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Critical, sustainable and threshold fluxes for membrane filtration with water industry applications

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ABSTRACT

Critical flux theory evolved as a description of the upper bound in the operating envelope for controlled steady state environments such as cross-flow systems. However, in the application of UF membranes in the water industry, dead-end (direct-flow) designs are used. Direct-flow is a pseudo steady state operation with different fouling characteristics to cross-flow, and thus the critical flux concept has limited applicability. After a review of recent usage of the critical flux theory, an alternative concept for providing design guidelines for direct-flow systems namely that of the threshold flux is introduced. The concept of threshold flux can also be applicable to cross-flow systems. In more general terms the threshold flux can be taken to be the flux that divides a low fouling region from a high fouling region. This may be linked both to the critical flux concept and to the concept of a sustainable flux. The sustainable flux is the one at which a modest degree of fouling occurs, providing a compromise between capital expenditure (which is reduced by using high flux) and operating costs (which are reduced by restricting the fouling rate). Whilst the threshold flux can potentially be linked to physical phenomena alone, the sustainable flux also depends upon economic factors and is thus of a different nature to the critical and threshold fluxes. This distinction will be illustrated using some MBR data. Additionally the utility of the concept of a threshold flux will be illustrated using pilot plant data obtained for UF treatment of four sources of water.

Contents

1. Introduction

The concept of critical flux will be briefly reviewed as part of the Introduction then two proposals will be made and defended: firstly that the concept of a sustainable flux should no longer be seen as deriving solely from the concept of a critical flux, and secondly that

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the concept of a threshold flux has utility. To understand the threshold flux the concept of a critical flux is viewed from three perspectives.

1.1. Critical flux: phenomenological perspective

A sound basis for the modelling of membrane filtration in the presence of fouling is given by the equation below. The driving force might be reduced by osmotic pressure due to concentration polarisation whilst the hydraulic resistance maybe greater than that of the membrane itself due to material accumulation on the membrane surface and/or in the membrane pores. Whether it is on the membrane surface or in the pores will affect the relationship between flux and the transmembrane pressure (TMP) but this is a detail of no concern at present. A three-fold division of the overall fouling resistance is introduced. These resistances can be considered to be in series with the membrane resistance. Hence:

$$J = \frac{\Delta P - \Delta\pi}{\mu(R_m + R_{ads} + R_{rev} + R_{irrev})} \quad (1)$$

The hydraulic resistance of the clean membrane is R_m. The first of the additional hydraulic resistances, R_{ads}, is for the resistance due to surface or pore adsorption that occurs independently of flux. This is measured by contacting the membrane with the feed in the absence of flux (say for a few hours) and then measuring a pure solvent flux at a known TMP. This enables a hydraulic resistance to be calculated as the difference between it and R_m giving R_{ads}. The experiment can be repeated for other contact times.

The other terms reflect the fouling that occurs during operation. The increased resistance can be divided into a reversible component, R_{rev}, (i.e. one is removable by physical means alone, e.g. a backwash or perhaps just a simple switch away from the feed and back to pure solvent) and an irreversible component, R_{irrev}, that reflects the deposition of material that is only removable (at best) by a chemical cleaning operation. (If no distinction is being made between the three fouling terms then their sum will have the symbol R_f.)

When considering these fouling mechanisms, the strong form of critical flux, J_{cs}, has been developed to discriminate no fouling conditions (where R_m is the only resistance in Eq. 1) from fouling conditions where other resistances also apply. It has been defined [1] as the flux at which the flux-TMP curve starts to deviate from linearity which pre-supposed that osmotic pressure effects were negligible (Fig. 1). So with the assumption that osmotic pressure effects are negligible

$$\begin{aligned} &\text{for } J < J_{cs} : J = \frac{\Delta P}{\mu R_m} \\ &\text{for } J > J_{cs} : J = \frac{\Delta P}{\mu(R_m + (R_{rev} + R_{irrev}))} \end{aligned} \quad (2)$$

where at least one of R_{rev} or R_{irrev} is non-zero.

In Eq. (2) R_{ads} is considered as negligible. If it were not then one can define the weak form of the critical flux as:

$$\begin{aligned} &\text{for } J < J_{cw} : J = \frac{\Delta P}{\mu(R_m + R_{ads})} \\ &\text{for } J > J_{cw} : J = \frac{\Delta P}{\mu(R_m + R_{ads} + (R_{rev} + R_{irrev}))} \end{aligned} \quad (3)$$

where at least one of R_{rev} or R_{irrev} is non-zero.

