Journal of Water Process Engineering 1 (2014) 121–138

Contents lists available at ScienceDirect

Journal of Water Process Engineering

journal homepage: www.elsevier.com/locate/jwpe

Review

Fouling and cleaning of ultrafiltration membranes: A review

Xiafu Shi [a], Galit Tal [b], Nicholas P. Hankins [a,*], Vitaly Gitis [b]

[a] Centre for Sustainable Water Engineering, Department of Engineering Science, University of Oxford, Parks Road, Oxford OX1 3PJ, UK
[b] Unit of Environmental Engineering, The Faculty of Engineering Science, Ben-Gurion University of the Negev, PO Box 653, Beer-Sheva 84105, Israel

ARTICLE INFO

Article history:
Received 24 March 2014
Received in revised form 10 April 2014
Accepted 10 April 2014
Available online 1 May 2014

Keywords:
Membrane fouling
Membrane cleaning
Physical cleaning
Chemical cleaning
Membrane integrity
Membrane degradation

ABSTRACT

Ultrafiltration (UF) is one of the best options for both one-stage and as part of multi-stage water and wastewater purification. This review summarises the known facts about the fouling processes and cleaning procedures and details of the most successful physical and chemical cleaning combinations. The optimum cleaning is closely linked to the nature of the fouling. Precise knowledge of both the fouling type (organic, inorganic, or biological) and the fouling mechanism (gel formation, adsorption, deposition, pore blockage, or cake formation) is the key to success in UF membrane cleaning.

Contents

* Corresponding author at: Centre for Sustainable Water Engineering, Department of Engineering Science, University of Oxford, Parks Road, Oxford OX1 3PJ, UK. Tel.: +44 1865 273179; fax: +44 1865 273010.
E-mail address: nick.hankins@eng.ox.ac.uk (N.P. Hankins).

http://dx.doi.org/10.1016/j.jwpe.2014.04.003
2214-7144/

1. Introduction

Modern ultrafiltration was originally developed as a fractionation technique in the late 1960s [1]. Since then, this technology has enjoyed continuous development, and its applications have spanned a wide variety of fields, from chemical recovery, water treatment, wastewater reclamation, juice concentration, dairy making, medical usage, to the harvesting of cells [1]. However, membrane fouling is still a severe problem limiting the potential of this technique. Fouling may result in an increase in operational costs, due to an increased energy demand, additional labour for maintenance, cleaning chemical costs, and shorter membrane life. It requires effective and efficient methods for its control and minimisation.

It may be possible to prevent fouling before its occurrence by methods such as pre-treatment of the feed streams, chemical modification to improve the anti-fouling properties of a membrane, and optimisation of the operational conditions. However, periodic membrane cleaning is still currently inevitable. It is indeed an integral part of most membrane processes in modern industries, and must be regularly carried out to remove the fouled materials and restore the productivity of the operation [2].

Study of membrane cleaning has always been a complement to developing deeper knowledge of fouling. However, the dedicated literature on membrane cleaning is notably less than that on fouling studies [3]. Many previous cleaning studies were actually subsidiary to that of relative fouling, and for which the study was far from comprehensive. However, owing to the greatly improved understanding of fouling in the last two decades, there have been an increasing number of dedicated studies on membrane cleaning. In particular, systematic studies have been made in many respects in recent years.

A quick scan of bibliographic databases shows that the number of research papers with respect to membrane cleaning has boomed in the last decade. This corresponds to the large, simultaneous expansion of UF processes in industries such as water, wastewater, food and biotechnology. The up-to-date information on membrane cleaning is constantly in demand because it is a vital part for the operation of most membrane systems.

