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A review of efforts to reduce membrane fouling by control of feed spacer characteristics

Hadeel Subhi Abid[a], Daniel James Johnson[a], Raed Hashaikeh[b], Nidal Hilal[a,*]

[a] Centre for Water Advanced Technologies and Environmental Research (CWATER), College of Engineering, Swansea University, UK
[b] Chemical Engineering Department, Khalifa University of Science and Technology, Masdar Institute, Masdar City, P.O. Box 54224, Abu Dhabi, United Arab Emirates

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ABSTRACT

A major problem for the operation of membrane based water treatment systems is fouling of the membrane surface. Within industrial modules, such as spiral wound modules, feed spacers are necessary to separate adjacent membrane layers. Engineering of feed spacers with novel characteristics is an attractive option for reducing fouling within the module, for instance by increasing surface shear forces. This paper reviews the characteristics of feed spacers which are important in fouling and efforts to design novel feed spacers with anti-fouling characteristics, such as by addition of surface coatings, modified feed spacer design and geometric considerations, 3D printing and use of electrically conductive feed spacers. This paper also provides a brief review of techniques available to assess aspects of feed spacer design. It is seen that appropriate feed spacer design can do much to mitigate fouling in membrane modules, but continued effort is needed toward enhancement of high flux and low-pressure drop in membrane modules.

1. Introduction

Successful application of membrane technology necessitates not only high membrane performance, but also the engineering of feed spacers which can effectively manage fluid-flow at the membrane surface. A major contributor to flux decline during membrane separation processes is concentration polarization (CP) of the solute, in conjunction with irreversible fouling at the membrane surface [1,2]. Both cross-flow profiles and permeate flux are altered by concentration polarization [3,4]. Fluid-flow management determines optimal membrane module performance, since it effectively enhances fluid-flow [5–7]. From an operational perspective permeate flux, cross-flow, module geometry and array shape control the extent of CP [8,9]. In addition CP has a major effect on inorganic fouling of the membrane surface, due to accumulation of solute happening at a greater rate than back diffusion to the bulk solution. To overcome these problems, a number of research strategies have focused on adapting feed channel spacer in membrane models to enhance membrane performance [10–14].

Feed channel spacers are an essential part of spiral wound module (SWM) design. The feed spacer ensures inter-membrane spacing and improving mixing [15,16], and has a major impact on membrane performance [7,17]. However, the feed channel spacer may offer localized dead spots with poor mass transfer that encourage fouling [18,19]. Thus, for better feed spacer performance, the designers should attempt to maximize the mass transfer whilst at the same time minimizing the pressure drop, as this will reduce fouling initiation [2]. However, the most significant impairment to the efficient operation of membrane units is membrane fouling, which seriously hampers the application and uptake of membrane technologies [20,21].

Fouling is a complicated phenomenon determined by the interplay of several mechanisms whose activity varies depending upon the specific conditions [22,23]. Fouling is defined as the detrimental deposition of retained particles, colloids, salts and macromolecules at the surface (surface fouling) and/or inside the membrane pores (internal fouling) [24–28]. Generally, several categories of foulants and fouling can be defined, depending on the physical and chemical nature of the foulant species: inorganic (scaling), organic, colloidal and biofouling [29–32]. The accumulation of foulants can come in the form of concentration polarization, physical pore blocking or cake/gel layer formation [56]. Membrane fouling sets-up a barrier layer or film on the surface of the membrane or blocks the membrane pores leading to inhibition of water flux, increasing the pressure drop across the membrane and reducing permeate productivity [33–35]. In spiral-wound membrane modules, pressure drop can be classified into two categories: the feed channel pressure drop (the pressure drop between feed and brine lines) and the transmembrane pressure drop (the differential pressure between feed and permeate lines). With the present of a feed spacer, during biofilm accumulation and biofouling generation, an

* Corresponding author.
E-mail address: n.hilal@swansea.ac.uk (N. Hilal).

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increment of transmembrane pressure drop occurs and the membrane flux declines. The impact of membrane fouling on the development of transmembrane pressure drop is insignificant in comparison with the transmembrane pressure drop due to feed spacer fouling [19,68]. Much research into fouling of membrane modules focusses on biofouling of the modules as a whole, rather than looking at specific interactions with the feed spacers directly, or at other types of fouling [118]. The consequences of fouling and resulting decline in flux ratio leads to an increase in the operating pressure necessary to maintain permeate output, as well as requirements for extensive pre-treatment and cleaning procedures and chemicals, leading to an increase in operating and maintenance costs of the affected water treatment system [36,25]. For these reasons, membrane fouling is a significant concern when considering the engineering aspects of membrane technology [37,38].

Organic fouling progression occurs due to adsorption is considered the most commonly mechanism conjoined with organic fouling and therefore, interaction between the organic foulant and membrane surface is of supreme significance issue. Biofouling is considered more specially challenging due to the prospect for membrane pores to become blocked. Also, biofouling can assistance the other types of fouling, such as inorganic fouling, as these channelling matters leads to the precipitation of soluble salts and, eventually, scaling [57].

