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Using a high shear rotary membrane system to treat shipboard wastewaters: Experimental disc diameter, rotation and flux relationships

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ABSTRACT

The permeate flux (J) and volume throughput (Q) dependence on rotation (ω), diameter (D), Reynolds Number (Re) and shear rate (γ) for a high shear rotary membrane system (HSR-MS) was investigated to determine if larger, slower rotated discs could lead to a smaller system weight and foot/cube-print which is needed for US Navy shipboard placement. The HSR-MS steady state flux (J_{ss}) was highly dependent on ω and D ranging from 10 to 433 L/m^2 hr (LMH). For every 100 rpm increase in ω, J_{ss} increased on average by 26 LMH. The outer membrane third provided $\geq 50\%$ of the total flow, with the inner third providing about 15%. The J_{ss}–γ relationship was extended to larger membranes (312 and 374 mm) and predicted that J_{ss} increased by about 15% for each increase in size. Q_{ss} was much more sensitive to increases in diameter and corresponding surface area – Q increased by 45% for $D = 267$ mm$\rightarrow$312 mm and 65% increased for $D = 312$ mm$\rightarrow$374 mm ($\approx 1\%$ increase in Q per mm increase in diameter). Collectively, the results show that larger discs, rotated at lower rotations, can produce similar or greater Q compared to smaller discs rotating faster.

1. Introduction

Navy ships are floating cities, requiring a variety of infrastructure, services and operational resources. Equipment/process selection is based not only on reliability, operational ease and cost but also on weight, footprint (area) and cube-print (volume). During normal operation Navy ships generate a variety of shipboard wastewaters (bilge water, blackwater, graywater, etc.). Membrane systems are relatively easy to operate and are robust, making them an attractive treatment alternative for the variety of wastes generated shipboard. The high shear rotary membrane system (HSR-MS) has shown a superior ability to concentrate solids (up to 40% solids) for both Navy and non-Navy wastewaters [1–3]. However, low process volume throughput (Q), attributed primarily to low packing density, has largely confined the technology to land-based applications where space is not as much of an issue. As will be discussed subsequently, increasing the membrane's diameter will not necessarily increase the volume throughput.

With the HSR-MS, membrane discs rotate about a hollow shaft inside a cylindrical housing. Pressurized feed enters the membrane chamber and permeate is forced through the membrane and discharges into a hollow center shaft (Fig. 1). The drawbacks of these types of dynamic filtration systems are the mechanical complexity and equipment cost [4]. Scale-up becomes challenging as current HSR-MS designs have maximum disc stacks near 25. Adding discs to increase total membrane area requires additional motors, shaft assemblies, membrane housings and other mechanical/electrical components, which adds to the total HSR-MS weight and foot/cube-print.

With conventional membrane configurations, increasing the permeate flow can be accomplished by increasing the membrane area, the cross-flow velocity or the transmembrane pressure (if working in the pressure-dependent region). With the HSR-MS, increasing these parameters is not as straightforward because of the unique relationship among the permeate flux (J), membrane diameter (D), rotation (ω), shear rate (γ), and transmembrane pressure (P_{TMP}). For example increasing ω increases the γ, but also increases the rotationally induced backpressure (P_{back}), which decreases P_{TMP}. A better understanding of the J–ω–D–γ–P_{TMP} relationship is needed to maximize the system Q, especially in challenging applications such as a shipboard setting. Specific

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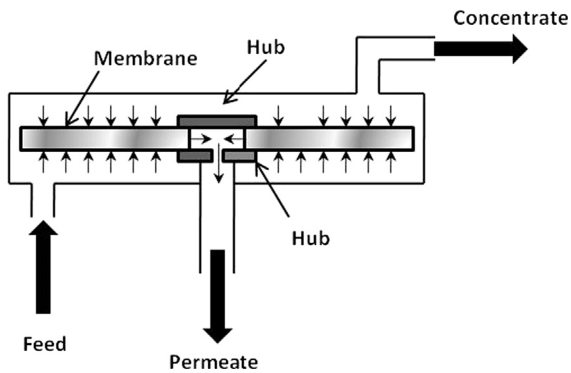

Fig. 1. HSR-MS process schematic.

objectives of this research are: (1) develop an understanding of J and Q as a function of D, ω and γ; (2) determine which method is better for increasing J and Q – increasing ω or increasing D; and (3) determine if larger, slower rotated discs can reduce the overall disc requirement, leading to an HSR-MS with a smaller weight and foot/cube-print.

