IMPACT OF SPACER GEOMETRY ON ULTRAFILTRATION PERFORMANCE IN A FILTER MODULE

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Abstract
In our research, we aimed to explore how the filtration efficiency of a specialized membrane filtration device could be enhanced using custom-made, 3D-printed spacers with various geometric designs. We performed experiments using model dairy wastewater with an average load, a polyethersulfone (PES) ultrafiltration membrane, and a membrane filtration device. The tests were performed with (and without) different spacer configurations.
During the experiments, we evaluated several factors, including the permeate flux, membrane retentions, resistances, and specific energy consumption. Our measurements clearly showed that the use of 3D-printed spacers significantly improved the filtering efficiency, with some geometric configurations yielding better results.

Introduction
In today's world, wastewater management poses a significant challenge due to limited resources, making it essential to treat and recycle as much waste as possible. Among the various wastewater treatment methods, membrane filtration holds the most potential [1]. This process uses semi-permeable membranes to filter water, allowing water molecules to pass through while retaining solid particles [2]. In our research, we focused on ultrafiltration (*UF*), a pressure-driven filtration process. *UF* effectively removes suspended particles, bacteria, and viruses, but cannot filter out sugars or mono- and multivalent ions. A key drawback of membrane filtration is the inevitable fouling of the membranes. As filtered solids accumulate on the membrane's surface and within its pores, permeate flux decreases, and energy consumption rises [3]. To address this, several mitigation strategies exist, such as backwashing, chemical cleaning, and the use of module vibrations or flow diverter spacers [4]. Our study focused on the impact of the last method. We conducted tests with flow diverter spacers, which were designed based on our own plans using reference models and produced via *FDM* (Fused Deposition Modeling) 3D printing. This manufacturing method was ideal for our research, as 3D printing technology has seen rapid advancements in recent years and is now widely applied not only in industry but also in everyday life [5]. Additionally, 3D printing allowed us to quickly modify and produce new models based on insights gained from previous tests and experiences.

Experimental
The tests were conducted on a 10 liters of a model dairy wastewater solution consisting of skimmed milk powder, with a mass concentration of 5 g/L, cleaning detergent, with 0.5 g/L and room temperature tap water. A *VSEP* Series L membrane filtration module was employed,

maintaining two constant parameters: a transmembrane pressure of 8 bars and a volumetric flow rate of 4 *GPM* (approximately 15.14 L/min) (New Logic Research, Inc., USA).

Throughout 5 experiments, we analyzed various factors, including permeate flux, membrane retention, resistance, and specific energy consumption. The experiments used four variations of spacers: Sp.1-4. (Table 1.) The spacers were 3D-printed using *PETG* and *PCTG* plastic filaments on our in-house 3D printer (filaments: Filatikum, Hungary; *FDM* printer: Creality CR-10S Pro V2, China).

During the 2-hour experiment processes, 9 samples were collected in each case at different time intervals (2 feed solutions, 4 permeates, and 3 concentrates). Each sample was analyzed for total dissolved solids (*TDS*), pH level, conductivity, and turbulence. The final permeates and concentrate samples were also tested for chemical oxygen demand (*COD*), milk fat, protein, lactose with an infrared device (Bentley Instruments, Inc., USA), and protein values with Kjeldahl method (Foss, Britain).

Results and discussion

In figure 1. the permeate fluxes and in figure 3. the specific energy consumption results were plotted. Values were compared over time and over volume reduction ratio (VRR). First, it can be concluded that the use of spacers produced better results compared to the control measurements. One of the designs, Sp.1 yielded the best overall performance across all parameters, including permeate flux, retention, resistance, and specific energy consumption.

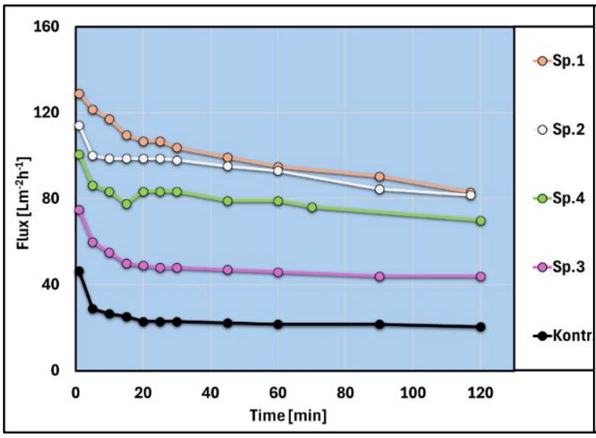

Figure 1. Permeate fluxes as a function of time (TMP=0.8MPa, q_{vrec}=15.14L/min, T=25±1°C)

