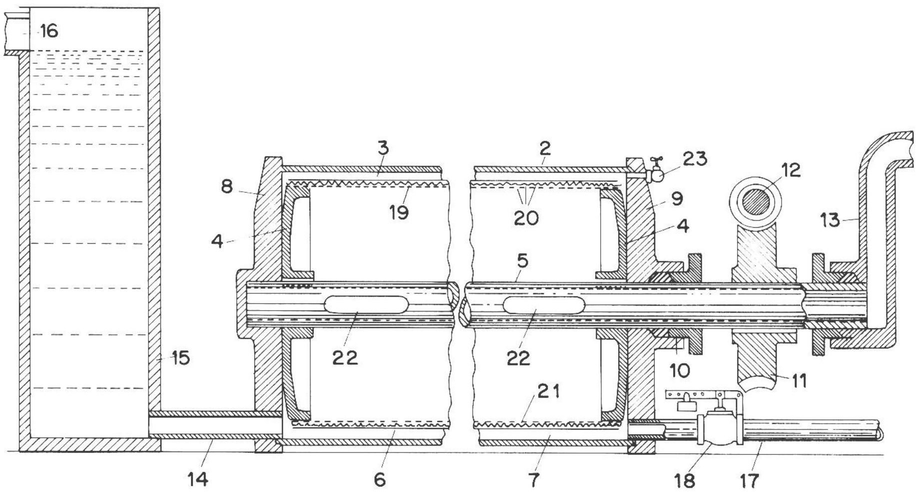

Figure 1.3 Sketch from C. D. Morton's patent application on rotary 'crossflow' filter.

The invention was as simple as its importance was fundamental. In spite of that—as often happens—this invention remained seemingly forgotten for very many years.

First in the 1960s the Russian Malinovskaja described a new kind of rotary filter[7,8,9,10] and the Czech Kaspar obtained a patent for such a device.[11,12] According to patent expertise, this patent was not really legally valid because of Morton's old patent.

It was not until almost half a century after Morton's patent had been granted that an industrial device embodying a similar idea was developed, and not until 1987, that the first industrial multipurpose filter and ultrafilter satisfying technical and economical requirements was introduced on the market.

Curiously enough, the idea of a filter, in which a rotating body imparts its velocity to the liquid (and where, consequently, the feeding of this liquid can be done by means of low-capacity pumps), was until now associated by all manufacturers with the thickening of particulate suspensions and not with clarification or ultrafiltration. The few high-shear rotary filters, which have been tentatively introduced on the market during the last 15–20 years, were made specially for dewatering suspensions and for delivering a thick concentrate. A design for clarification of dilute suspensions, for micro- and ultrafiltration, was not even attempted. A multipurpose rotary high-shear filter covering thickening as well as micro- and ultrafiltration was eventually successfully developed by one of the authors in laboratories of Alfa-Laval. The developed technique and design constituted the starting point for a thorough development of a significantly improved commercial unit and an improved technology by ASEA BROWN BOVERI, who are now starting the introduction of this new filter on the market.

TABLE 1.1 Fields of application of different filtration techniques

Suspension to be filtered / Method	Suspensions of particles above micron size	Suspensions of particles below micron size	Solutions Emulsions Colloidal suspensions
Dead-end	Traditional field of filtration	Only with filter aids, flocculants, low concentration	No interest
Low-shear crossflow filtration	Seldom used Seldom suitable	New membrane technique higher concentration possible	Ultrafiltration Hyperfiltration
High-shear crossflow filtration	New technique for thickening and clarification	New technique for clarification (wide conc. interval)	New method to perform ultrafiltration