The simplest definition of critical flux is the flux at which fouling is first observed for a given feed concentration and given cross-flow velocity. Whether it exists should be a question that is considered when designing all pressure driven processes.

In addition to the original forms of the critical flux, namely the strong form J_{cs} and the weak form J_{cw}, there has been one uncontroversial addition which was the critical flux for irreversibility J_{ci} which has a clear link, for colloidal systems, to a physical phase transition. For this and an advanced discussion on the concept of critical flux and its evolution, see Bacchin et al. [2].

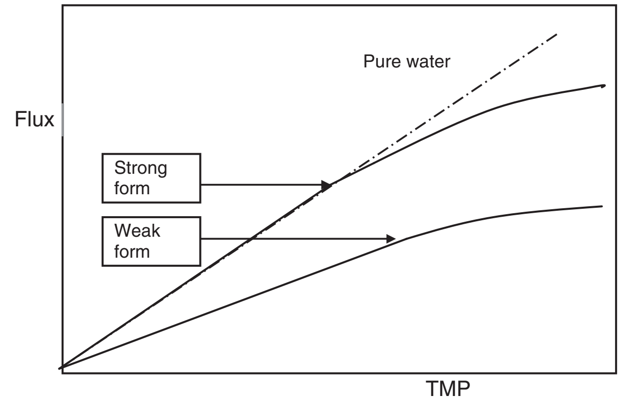

Fig. 1. Forms of critical flux as originally defined by Field et al. (1995).

Also in the review [2] it was noted that the strong form and weak form of the critical flux, J_{cs} and J_{cw}, must be evaluated via a check on whether or not the overall resistance has remained invariant. This is important because in flux stepping experiments, TMP may indeed be seemingly invariant at the new flux but this does not guarantee that the resistance has remained unchanged; a small amount of fouling may occur rapidly on making a step change in flux such that there is no subsequent increase of TMP with time (beyond that observed at the point of change) but that is no guarantee that the increase in TMP from that at the previous flux was proportional to the increase in flux. This point, and the unobserved small amount of fouling, was often ignored in the 1990's, and that is sometimes still the case today.

1.2. Critical and limiting fluxes

The physical basis of critical flux, and the nature of the criticality, has been discussed by researchers at Toulouse in particular. Recently [3] they developed a filtration procedure to measure the reversibility of fouling during cross-flow filtration which differentiates the reversible accumulation of matter on a membrane surface from the irreversible fouling of it. By distinguishing between these two forms of attachment the critical flux for irreversibility J_{ci} was determined. The method was applied to latex suspensions with different degrees of destabilisation and at different cross-flow velocities. Account was taken of the osmotic pressure of the colloidal dispersion. A little earlier [4] a possible link between the limiting and critical fluxes was suggested, where the limiting flux is the plateau flux which is achieved at high TMP; further increases in TMP do not increase the flux (see textbook such as [5]). With certain assumptions, it was shown that the critical flux is equal to 2/3 of the limiting flux.

A different limiting flux model was recently developed elsewhere [6,7] for predicting the fouling behaviour of reverse osmosis and nanofiltration membranes by organic macromolecules. Amongst the findings it was observed not only that the there was a maximum pseudo-stable flux (the limiting flux) beyond which further increase in applied pressure did not translate to a greater stable flux but that the limiting flux had a strong dependence on the feedwater composition, such as pH, ionic strength, and divalent ion concentration. Conditions enhancing foulant-deposited to foulant-in-suspension repulsion resulted in greater limiting flux values. Such observations agree well with a theoretical model capturing both hydrodynamic and DLVO interactions. It will have been noted that this model assumes a fouled membrane and that the model is for limiting flux. In a modified form it should also yield a critical flux, but unlike the limiting flux this will be membrane dependent. This model is mentioned because limiting fluxes are of interest and because for very low osmotic pressures, this model is more appropriate than traditional models [e.g. 8]. Charge is a factor in the new model and with regard to the spiral ultrafiltration of modified skim milks, the zeta potential and size of caseins has a major influence on the limiting and critical fluxes [9]. Although not stated the critical fluxes seem to be of the weak form.

