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Dynamic crossflow filtration with a rotating tubular membrane: Using centripetal force to decrease fouling by buoyant particles

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ABSTRACT

This paper describes a dynamic membrane filtration system that combines crossflow filtration and centrifugal separation in a rotating tubular membrane. Because of the no-slip boundary condition, membrane rotation leads to higher centripetal force near the lumen wall than introduction of a rotating flow. In this fundamental exploratory study, hollow glass microspheres (5–35 μm diameters) serve as model low-density, separate-phase foulants during filtration of aqueous suspensions through a tubular ceramic membrane (nominal 0.14 μm pore size). At low crossflow rates, membrane rotation at 1725 rpm decreases fouling and shifts the microsphere size distribution in the membrane cake toward smaller diameters. Force balance calculations suggest that centripetal force should move particles with diameters >~17 μm away from the lumen surface. Moreover, azimuthal and longitudinal shear stresses will also selectively remove larger particles from the membrane cake. Computational fluid dynamics (CFD) simulations show that the rotational flow does not fully develop in the membrane lumen and the fluid radial velocity peaks before the membrane wall. Both of these factors will decrease movement of low-density particles away from the lumen wall. Nevertheless, consistent with experimental data, CFD simulations show greatly decreasing encounters of particles with the membrane wall as particle size increases.

1. Introduction

Crossflow filtration is a membrane-based separation technique with many applications including desalination (Lee et al., 2011), wastewater treatment (Carstensen et al., 2012; Le-Clech et al., 2006), beverage production (El Rayess et al., 2011; van der Sman et al., 2012), and hemodialysis (Nie et al., 2015). In contrast to conventional crossflow filtration where liquid flows along stationary membrane surfaces to reduce concentration polarization or cake formation, dynamic crossflow filtration (DCF, also called dynamic filtration or shear-enhanced filtration) involves movement of solid boundaries such as the membrane itself or other surfaces positioned in the membrane's proximity (Jaffrin, 2008, 2012). Importantly, dynamic shear-enhanced filtration can decouple crossflow velocity and shear to control them independently (Jaffrin, 2008).

Since its conceptual introduction in the late 1960s, DCF has been proposed or applied to separate a broad range of feeds including oil-in-water emulsions (Li et al., 2009; Reed et al., 1997; Viadero et al., 2000) (milk, in particular Ding et al., 2003; Frappart et al., 2006); suspensions of latex particles (Mikulášek

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Nomenclature

δ_e	cut-diameter (due to erosion, particles larger than δ_e are prevented from depositing on the membrane surface)
$\dot{\gamma}_w$	shear rate at the lumen wall
θ	angle of repose of a particle
κ	erosion parameter
μ_l	viscosity of the dispersion phase (water)
ρ_l	density of the dispersion phase (water)
ρ_p	density of the particles
ϕ	wall correction factor to the drag force on a particle
ω	angular velocity
a_D	absolute value of drag force per unit mass of particle
C_f	concentration of microspheres in the feed suspension
C_D	drag coefficient
C_w	concentration of microspheres at the membrane wall
d_p	diameter of the particle
d_p^*	critical particle diameter (due to the rotation-induced centripetal force, particles larger than d_p^* are prevented from reaching the membrane surface)
$\vec{e}_r$, $\vec{e}_z$, and $\vec{e}_\theta$	unit vectors in the radial, vertical, and azimuthal directions, respectively
$\vec{F}_c$	centripetal force on particles
$\vec{F}_D$	total drag force on a particle
$\vec{F}_J$	drag force on a particle due to permeate flux
G_R	reduced grade efficiency
G_T	total grade efficiency
j	permeate flux
$\dot{m}$	mass flow rate of particles
$N_{i,f}$	number of particles of a given size in the feed
$N_{i,wall}$	number of particles of a given size in the cake at the end of the filtration
R	radius of membrane channel
Re	Reynolds number
Re_p	particle Reynolds number
r	distance from the center of the membrane channel
Q_{cf}	crossflow rate
Q_f	volumetric feed flow rate
Q_r	volumetric retentate flow rate
Q_p	volumetric permeate flow rate
S_w	Swirl number
t	total filtration time
$\vec{v}_{cf}$	crossflow velocity
$\vec{v}_l$	velocity of the dispersion (liquid) phase
$\vec{v}_{lift}$	velocity of particle due to inertial lift
$\vec{v}_p$	velocity of particle
$v_\theta \vec{e}_\theta$	azimuthal velocity
$v_r \vec{e}_r$	radial velocity
$v_z \vec{e}_z$	axial velocity
V_f	volume of the feed suspension

