Turbulence Promoters in Membrane Processes

Virtual Special Issue

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Section 1. Introduction

Despite major advances in the performance of available membrane materials, we are still facing the problems of concentration polarisation (CP) and/or fouling, especially in pressure driven membrane filtration processes. Both, CP and fouling depend on numerous factors such as the interactions of the membrane material and components in the feed, the module geometry, and device operating conditions, such as the transmembrane pressure drop distribution across the module, the cross-flow velocity, and / or the imposed filtrate flow rate, i.e. flux. The boundary layer (BD), in which CP occurs, is very thin, on the order of magnitude of micrometers. It is a challenge to disrupt it and enhance mass transfer [1].

CP and fouling can be partially overcome by operating the process as cross-flow (tangential flow) filtration in which the flow directions of the feed/retentate and permeate are arranged perpendicular to each other. The retentate flows parallel to the membrane surface, reducing the thickness of the boundary layer. The fouling extent decreases with an increase of the cross-flow velocity due to the increase in the local shear stress. To observe the effect of BL disruption very high cross-flow velocities are needed, e.g., 5 - 10 m s^{-1}. Nevertheless, fouling still occurs and the high cross-flow velocity leads to high pressure drop through the module. In turn, this leads to uneven transmembrane pressure across the membrane length as well as increased energy consumption.

An elegant approach to improve hydrodynamic conditions in the membrane module without significantly increasing energy consumption and investment costs is to insert static turbulence promoters in the membrane module. Even though turbulence can also be promoted using dynamic means; here we will focus on static promoters. These have several advantages: they use only energy of the moving fluid, there are no moving parts so there are no additional maintenance costs and, can be inserted into existing systems.

The main role of static turbulence promoters is to disrupt the BL near the membrane surface so to reduce concentration polarization and prevent or minimize fouling. In this case, the concept of BL disruption relies not only on the increased local velocity nearby the membrane wall, but also on the changes in the flow field appearing as secondary flows. To generate secondary flow fields, it is necessary that the turbulence promoter has a certain geometry. For example, the use of a simple rod baffle or smooth plate inserted in a tubular membrane will increase the cross-flow velocity, accelerating the fluid, but it will not cause any secondary flow. In contrast, vortices can be generated using spacers that are curly or helically shaped. Since spacer geometry also greatly influences the pressure drop, it is necessary to choose and optimize the geometry in a way that provides the best compromise between the flux and energy consumption.

There are two basic concepts of turbulence promotion used in membrane modules: turbulence promoters (TP-s) in tubular modules and membrane spacers which primarily keep membranes apart but also introduce secondary flow patterns and local turbulence. The role of TP-s used in tubular membrane systems is primarily to improve hydrodynamic conditions in the membrane channel. So any kind of baffle which can be inserted in the membrane channel can be used for that purpose. Spacers were introduced to separate membrane sheets, usually in flat sheet and spiral wound membrane modules, and simultaneously to improve hydrodynamics in the channels. Wide varieties of geometries have been studied in both concepts so it is very difficult to make classification based solely on geometry. Among plenty of published papers, mainly dealing with broad application of spacers, we have chosen to present those studying innovative geometries. Influence of geometry is evaluated either (a) by the magnitude of the flux improvement and energy consumption or, (b) characterisation of hydrodynamic conditions and flow pattern development.

Geometries of TP-s used in tubular membranes include smooth rods, helical screw-thread, spiral wire, conical inserts, twisted tapes (Fig. 1a), KM Kenics™ and blade static mixers (Fig. 1b). Modifications of geometrical characteristics includes change of length element shape, alternation of its orientation, and changes in the ratio of the element length to diameter ratio. More details on the TP in tubular membranes used mainly in the MF and UF processes can be found in the paper of Popovic et al. [2]. The most frequently used turbulence promoter has been KM Kenics™ mixer which has alternating helical geometry. But, the alternation significantly enlarges pressure drop, so the KM mixer can be energetically less effective compared to some other more simple geometries such are twisted tapes [3]. Nevertheless, all TP kinds are more efficient than the conventional operation from the point of view of both the flux increase and energy consumption.

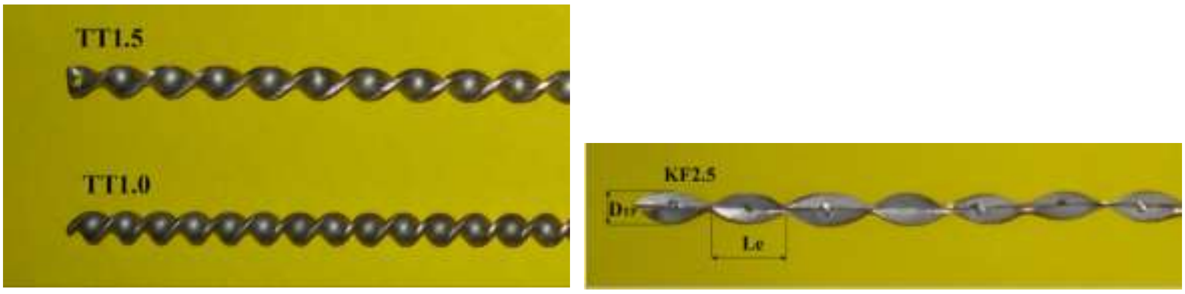

Figure 1. Twisted tape (TT) and blade type turbulence promoters for tubular membrane [2, 3].