With larger particles insight can be gained using the Direct Observation Through Membrane (DOTM) technique. Larger flocs typically yielded higher critical fluxes as in monodisperse suspensions but recently it was observed [10] that the effect of particle size was less pronounced for the more porous flocs. Also the critical flux was also found to increase with the fractal dimension, especially for the larger flocs. In a related study [11] on colloidal fouling in reverse osmosis critical flux was defined as the flux at which the rate of deposition of colloidal silica (20 nm) on the membrane, became zero, i.e. $dm_f/dt = 0$. It was found that the critical flux concept was applicable to colloidal silica fouling in the RO process. The critical flux was strongly influenced by the crossflow velocity. One of the interesting observations was the determination of the fractional deposition constant, Φ, defined as the amount of particles finally deposited on the membrane surface to the amount of particles convected to it. At low crossflow (<0.1 m s^{-1}, shear rate <430 s^{-1}) $\Phi = 1.0$, but at 0.22 m s^{-1} (shear rate $= 940$ s^{-1}) Φ dropped to about 0.1. Also the authors determined a cake enhanced osmotic pressure (CEOP) and not only showed that it is more severe at high flux and low crossflow velocity conditions, due to formation of a thicker cake layer, but that this CEOP effect can readily exceed the R_f effect due to fouling.

Although powerful, the concept of critical flux does not delineate all typical fouling circumstances found in membrane filtration. Two major exceptions are biofouling (which will be covered when discussing MBRs) and the slow flux decline that is observed in many industrial membrane applications. A better understanding of this was recently achieved [12] through a consideration of slow aggregation kinetics. This is important within the mass transfer boundary layer on an ultrafiltration or microfiltration membrane. The results showed that whereas the critical flux is a key limit in cross-flow filtration of stable colloids, it should be combined with the kinetics of (slow) aggregation for metastable colloids of intermediate stability.

1.3. Critical flux and related terms: recent usages

To complete the contextual introduction a few more general points are added. For operation at constant pressure, fouling will lead to flux decline that is typically rapid over the first few minutes and afterwards more gradual over tens of minutes; in many cases a steady-state is reached. Accumulation will cease when there is a balance between "flux of solids in" and "removal away". Now if instead of operation at constant pressure, there is operation at constant flux, then fouling leads to increases in TMP. However if the fouling rate is low, this mode of operation has much to commend it as productivity is fixed. With a constant flux, the rate of TMP increase is generally either linear or concave upwards. In Fig. 2 the straight line after 15 min is indicative of cake formation on top of the membrane; the slightly higher slope before that reflects the fact that the initial layers of cells partially blocked the membrane and so had a greater effect per unit mass of yeast cells convected to the membrane surface. The paper mentioned "nominally sub-critical conditions" because as others have noted [14,15] there is perceptible fouling during filtration of liquids such as natural water, even operating under low flux (which might have been considered sub-critical). This encouraged the appearance of the notion of "sustainable flux" [2,15]. The term "sustainable flux" has been used [16] to describe the flux above which the membrane system will have a sharp increase in fouling as evidenced by a sharp increase in the rate dTMP/dt. At fluxes below it,

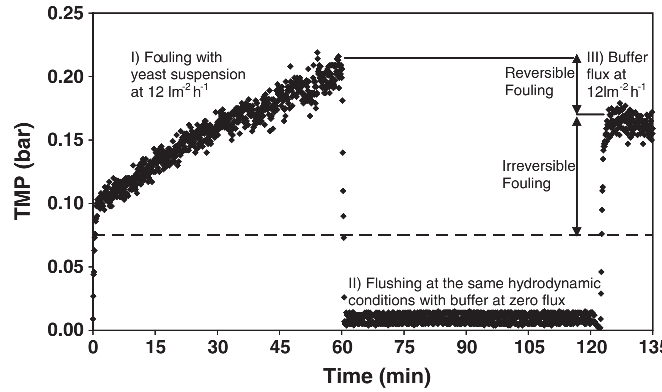

Fig. 2. Example of operation at constant flux showing slightly higher fouling rate in the first 15 min compared with post 15 min. The level of irreversible fouling is shown to be greater than that of reversible fouling [13]. Dotted line is the TMP corresponding to same flux of pure water.

operation of the membrane system will generate much slower fouling rates that are sustainable in real practise. Later this will be labelled the "threshold flux" and distinguished from the "sustainable flux".