and Doleček, 1994), glass microspheres (Engler and Wiesner, 2000), yeast (Brou et al., 2002; Lee et al., 1995; Liu et al., 2012), bacterial cells (Frenander and Jönsson, 1996; Kroner and Nissinen, 1988), algae (Ochirkhuyag et al., 2008), and clay (Liu et al., 2012); black liquor (Bhattacharjee and Bhattacharya, 2006); aqueous slurries of SiO_2 (Choi et al., 1999; Engler and Wiesner, 2000) and $CaCO_3$ (He et al., 2007; Liu et al., 2012; Tu and Ding, 2010); protein solutions (Holeschovsky and Cooney, 1991); pulp (Ochirkhuyag et al., 2008); and navy ship wastewater (Bendick et al., 2014). Although desalination by reverse and forward osmosis (Sherwood et al., 1967) was the initial DCF target and some studies utilized nanofiltration membranes (e.g. Frappart et al., 2006), most DCF developments relate to porous membranes for ultrafiltration (Bhattacharjee and Bhattacharya, 2006; Ding et al., 2003; Hallstrom and Lopez-Leiva, 1978; Holeschovsky and Cooney, 1991; Li et al., 2009; Reed et al., 1997; Viadero et al., 2000) and microfiltration (Aubert et al., 1993; Brou et al., 2002; Engler and Wiesner, 2000; Espina et al., 2008; He et al., 2007; Lee et al., 1995; Li et al., 2009; Mikulášek and Doleček, 1994; Tu and Ding, 2010).

Typical DCF processes employ vibration (Beier et al., 2006; Genkin et al., 2006) or rotation of disks (Bouzerar et al., 2000; Brou et al., 2002; Ding et al., 2003, 2006; Espina et al., 2008; Frappart et al., 2006; Frenander and Jönsson, 1996; He et al., 2007; Lee et al., 1995; Li et al., 2009; Mänttäri et al., 2006; Sen et al., 2010; Tu and Ding, 2010) or membranes (Aubert et al., 1993; Beaudoin and Jaffrin, 1989; Belfort et al., 1993a,b; Bendick et al., 2014; Bhattacharjee and Bhattacharya, 2006; Choi et al., 1999; Dolecek et al., 1995; Engler and Wiesner, 2000; Hallstrom and Lopez-Leiva, 1978; Holeschovsky and Cooney, 1991; Kaplan and Halley, 1990; Kroner and Nissinen, 1988; Kroner et al., 1987; Liu et al., 2012; Mikulášek and Doleček, 1994; Murase et al., 1991; Ochirkhuyag et al., 2008; Park et al., 1994; Reed et al., 1997; Rock et al., 1986; Sarkar et al., 2011; Sen et al., 2010; Serra and Wiesner, 2000; Sherwood et al., 1967; Viadero et al., 2000; Vigo et al., 1985). The disks rotate in close proximity to a stationary membrane and can include multiple shafts (Ding et al., 2006; Espina et al., 2008; He et al., 2007; Tu and Ding, 2010) and vanes (Ding et al., 2003; Li et al., 2009; Sen et al., 2010). The family of rotating membrane systems includes an important subgroup of rotating annular filters (Belfort et al., 1993a,b; Choi et al., 1999; Dolecek et al., 1995; Hallstrom and Lopez-Leiva, 1978; Holeschovsky and Cooney, 1991; Kroner and Nissinen, 1988; Kroner et al., 1987; Mikulášek and Doleček, 1994; Murase et al., 1991; Park et al., 1994; Sherwood et al., 1967; Vigo et al., 1985). In these filters, the feed flows through the annular gap between two concentric cylinders, where the porous membrane is the inner rotating cylinder and an impermeable cylinder is the outer and stationary wall; Taylor vortices that form in such flow channels can greatly enhance membrane performance as demonstrated in applications ranging from blood plasma filtration (Rock et al., 1986) to ultrafiltration of cutting oil emulsions (Vigo et al., 1985). Several studies also employed flat membranes in DCF (Aubert et al., 1993; Bendick et al., 2014; Bhattacharjee and Bhattacharya, 2006; Engler and Wiesner, 2000; Ochirkhuyag et al., 2008; Reed et al., 1997; Sarkar et al., 2011; Sen et al., 2010; Serra and Wiesner, 2000; Viadero et al., 2000); in such systems, a membrane mounted on a porous support rotates next to a wall that is stationary or rotating in the opposite direction to enhance shear. Other configurations such as a rotating helical membrane (Liu et al., 2012) and a rotating impermeable tube just upstream of a stationary tubular membrane (Shan, 2010; Shan et al., 2010) have been explored as well.

DCF studies to date focused on increasing wall shear stress and turbulence, or on employing local hydrodynamics (e. g. Taylor vortices in rotating annual filters) to minimize concentrate polarization and cake formation. Although rotating disks