There exist a few excellent summary works and pioneering early reviews regarding membrane cleaning. Many of them are parts of more general reviews of fouling and its control technology [4–6]. Full reviews on membrane cleaning were written about two decades ago [7], including one on reverse osmosis [8]. There are also works dedicated to specific areas in this realm such as conventional cleaning [9], ultrasonic cleaning [10], membrane cleaning in the food industry [2] and chemical cleaning in the water industry [3,11]. However, the increasing number of UF applications and the rapid development in UF cleaning constantly brings out new ideas and results. An updated review is therefore timely and useful.

In our opinion, the comprehension of membrane cleaning involves gaining knowledge of many separate aspects and making the links between them. It should include the target (common fouling problems in these industries), removal (various cleaning methods), results (cleaning effectiveness and any side effects such as membrane damage) and optimisation (effect of operational parameters). Thence, the scope of this paper is to produce a review in a comprehensive manner about current cleaning processes and techniques for UF fouling in various industries. We have restricted the coverage to major UF applications in solid–liquid separation. We have also included some innovative cleaning techniques which are not yet in common practice.

A brief introduction is given on the understanding of UF fouling to know better what the problem is. A discussion of membrane cleaning, including physical, chemical, conventional and non-conventional methods, is followed by the cleaning processes, factors and optimisation. Finally, the side effects of cleaning are discussed.

2. Membrane fouling

Optimisation of membrane cleaning protocols requires in-depth understanding of the complex interactions between the foulant and the membrane. Most cleaning studies reported are based on trial-and-error methods [7,12]. A more systematic approach is required to study the various aspects of fouling control [13]. In addition, it is important to consider the economic impact of cleaning procedures, including the costs of the cleaning process itself along with the effect of the procedures on membrane lifetime and efficiency [14].

2.1. Nature of flux decline

The reduction in the membrane flux below that of the corresponding pure solvent flow over time (under constant driving force – the transmembrane pressure (TMP)) is due to two important effects [15].

Firstly, concentration polarisation, which is a natural consequence of the semi-permeability and selectivity of a membrane, results in an accumulation of rejected solutes or particles in a mass transfer boundary layer adjacent to the membrane surface [15–18]. In UF, this is a particular problem during filtration of low molecular-weight solutes or macromolecules [16]. When these solutes are carried towards the membrane surface by the permeation flow, solvent molecules pass the membrane but the larger solutes are rejected and retained at the membrane surface. These rejected molecules are relatively slow to diffuse back to the bulk solution, which causes a concentration gradient just above the membrane surface. Sometimes, the concentration of those molecules near the membrane wall can reach 20–50 times that in the bulk solution [19]. Such a high amount of material accumulating at the membrane impedes the solvent flow through the membrane [15], and creates an osmotic back pressure that reduces the effective TMP of the system. Concentration polarisation is inevitable but a reversible phenomenon that does not itself affect the intrinsic properties of a membrane [16]. The flux loss can be fully recovered by switching the feed with a pure-solvent stream. However, the resulting highly localised high concentration is relevant to the phenomenon discussed in the following.

Secondly, there is membrane fouling, taking place when the matter in the feed solution leaves the liquid phase to form a deposit on either the membrane surface or inside its porous structure [2]. Fouling in UF causes a build-up of material on the surface (i.e., external fouling) and/or in the pore structure (i.e., internal fouling) of a membrane. In contrast to the reversible nature of concentration polarisation, fouling may cause irreversible loss of the permeability of a membrane. In fact, reversibility is a defining characteristic of fouling. Many researches distinguish reversible and irreversible fouling, based on their relative resistance to cleaning [20,21]. Reversible fouling is the type that can be removed easily with certain cleaning methods, while irreversible fouling still remains after the cleaning. The part of fouling that cannot be cleaned by hydraulic means is termed as hydraulically irreversible fouling. Similarly, that left over after chemical cleaning can be named chemically irreversible fouling.

2.2. Forms of fouling

UF fouling usually arises through several mechanisms including adsorption, pore blocking and cake or gel formation.

Adsorption occurs when specific interactions between solutes/particles and the membrane exist. It is a consequence of surface