Fig. 2 also illustrates the distinction between the reversible component of fouling, R_{rev}, i.e. one that is readily removed after switching from the feed to buffer (the presence of salts in the buffer is irrelevant) and an irreversible component, R_{irrev}, that reflects the deposition of material that is only removable (at best) by a cleaning operation. Finally the introduction is concluded by noting that on the one hand considerations of critical flux are concerned with the prevalence of fouling resulting from the properties of the feed liquid, the membrane properties and the flux, and in particular with the flux below which fouling does *not* occur. On the other hand critical flux theory is *not* concerned with the rate of fouling and does not consider the economics of an operation. For this reason careful consideration is now given to the meaning of the term "sustainable flux" after which the term threshold flux will be considered.

2. Sustainable flux

2.1. Economic aspects of sustainable flux

The question of whether sustainable flux is a member of the critical flux family is now considered. In preparation for an Oxford workshop on critical flux, an industrialist [17] proposed that sustainable flux was the "Net flux that can be maintained using mechanical and chemical enhancing means to meet an operation cost objective over the projected life of the membrane". Thus Sustainable Flux Design is a pragmatic concept for commercial operations in which there is controlled fouling which gives an optimal balance between moderate operating costs (opex) and moderate capital costs (capex). Net flux was mentioned in the proposed definition to allow for permeate consumption during possible backwash. Backwash efficiency is important in the water industry [16,18].

The balancing of opex and capex will depend upon feed quality, membrane costs and energy costs amongst many other factors [19]. Whilst research is needed to determine the operating envelope, economic factors will also influence decisions on the flux to be chosen. A summary of the situation is shown in Fig. 3.

Given the twin influences determining sustainable flux it is concluded that it is not a member of the critical flux family that includes the strong form J_{cs}, the weak form J_{cw}, and the critical flux for irreversibility J_{ci}. Earlier [2] it was stated that, "The sustainable flux is usually defined in relation to a flux policy (that might be implicit rather than explicit) in which fouling is minimised to avoid frequent

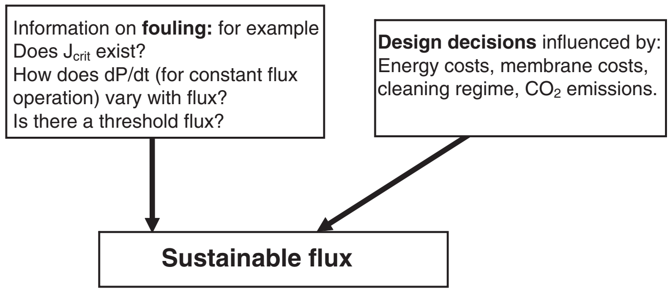

Fig. 3. Illustration of some of the factors effecting establishment of the chosen operating flux. In particular note that it is not determined exclusively by physico-chemical factors.

cleaning." This paper takes the view that the definition should be explicit about the inclusion of economic factors.

2.2. Sustainable flux in the water industry

Two greatly expanding applications of UF are waste water treatment and drinking water filtration. The former relates particularly to aerobic MBRs. With aeration in MBRs providing decent shear at membrane surfaces, the critical flux hypothesis suggests that it is worth exploring whether one can operate below it or close to it. In both hollow fibre and flat plate systems the membranes are submerged in the aeration tank and operated at constant flux with the driving force being provided by suction on the permeate side. The systems give a combination of biological treatment with excellent filtration that excludes bacteria and viruses from the permeate that is the final product water. The systems can be adapted to treat municipal, commercial or industrial wastewaters and the permeate can be reused *in lieu* of fresh water. The hollow fibre membrane bioreactor systems can be backflushed which limits the need for chemical cleans. The literature suggests [e.g. 20,21] that the economic flux is a controlled flux in excess of the critical flux of some species and thus the system is operated with gentle fouling. Clearly economic factors have rightly played a role in this decision. It thus follows that the determined economically sustainable flux should not be confused with a critical flux. The latter will be unchanging for given water quality, aeration rate and a set of physical parameters, but the former will not be. Sustainable flux is influenced by choices of the plant designer and operator. A flux regarded as sustainable in one set of circumstances may not be so elsewhere due to different constraints in chemical usage for example. Also for the same set of physical parameters, the optimal flux will change if energy prices increase and or if membrane costs fall.

2.3. MBR

We now consider some data from a Korean MBR pilot in which the variation of TMP with time was monitored for three different fluxes [22]. The membranes were flat sheet modules in the same aerated tank. The authors kindly forwarded the data on pressure rise and our analysis of the data suggests that the most sustainable flux is not the one with the lowest TMP rise over the first 20 days. This may seem surprising but productivity has to be considered. The reason for including this example is the desire to acknowledge and illustrate that flux-TMP relationships are not always the key. Their data are reproduced in Fig. 4.

