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Microfiltration: Effect of channel diameter on limiting flux and serum protein removal[1]

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ABSTRACT

Our objective was to determine the limiting flux and serum protein (SP) removal at 8, 9 and 10% true protein (TP) in the retentate recirculation loop using 0.1-μm ceramic graded permeability (GP) microfiltration (MF) membranes with 3 mm channel diameters (CD). An additional objective was to compare the limiting flux and SP removal between 0.1-μm ceramic GP membranes with 3 mm CD and previous research using 4-mm CD membranes. The MF system was operated at 50°C, using a diluted milk protein concentrate with 85% protein on a total solids basis (MPC85) as the MF feed. The limiting flux for the MF of diluted MPC85 was determined at 8, 9, and 10% TP concentration in the recirculation loop. The experiment using the 3-mm CD membranes was replicated 3 times for a total of 9 runs. On the morning of each run MPC85 was diluted with reverse osmosis water to a MF feed TP concentration of 5.4%. In all runs the starting flux was 55 kg/m^2 per hour, the flux was then increased in steps until the limiting flux was reached. For the 3-mm CD membranes, the limiting flux was 128 ± 0.3, 109 ± 4, and 97 ± 0.5 kg/m^2 per hour at recirculation loop TP concentrations of 8.1 ± 0.07, 9.2 ± 0.04, and 10.2 ± 0.03%, respectively. For the 3-mm CD membranes, increasing the flux from the starting to the limiting flux decreased the SP removal factor from 0.72 ± 0.02 to 0.67 ± 0.01; however, no difference in SP removal factor among the target recirculation loop TP concentrations was detected. The limiting flux at each recirculation loop target TP concentration was lower for the 3- compared with the 4-mm CD membranes. The differences in limiting fluxes between the 3- and 4-mm CD membranes were explained in part by the difference in cross-flow velocity (5.5 ± 0.03 and 7.0 ± 0.03 m/s for the 3- and 4-mm CD membranes, respectively). The SP removal factor was also lower for the 3- compared with the 4-mm CD membranes, indicating that more membrane fouling may have occurred in the 3- versus 4-mm CD membranes.

Key words: microfiltration, limiting flux, serum protein removal

INTRODUCTION

Microfiltration (**MF**) has been used to remove serum protein (**SP**) and other low molecular weight components (i.e., lactose and NPN) from skim milk (Fauquant et al., 1988; Zulewska et al., 2009) or a milk protein concentrate (**MPC**; Hurt et al., 2015b). As a feed material for MF, MPC will have had a large amount of lactose, soluble minerals, and NPN removed before MF compared with skim milk. The use of a diluted MPC as an MF feed would produce a micellar casein concentrate (**MCC**) with a lower lactose and NPN concentration compared with the use of skim milk as the MF feed. An MCC would have a low concentration of heat-labile components, such as SP and lactose, and may be suitable for the formulation of high-protein, shelf-stable beverages. Both the membranes used for MF and the operating conditions (including flux) could affect the MCC composition and the MF membrane area required to produce the MCC.

In MF there are 3 important fluxes: critical, limiting, and sustainable flux. The critical flux is the flux at which membrane fouling begins to occur (Bacchin et al., 2006). Below the critical flux a linear relationship exists between flux and increasing transmembrane pressure (**TMP**), and as flux exceeds the critical flux the membrane starts to foul and the relationship between flux and TMP is no longer linear. The limiting flux is the highest flux that can be achieved by increasing the TMP (Bacchin et al., 2006). The critical and limiting fluxes are shown in Figure 1. The third important flux is the sustainable flux. A sustainable flux is a flux that the system can operate at for extended periods of time, such as a production run (Bacchin et al., 2006). The sustainable flux would fall somewhere between the critical and limiting fluxes, where the rate of membrane fouling is low (Bacchin et al., 2006).

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[1]Use of names, names of ingredients, and identification of specific models of equipment is for scientific clarity and does not constitute any endorsement of product by authors, Cornell University or the Northeast Dairy Foods Research Center.

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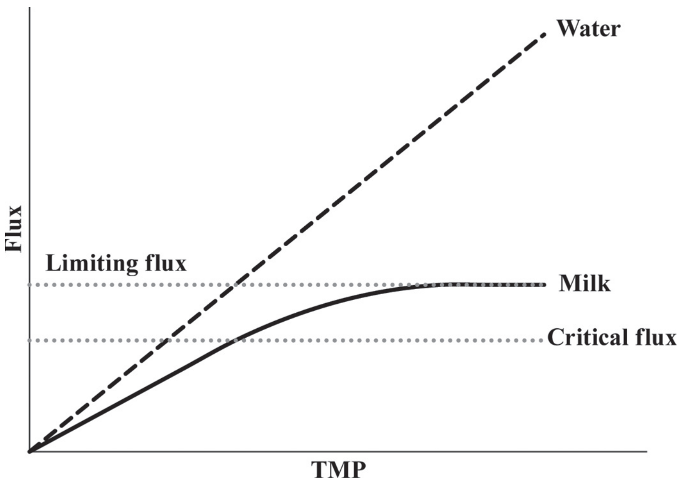

Figure 1. Limiting flux and critical flux on a graph of flux as a function of transmembrane pressure (TMP). Adapted from Bacchin et al. (2006) with permission.