Applications of spacers are manifold: mostly they are used in spiral-wound membrane modules for water and wastewater treatment membrane processes. The spacer acts both as a mechanical support for the channel geometry and as a turbulence promoter for the disruption of BL. Studies focus on optimizing spacer configuration, either experimentally or theoretically, with the aim to improve hydrodynamic conditions and extend the operating time of the membrane module. Methods of optimizing spacer configurations reported in the literature include varying the characteristic angle toward the feed direction of the spacer, the diameter, shape and spacing of filaments in a spacer, and multi-layer arrangement [4]. There exist two basic types of spacers: net and woven spacers. Recently, novel spacers having a multilayer structure (sandwich of spacers containing a bigger spacer in the middle with two thin outside spacers) or spacers having alternating helical elements (Fig. 2) have been developed [5-7]. Furthermore, spacers integrated into a membrane have been studied in the process of electro-dialysis [8]. Possible disadvantages of spacers' application can be low effectiveness in the case of systems with significant biofouling, e.g., in water treatment [9,10]. In the cases of CP or surface fouling caused by macromolecules, particles or ions, spacers are proven to work effectively. Once fouled, spacers can be cleaned: a recent paper discusses the high efficiency of bubble nucleation on spacers [11].

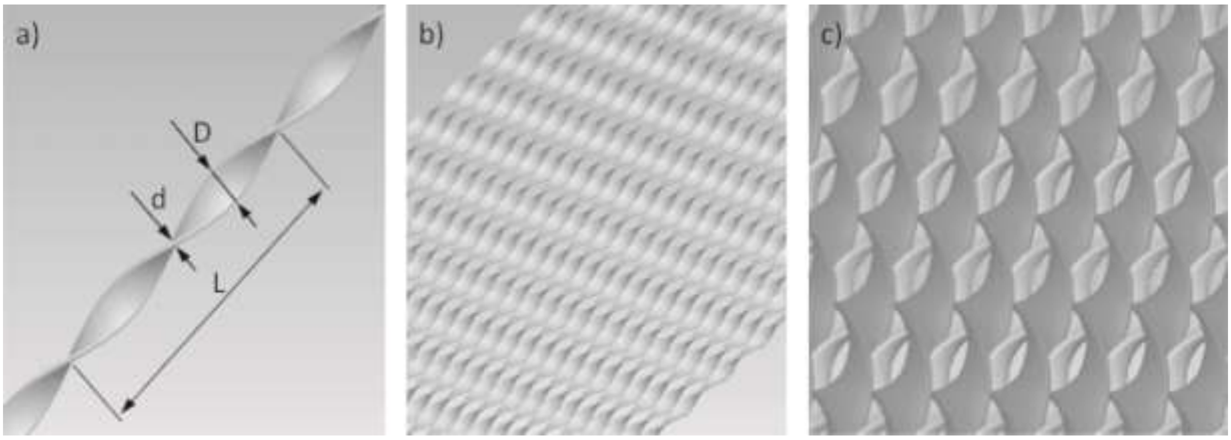

Fig. 2. (a) Double-helix form twisted filament, (b)single layer of twisted elements, and (c) two-layer spacer [7].

Even though the benefits of BL disruption and mass transfer enhancement outweigh the disadvantage of increased pressure loss, energy consumption should be always carefully considered. While the increase of flux can range up to 700%, energy consumption (per volume of permeate produced) can be reduced up to 80% compared to the conventional operation without any type of TP [3]. So far in the Journal of Membrane Science more than 100 papers have been published dealing with application of spacers and turbulence promoter in a sense of improved membrane process, mass transfer and hydrodynamic conditions. Review papers on the subject of turbulence promotion in membrane modules are very scarce. In the Journal of Membrane Science only one review paper on the subject of spacers in the spiral wound modules has been published ten years ago [12]. This Virtual Special Issue highlights contemporary achievements in the field of intensification of membrane processes by application of static turbulence promoters, both spacers for flat sheet and spiral wound modules and, turbulence promoters for tubular membrane modules.

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Section 5. Concluding remarks

Intensification of membrane processes by application of turbulence promoters plays significant role in the sustainability of membrane technologies and has attracted attention in recent years. Studies are mainly focused on the mitigation of membrane fouling expressed over the flux improvement and energy consumption, the optimisation of promoter's geometry, simulation and modelling of hydrodynamic conditions.
Breakthroughs in novel spacers and turbulence promoters design are expected in the near future. They are related to the 3D prototyping technologies and computation fluid dynamics (CFD) software development. CFD software development will facilitate and shorten the time of design of the optimal geometry by simulations and modelling of hydrodynamics and mass transfer in the module. Improvement of 3D printing technologies will assure the production of various geometries of turbulence promoters, their integration in a membrane module so production of systems with a high optimal efficiency.