A misguided focus upon Fig. 4 would suggest that operation at 13 $\mathrm{lm^{-2}\,h^{-1}}$ is to be preferred as the available operating time before the limitation of 30 kPa was reached was substantially longer. However a plot of volume permeated per m^2 shows that as much permeate is obtained at the middle flux of 20 $\mathrm{lm^{-2}\,h^{-1}}$ before the TMP limitation was reached as was obtained at the flux of 13 $\mathrm{lm^{-2}\,h^{-1}}$. In Fig. 5 resistance is plotted against volume collected per m^2. This

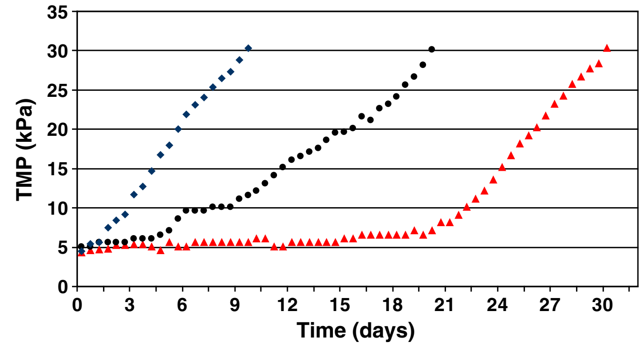

Fig. 4. Pressure increases for three fluxes: 27, 20 and 13 $\mathrm{lm^{-2}\,h^{-1}}$.

confirms the statement just made and also illustrates the fact that a TMP limitation for different fluxes implies different final resistances.

Probably the cleaning of the membrane for the middle flux was no harder that it was for the lowest flux. The authors have labelled the operation at the lowest flux as being sub-critical for the first 10 days or so. The operation does approximate to being below the J_{cw} limit but it is seen that the economic flux is a controlled flux in excess of the critical. The overall productivity is greater if the system is operated with gentle fouling from the beginning, at 20 $\mathrm{lm^{-2}\,h^{-1}}$, rather than 13 $\mathrm{lm^{-2}\,h^{-1}}$.

Subcritical flux operation was originally reviewed by Howell [23] who discussed the complexities of mixtures in which different components have different critical fluxes. Sometimes cleaning is easier if one operates *above* the critical flux of a component that acts as a filter aid and is also easy to remove. Nominally sub-critical operation was discussed more recently [13] but subsequent to that the concept of a threshold flux has emerged and this is addressed in Section 3. But some final remarks on biofouling; the biology is important. As biofouling occurs irrespective of flux it is a good question to ask, "Is there a critical flux to avoid biofouling… Fact or fiction?" Some have concluded [24] that since fouling occurs irrespective of the actual flux, the critical flux concept stating that "below a critical flux no fouling occurs" is not a suitable approach to control biofouling in reverse osmosis and nanofiltration membrane systems. However it has also been found [11] that the growth of biofilm at constant flux following initial bacteria colonisation of the membrane surface increased with imposed flux. Thus whilst there is not always a critical flux, break points do exist and appropriate names for these break points (and the avoidance of misuse) are important.

For example when the measurement of critical flux is of the critical flux (weak form), it would be useful if this were stated. Fan et al. [25], who studied the effects of sludge characteristics on critical flux using a submerged membrane bioreactor pilot plant defined their measurement of critical flux as being the average of (i) the maximum flux at which the TMP increases linearly with the flux and (ii) the minimum flux at which this linear relationship between TMP and flux failed. This

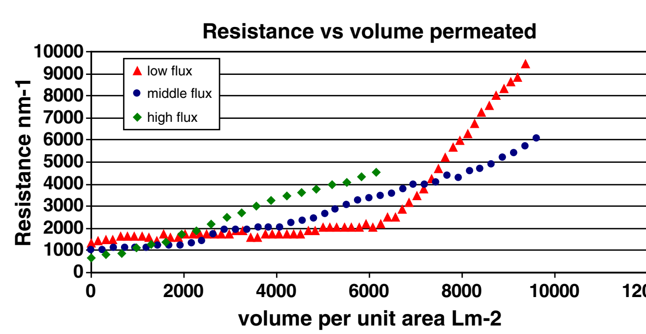

Fig. 5. Resistance increase vs volume permeated per unit area.