The MF membranes used to produce an MCC could affect both the SP removal and the overall flux and performance of the MF system. Previous work has compared the flux and SP removal of ceramic versus polymeric membranes (Zulewska et al., 2009). In general, flux and SP removal are lower with polymeric membranes (Zulewska et al., 2009) than ceramic membranes. Different types of ceramic membranes have been used to MF milk. Ceramic membranes typically operate at high cross-flow velocities (2 to 6 m/s; Cheryan, 1998). A large longitudinal pressure drop (**ΔP**) on the retentate side of the membrane is required to achieve high cross-flow velocities. A high cross-flow velocity results in a TMP at the inlet end of the membrane that is much larger than the TMP at the outlet end of the membrane, which could result in higher fluxes at the inlet end of the membrane and increased membrane fouling at the inlet end.

There have been several methods developed to create a uniform flux along the length of ceramic membranes. In the uniform transmembrane pressure (**UTP**) system, a permeate recirculation pump is used to produce co-current flow of permeate in parallel to the retentate, which produces a gradient of back pressure on the permeate side of the membrane; this creates a pressure drop on the permeate side of the membrane that matches the pressure drop on the retentate side of the membrane (Holm et al., 1990). Another method is to manufacture the membranes with a resistance gradient so that the flux is constant along the length of the membrane even with a large ΔP. Two commercially available ceramic membranes with a resistance gradient are the graded permeability (**GP**) membranes (Pall Corp., Cortland, NY), which have the resistance gradient on the outside of the support layer (Garcera and Toujas, 2002), and Isoflux membranes (TAMI, Nyons, France), which has the resistance gradient built into the separating layer of the membrane (Grangeon et al., 2002).

Zulewska et al. (2009) reported that in a 1-stage, 3× MF process, 64% of the SP was removed in a UTP system [0.1 μm, 4-mm channel diameter (**CD**)] and 61% of the SP was removed using GP membranes (0.1 μm, 4 mm CD). Isoflux membranes have been reported to remove less SP (40%) than the UTP or GP membranes (Adams and Barbano, 2013). Whereas SP removal was similar for the UTP and GP systems, the GP system does not require a permeate recirculation pump, and a system with GP membranes would have both a lower fixed and operating cost.

Graded permeability membranes come in several configurations; GP membranes are available with both 3 and 4 mm CD (Sondhi et al., 2003). The GP membranes are designed to operate at a specific ΔP (Garcera and Toujas, 2002).The 3-mm CD membranes have a greater surface area (46%) per stick compared with 4-mm CD membranes. The limiting flux and SP removal factor for 4-mm CD membranes at 8, 9, and 10% target true protein (**TP**) concentrations in the recirculation loop were reported by Hurt et al. (2015b); however, little information is available on the performance of 3-mm CD membranes for the production of an MCC using diluted MPC as a feed material.

Limiting flux and SP removal could be a function of the MF membrane CD. The limiting flux is a function of the back transport of molecules away from the surface of the membrane (Belfort et al., 1994). Several factors could affect the back transport of molecules, including viscosity, particle size, concentration, and shear rate at the surface of the membrane (Belfort et al., 1994). From the literature it is not clear what effect CD will have on membrane fouling and, thus, limiting flux or SP removal factor. In a review by Belfort et al. (1994), 4 models for the prediction of limiting flux were presented. Channel diameter does not appear explicitly in any of the models, but in all of the models increasing the shear rate at the wall was predicted to increase limiting flux.

The shear rate at the wall could be a function of CD. Reynold's number is defined in Equation 1:

$$\text{Reynold's number} = \frac{\text{density}\left(\frac{\text{kg}}{\text{m}^3}\right) \times \text{cross-flow velocity}\left(\frac{\text{m}}{\text{s}}\right) \times \text{channel diameter}(\text{m})}{\text{retentate viscosity}(\text{Pa}\cdot\text{s})}. \quad [1]$$

For laminar flow [Reynold's numbers <2,100 (Denn, 1980)], shear rate at the wall is proportional to cross-