2. Background

During filtration solute accumulates at the membrane surface, thereby forming a dynamic membrane surface that often controls the magnitude of J. Solute accumulation at the membrane surface and within the membrane pores is the key factor limiting membrane performance. Cross-flow membrane filtration relies on turbulence at the membrane surface to reduce the accumulation of solute [5]. Conventional cross-flow systems (*e.g.*, tubular membranes) use high feed flow rates to produce large tangential velocities/shear near the membrane surface – the surface is scoured, minimizing the thickness and density of the solute boundary layer. High pumping rates are maintained by either recycling the retentate back to the membrane feed tank (about 98% recycled) or by using multiple staged single-pass systems (the concentrate from stage n is the feed to stage $n+1$) [2]. As feed concentration increases (with time or stage number) it becomes increasingly difficult to maintain high velocities because of the increased feed viscosity. The lower cross-flow velocity and higher solute concentration lead to a reduction in J and an increased likelihood of membrane fouling/plugging. In the HSR-MS, turbulence/shear is obtained by rotating the membrane disc versus moving the bulk fluid. The pump is only required to provide pressure and feed to the system. Energy for surface scouring is applied exactly where it is needed (*i.e.*, membrane surface) unlike conventional configurations where energy is provided across the entire flow channel. In the HSR-MS system, maximum liquid velocities of $\sim$18 m/s are possible compared with 4.5 m/s for conventional cross-flow systems [2]. Also, because the feed delivery/pressurization is decoupled from turbulence/shear promotion, the HSR-MS can be operated at lower pressures, which decreases solute boundary layer compaction (decreased resistance, increased permeate flow) and pore plugging. Decoupling of feed delivery from turbulence promotion allows the HSR-MS to produce highly concentrated wastes [1,3,6,7,8].

2.1. J–ω–D–γ–Re–P_{TMP} relationship

HSR-MS flux (J) performance depends on many interrelated and often opposing variables. The relationship between the primary controllable variables, rotation (ω), transmembrane pressure (P_{TMP}) and disc diameter (D) provides for conflicting advantages and disadvantages.

To maximize surface scouring, membrane discs are often operated at high rotation (ω) based on the belief that greater surface scouring will provide for greater J. The surface scouring impacts from varied ω are quantified using the Reynolds number (Re) and shear rate (γ) as follows [4,9,10]:

$$\mathrm{Re} = \omega r^2/\nu \text{ (at any } r) \tag{1}$$

$$\mathrm{Re} = \omega I^2/\nu \text{ (for a given membrane section)} \tag{2}$$

$$I = [(R_i^2 + R_o^2)/2]^{1/2} \tag{3}$$

$$\gamma_{\mathrm{lam}} = 1.81(k\omega)^{1.5} r \nu^{-0.5} \tag{4}$$

$$\gamma_{\mathrm{turb}} = 0.057(k\omega)^{1.8} r^{1.6} \nu^{-0.8} \tag{5}$$

Here γ_{lam}=shear rate under laminar flow conditions, γ_{turb}=shear rate under turbulent flow, r=radial distance, ν=kinematic viscosity; I=radius of gyration, and k=velocity coefficient (0.4–0.5 for a smooth disc). For a given membrane area, I (average radial property of a rotating body) is used in place of r where R_i and R_o are the inner and outer radii. Ketola et al., estimated that turbulent conditions exist for Re $\geq$ 200,000 for a partially wetted rotating disc and this Re value will be used as a cut-off between laminar and turbulent conditions [11]. Jaffrin indicated that the γ for a rotating disc outer diameter can easily reach 3–4 $\times$ 10^5 s^{-1} [14].

In addition, membrane discs are often operated at high applied pressure based on the belief that the greater driving force will provide for greater J. The pressure impacts are quantified based on the applied pressure (P_{applied}) and the rotation induced radial dependent backpressure (P_{back}) which reduces the net transmembrane pressure (P_{TMP}) as follows [12,13]:

$$P(r)_{\mathrm{back}} = (\rho(\omega r)^2)/2 \text{ (at any } r) \tag{6}$$

$$P(I)_{\mathrm{back}} = (\rho(\omega I)^2)/2 \text{ (for a given membrane section)} \tag{7}$$

$$P(r)_{\mathrm{TMP}} = P_{\mathrm{applied}} - P(r)_{\mathrm{back}} \text{(at any } r) \tag{8}$$

$$P(I)_{\mathrm{TMP}} = P_{\mathrm{applied}} - P(I)_{\mathrm{back}} \text{(for a given membrane section)} \tag{9}$$

Eqs. (1)–(5) demonstrate that surface scouring will increase with rotation and diameter. Eqs. (6)–(9) demonstrate that pressure will decrease with rotation and diameter. So collectively, Eqs. (1)–(9) demonstrate that the inner membrane area is subjected to the highest P_{TMP} and the lowest γ while the outer membrane area is exposed to the lowest P_{TMP} and the highest γ (opposite to what is desired). Increasing ω can increase inner membrane area performance but can decrease the performance of the outer membrane area because of increased P_{back} (decreased P_{TMP}). P_{back} can be reduced by decreasing ω but a lower γ (and J) will result [6,8]. Again, this P_{TMP}–ω–γ relationship is opposite of what is desired.

Another potential method to increase Q/J is to increase γ by increasing the membrane diameter (Eqs. (4) and (5)); unfortunately increasing D results in a higher P_{back} and lower P_{TMP} (Eqs. (7) and (9)). P_{applied} can be increased to offset the increased backpressure at the outer portion of the disc, but then the inner portion of the disc, which has minimal P_{back}, is subjected to high P_{TMP}. Bouzerar reported that for a stationary membrane near a rotating disc the local permeate flux was higher at the periphery than in the central part, but the increase was significant only at high rotations [15]. Ideally, ultrafiltration/microfiltration (UF/MF) systems should be operated at lower pressures to minimize cake buildup/compaction (MF) and concentration polarization (UF). Increasing the size of the disc also introduces membrane structural concerns – at higher ω, discs can bend, thereby risking membrane