is clearly stated but a link to the clean water flux at the same TMP seems to be missing. Nevertheless it is interesting to note that they found the critical flux concept useful; the critical flux measured by the stepwise flux method was almost solely related to the colloidal TOC despite differences in the sludges tested. In contrast, MLSS (mixed liquor suspended solids (g/L)) was shown to have little impact on the critical flux. Very recently others [26] have also studied the relationship between activated sludge characteristics, fouling rate and critical flux. Other recent studies [27–29] are also concerned with critical flux in submerged membrane bioreactors. For a discussion of the effect of bubbling, one should consult the 2003 review [30] and a study on inter-fibre two-phase flow [31].

3. Threshold flux

3.1. Initial remarks

The concept of critical flux does not provide sufficient guidance for the membrane plant designer or operator in the water industry. Instead, it is proposed that attention should be focused on determining the threshold flux for a particular operation. The threshold flux is that flux at or below which a low and near constant rate of fouling occurs but above which the rate of fouling increases markedly.

It can be argued that the rate of fouling is the key. This is particularly true for multi-component applications where industry typically operates at an acceptable fouling rate between cleanings. This allows a higher throughput of permeate to be achieved throughout a run before cleaning. Operation of most large water plants is controlled by the required flux and limited by the available pressure. Thus a lower rate of fouling makes for longer runs. Normally backwash and air scour controls fouling to a degree [32,33], but a maintenance procedure is also needed and this is commonly a chemical wash or Chemical Enhanced Backwash (CEB) to counter the effect of slight progressive fouling inherent in the pseudo steady state design of direct-flow [34,35]. If fouling rates are low, the next step, Clean In Place (CIP) will be infrequent. As flux increases, and fouling rates are higher and the use of CIP will have to increase [36]. The goal of a successful design is to achieve a sufficiently high flux, whilst keeping fouling rates acceptable.

The flux at which this can be achieved is the economic sustainable flux but how does this relate to the rate of fouling? If there is a break point in the rate of fouling vs flux curve a threshold flux can be determined. It is conceivable that the rate of fouling approach will identify both a value of the threshold flux provided that that there is a break point in the curve and possibly a critical flux. However, in some applications, a zero rate of TMP increase may never be obtained, for example during trials with real and synthetic sewage [37]. Thus use of the flux-step or any other method to determine critical flux may yield a result that it may not exist. The result of the aforementioned study [37] showed that if it exists, the value of critical flux is less than 2 $\mathrm{lm^{-2}\,h^{-1}}$. The useful results from experiments in this area relate to the rate of fouling. Significant differences above and below clearly defined fluxes have been found around fluxes of the order of 10 $\mathrm{m^{-2}\,h^{-1}}$. So as already indicated, the term threshold flux will be more appropriate in order to make a distinction between low and high fouling rates.

3.2. Threshold flux: an illustration from the water industry

Fouling data have been obtained from pilot studies with four different water types, representing the cross section of applications encountered in water and wastewater. The fouling propensity depends on characteristics of the feed and the membrane, and the interaction between them [38,39]. In each case, the membrane used for the evaluation was hydrophilic polyethersulfone (PES) from two different manufacturers. Details of the membrane system are shown in Table 1.

Table 1
Pilot membrane system characteristics.

Membrane characteristics	Hydrophilic PES; coarse UF rating—150 kDa
Module design	Inside feed; can be permeate backwashed
Process design	Pressure driven

The feed waters covered are: a waste water, a groundwater, and two surface waters one of which was clarified. The number of days of operation was respectively: 200, 70, 180 and 270. In each case, operation was optimised during the course of the trial, with attempts to increase flux. In some cases, fouling was controlled by feed dosing, whilst in others, automated CEB was used. The goal was to obtain as high a flux as possible without having to resort to an excessive cleaning frequency through the use of CIP. Details of the feeds and pilot operation are provided elsewhere [40]. The aim here is to introduce a concept and not to discuss water specific details. However as a final contextual matter it is noted that industrial practise in North America has established a 30-day interval between CIPs as a desirable goal to minimise the use of cleaning chemicals, restrict chemical waste production, and keep operational labour to a minimum [41].