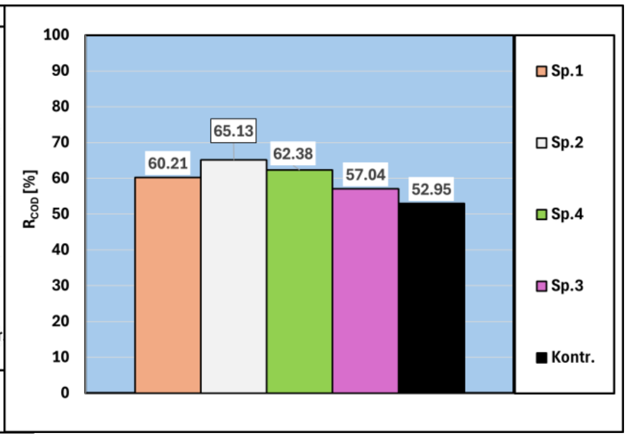

Figure 2. Retentions compared within each spacer (TMP=0.8MPa, q_{vrec}=15.14L/min, T=25±1°C)

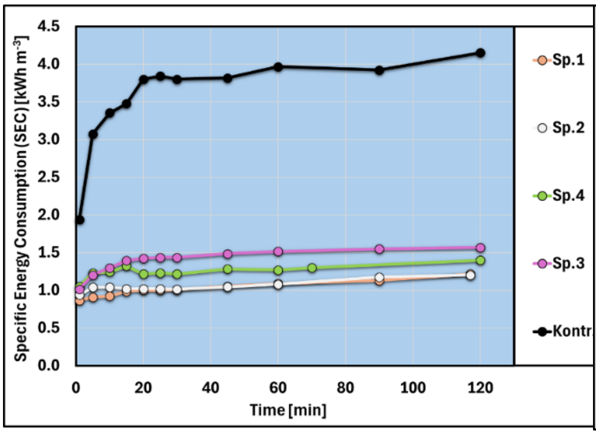

Figure 3. Specific energy consumption as a function of time (TMP=0.8MPa, q_{vrec}:4, T=25±1°C)

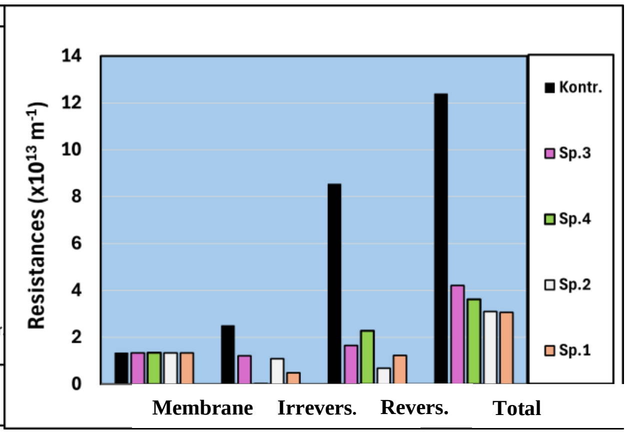

Figure 4. Irreversible and reversible resistances compared to total resistance (TMP=0.8MPa, q_{vrec}:4, T=25±1°C)

Differences between the geometric spacer designs were observed. The first two designs (Sp.1 and Sp.2) significantly outperformed the latter two (Sp.3 and Sp.4) based on the flux results. However, it's important to highlight that Sp.3 and Sp.4 required considerably less plastic for the printings. Furthermore, it can be seen from Figure 3 that the use of spacers reduced the specific energy consumption values by about one third. The fourth figure shows that the value of the total

resistances have also been greatly reduced compared to the control measurements. In addition, the first two designs gave better results than the third and fourth, as the resistances were the lowest.

Sp.1 *– First design*
Sp.2 *– First design, cone variant*
Sp.3 *– Tesla-valve inspired design*
Sp.4 *– Strengthened Tesla-valve inspired design*

Table 1. Spacer designs meanings

Conclusion

The key finding from our results is that to achieve optimal performance, a spacer with a certain geometry should be used. This approach significantly boosts the initial flux and extends the time before a substantial drop in performance occurs. As a result, the filtration process becomes more efficient, reducing the time required to treat a given volume of wastewater and lowering overall energy consumption. The average of flux values taken with the best spacer indicate a staggering 309% improvement when compared to the average of the control measurements. In the case of energy consumption, an 70% decrease is observable, when compared to the control values.

Given the lower resource and energy demands of the latter designs, it warrants further investigation to determine whether their reduced performance is offset by these savings. Future studies should assess whether the decreased performance of Sp.3 and Sp.4 can be justified by their more efficient material and energy use, particularly for large-scale applications.

Further research should also explore the combination of using multiple anti-fouling techniques, such as using spacers and module vibrations simultaneously. Our preliminary experiments in this area have shown highly promising results, warranting continued investigation. Future studies will focus on further examining this approach.

Acknowledgements
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