During industrial scale membrane processes, the exclusion of contaminants in order to gain clean water is most often performed by means of SWM modules. Accordingly, optimisation of the performance of these membrane modules has been focussed on the development of membranes [39] and engineering of the feed channel spacer design [40]. In the case of feed spacer optimization, the reported research works can be classified into two categories: (a) efforts to enhance the conventional plastic spacer design by studying the impact of the spacers orientation and geometry, for instance spacer thickness, filament diameter, and mesh length on water treatment process performance; (b) novel feed spacer designs which can surpass the conventional feed spacer performance [41]. The majority of feed spacer modification investigations are either experimental or numerical modelling studies aimed at estimation of the underlying phenomena and with optimizing the feed spacer configuration [42]. The effect of hydraulics on spiral-wound membrane systems performance as well as electrically conductive spacer meshes, for application of effective cleaning strategies using electrolysis have been of much recent interest [43,44]. Approaches for controlling biofouling focussing attention on the feed spacer have comprised changing the feed spacer thickness or orientation [45], periodic air/water cleaning [46],and coating of biocides on the net-spacer [47,48].

Consequently, it is essential to provide an up-to-date review of feed spacer modification and its role in improving membrane fouling control. There are a large number of studies that have adopted different approaches in the development of novel membrane modules for water treatment applications. However, the focus of this review is concentrated on the modification of feed spacers. This includes firstly looking at the fundamentals of feed spacer configuration, followed by other important aspects such as feed spacer modification and applications for membrane fouling mitigation. Finally, recently reported techniques to characterize feed spacer surface morphology and its relationship to fouling are summarised, with a discussion of the main issues and challenges which need to be addressed in future investigations (see Fig. 1).

2. Effect of feed spacer modification on fouling

The conventional commercial membrane configuration is the SWM, which presents a large membrane surface area. This configuration includes polymeric separation grids, which act as spacers between adjacent membrane sheets, keeping an open flow path while also offering flow disturbance that may contribute to decreased CP by improving feed mixing. Alteration of feed spacer geometry is a potential option to reduce the impact of fouling on the performance of membrane systems. Commercially, there are two main feed spacer configurations available: woven and nonwoven [50,51]. Good spacer configurations should reduce a build-up of fouling deposits and decrease CP *via* keeping the solute concentration in the layer of fluid in contact with membrane surface at close to the bulk concentration [52,53]. Rejected species accumulation can be suppressed by encouraging back-mixing from the solution layer adjacent to membrane to the liquid bulk [50]. An emerging methodology is to modify feed spacer configuration to reduce fouling. Generally, several strategies have been adopted to develop mesh-type spacers such as by surface coating [54], altered geometry design [55] or three-dimensionally printed feed spacers [41], and use of electrically conductive spacers [43].

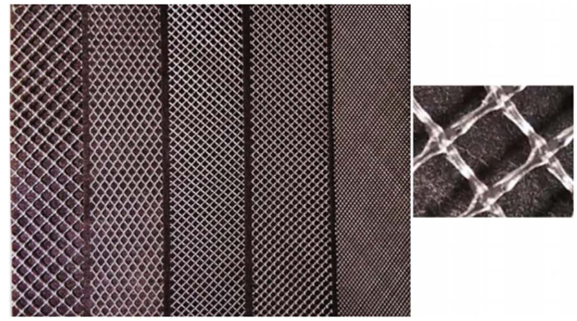

Fig. 1. Images of several conventional mesh-type feed spacers.
Reproduced from [49].

2.1. Effect feed spacer surface coating modification

Many approaches have been adopted to modify the features of feed spacer surfaces through coating as a strategy for improving filtration performance and reducing fouling impact. Several attempts have been reported in this field, for example Hausman et al. [56,57] studied the efficiency of the biocidal properties of polypropylene as a membrane feed spacer for reverse osmosis, wherein a spacer arm was functionalized with chelating ligands charged with the ions of copper to purify water from microbial biofilms. Modified and Virgin films were submerged in solutions in contact with 3.0×10^5 *Escherichia coli*/mL. Fouling analysis revealed that the number of cells adhered to virgin sheets after 7 days was an order of magnitude greater than those attached to the modified sheets.

Yang et al. [48] investigated the potential of biofouling control through the membrane and feed spacer surface modification with a nano-silver coating. Silver nanoparticles were directly coated on the reverse osmosis membrane and feed spacer surface using a chemical reduction technique. The antifouling performance of modified membrane with unmodified feed spacer as well as the coated feed spacers along with a virgin membrane was tested in a cross-flow cell, and their fouling control performance compared. Permeate flux decline, salt rejection and microbial activity progress on the membrane cell were monitored and quantified. They stated that the analysis results exhibited that both coated membrane with uncoated feed spacer and coated feed spacer with unmodified membrane presented better than the uncoated membrane and feed spacer in terms of decline in permeate flux and salt rejection. Also, they stated that the effect of coated feed spacer on antimicrobial activity was more durable (see Fig. 2).

Araújo et al. [47] investigated the effects of metal coating on feed spacers in commercially spiral wound membrane modules and studied their potential for anti-biofouling activity. The influence of metal coating on biofilm activity was examined with six parallel-operated membrane fouling simulators. Copper and silver were adopted as biocides for the control of biofouling. The effect of gold coating was also employed to compare with silver and copper coating. Surprisingly, they noticed that the feed spacers coated with copper and silver did not