With regard to the filtration of alginates it has been observed [42] that the filtration resistance is fully reversible at low filtration flux, whilst slow irreversible fouling occurs at high flux. Others investigating fouling in submerged membrane bioreactor for wastewater treatment have developed [43] a two part model where one part is independent of the hydrodynamics and the other is not. The former describes the fouling caused by adsorption of micro-colloidal and soluble fractions over the external membrane surface. Thus regarding the filtration of various feedwaters it may be reasonable to suppose that some components foul the membrane irrespective of the actual flux whilst others foul at a rate related to the degree to which the flux is above a threshold. Below this flux there is no contribution from the second component. For crossflow situations one could argue, following others [e.g. 10], that there is critical Peclet number, $(J/k_m)_{crit}$, where k_m is a mass transfer coefficient or include a model with a critical shear stress [44]. However for direct-flow systems this is inappropriate. As the actual mechanisms of fouling for the various waters are not fully known, and also to maintain utility, a simple model for permeability loss (L/m^2 h/bar/day) can be developed as follows:

$$\text{Rate of permeability loss} = a + b.(J - J^*) \text{ for } J > J^* \tag{4a}$$

$$\text{Rate of permeability loss} = a \text{ for } J \leq J^* \tag{4b}$$

where J^* is the threshold flux.

The rate of permeability loss is directly related to the rate of increase of resistance which in turn can be related to dm_f/dt, where m_f is the mass of foulant. This in turn can be split into two classes, one accumulates irrespective of the flux but the other is flux dependent.

Parameters “a” and “b” are fitting parameters; no distinction has been made with respect to reversible and irreversible fouling both of which can contribute to “a” and “b”. It has been suggested to us that the value of the flux independent term (i.e.“a”) will itself be altered by the extra foulants that accumulate once $J>J^*$. Indeed the foulants that were modifying the membrane's permeability when $J<J^*$ will now be partially screened from the membrane. Further research might well establish that for some systems “a” in Eq. (4a) takes a different value from that in Eq. (4b). One can, based upon the literature, conceive of two broad categories [13]. The cake filtration situation in which the cake acts as a *filter-aid* (relevant to $J>J^*$) occurs where cells or relatively large particles can act as a secondary membrane, and are beneficial to filtration performance by screening out material that would otherwise have a high fouling impact at the membrane surface. For this situation the value of “a” would be less for $J>J^*$. In the second situation the interstices of the cake, formed for $J > J^*$, become clogged with either fine particles or soluble components. Such clogging of the cake will have a detrimental effect on fouling, as measured by rate of TMP rise. This was termed the *overclogging* situation [13]. An example can be found in Okamoto et al. [45] who found that the resistances of the washed cells and soluble broth components when filtered separately summed to much less than when filtered together. The difference can be attributed to clogging of the cake of cells by soluble broth components and in this situation "a" would be greater and not less for $J > J^*$. For the present a is considered to be invariant as there is insufficient data to do otherwise.

For the four waters the values of a, b and J^* were determined to be as shown in Table 2.

A comparison between model and data is given in Fig. 6. The amount of data are limited as the individual runs were over tens of days but the sensitivity of the permeability loss to flux was found to be very pronounced.

Of the four water sources, the lowest rate of fouling occurs with the clarified surface water, where the flocculant has a beneficial effect [46]. However, the threshold flux for this source is relatively low, indicating that a low degree of fouling occurs even with low flux operation. For this type of application, it would normally be acceptable to increase the design flux to a level significantly greater than the threshold flux, since the fouling penalty for doing so is low.

Secondary wastewater represents the opposite extreme. This feed has the lowest threshold flux, despite the addition of coagulant to the feed, and it also has the highest rate of fouling. For this application, the sustainable flux will be the same as or close to the threshold flux. This is similar to the findings of Mortensen et al. [47] who found that the tertiary treated effluent from the Truckee Meadows Water Reclamation Facility (TMWRF) is not an acceptable direct source for a membrane desalination plant as both RO and NF membranes foul rapidly when directly exposed to TMWRF's effluent. However they also found that coagulation-enhanced UF pretreatment was a very effective process for conditioning the feedwater for RO and NF processes.

Raw surface water, has a higher threshold flux than wastewater, but almost as high a fouling sensitivity, so it too has a sustainable flux close to the threshold value. Ground water has a higher threshold and a lower fouling rate, so this can have a higher sustainable flux.

In summary those waters displaying a very sharp threshold flux will always have an economically sustainable flux close to this threshold value. For others, such as the clarified surface water, it can be above the value of J^*.

3.3. Threshold flux in other systems

Some have referred to situations where "within critical flux conditions, only reversible fouling can occur, which can be periodically soft-cleaned" [48]. This makes an incorrect use of the term critical flux, as normally defined, but fits perfectly with the concept of a threshold flux. Others [49] seem to contradict themselves by referring to initial fouling rates at sub-critical flux conditions. For the filtration of unwashed and washed yeast cells it is unlikely that the fouling was reversible and therefore a different term such as threshold flux would have been more appropriate. Indeed the need has existed for a while. In defining the critical flux in two different ways, some

Table 2
Parameters for Eq. (1) determined from temperature corrected permeability loss data given as $lm^{-2}h^{-1}$ bar/day.

Water source	a ($lm^{-2}h^{-1}$/bar/day)	b ($bar^{-1}day^{-1}$)	J^* ($lm^{-2}h^{-1}$)
Groundwater	Insufficient data	0.113	127
Surface water clarified	0.043	0.051	67
Surface water raw	2.92	1.32	100
Wastewater (2ry)	~4.4 limited data	4.45	59

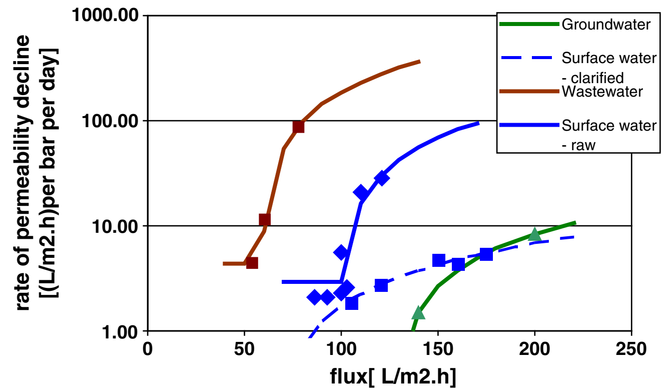

Fig. 6. Dependency of permeability decline upon flux for four different sources of water. Note the log scale on the y-axis.

[50] have used a "strong and mild definition". Below the strong form of critical flux there was no deposition. For the weak form, "flux can be assumed below critical flux if the deposit layer does not interfere with flux". Strictly one should add the adverb, "significantly". Again the usage of the mild form of critical flux is not consistent with the original definition of the weak form but is fully consistent with the concept of a threshold flux. When consulting membrane fouling guidelines for UF/MF [e.g. 51], it would be useful to view some of them through the lens of threshold flux.

4. Concluding remarks

The critical flux concept, initially proposed for steady state systems, is inappropriate to describe the pseudo steady state dead-end systems normally used in water and wastewater applications, because a low degree of fouling is inherent to dead-end systems, even at low flux, due to the absence of back transport. So whilst one can refine the methods of measuring critical flux for "clean" systems [52,53] the concept applies neither to the aforementioned systems (for any feed) nor to complex mixtures for which the notion of no fouling is not applicable at realistic flux levels.

Herein it has been suggested that two additional distinct terms are required. Firstly the concept of a threshold flux is useful to distinguish between regions of low fouling and high fouling both in direct-flow and crossflow systems. Whilst this was developed when analysing the permeability decline versus flux data for the UF treatment of water, the concept should have wide applicability for many multi-component feeds, and for cross-flow as well as direct flow systems. Secondly it is suggested that it is important to recognise that the concept of sustainable flux embodies economic factors. The sustainable flux for a plant can be defined as the flux at which there is an acceptable degree of fouling, but that the fouling is easily removed in a cleaning procedure of acceptable frequency, such that there is an appropriate balance between capital and operating costs.

The economically sustainable flux may be greater than the threshold flux and is a pragmatic value at or below which an 'acceptable' rate of fouling occurs. The concept of sustainable flux recognises not only that a degree of fouling is inherent in some designs, such as direct-flow ones, but it also allows the designer and operator to accept a degree of fouling resulting from a higher flux, in return for a level of cleaning that is practical for the operator. Thus the sustainable flux represents a trade-off between capital and operating costs. From a purely economic point-of-view, an economically sustainable flux is one that meets a cost objective over the projected life of the membrane plant.

If either the concept of a threshold flux, or the concept of a sustainable flux, is to be related to that of critical fluxes, then they must embody some notion of criticality. This is not the case for sustainable flux but where a threshold flux exists, it is perfectly reasonable to conceive of certain components fouling the membrane above this threshold flux and not below it. Thus there is an element of criticality with respect to the threshold flux.

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