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Nature-Inspired Hydrodynamic Techniques to Enhance Membrane Separation Performance – A CFD+DEM Case Study

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Extended Abstract

According to the United Nations (UN) World Water Development Report from 2023, in 2010 around 32-46% of the world's population lived under water stress for at least a month per year.[1] It is expected that by 2050 the world's population will have increased from 8 billion now to approximately 9.8 billion.[2] If global living standards continue to improve, the demand for clean water will be, roughly, the fresh water resources of three planets Earths by 2050.[3]

Membrane-based filtration processes are increasingly used in industrial environments, for being energy-saving, cost-effective and space efficient. However, these processes also have some drawbacks, membrane fouling being one of the most difficult to deal with.

Natural filtration processes such as the kidney's blood filtration, and the filter-feeding system of certain animals are examples of highly effective membrane filtration techniques. Their efficiency is likely a result of multiple factors, such as the physicochemical characteristics of the membranes and the geometrical characteristics of the membrane sites.

When seeking to develop a nature-inspired membrane, one should understand the underlying mechanisms behind such natural systems, from the nanoscale to the macroscale, in addition to possible dynamic factors.[4] Previous research drawing inspiration from the kidney has shown that tuning charge and hydrophilicity of the membrane surface can affect their antifouling properties.[5] Also, a cell membrane-inspired graphene nanomesh membrane exhibited superior antifouling properties, while maintaining a high water flux through the membrane.[6]

Since multiple scales are important in natural systems, hydrodynamics might also influence anti-fouling in membrane filtration. The glomerulus curvature, and the oral cavities of filter feeding species might generate fluid instabilities that decrease fouling. The membrane placement on filter-feeding species and the glomerulus' blood vessels' curvature are the inspirations for the concept that membrane placement and the formation of Dean vortices, the increased near-wall velocity, and particle focusing provided by curved channels can decrease fouling in membrane separation.

Inspired by these natural phenomena, CFD-DEM simulations were performed to investigate how hydrodynamics influence membrane filtration. The results showed that, for a membrane-module with patterned membrane positioning and where the membranes are represented by a square wire screen, it was beneficial to have a spiralling tube instead of a straight tube, as this increased the number of particles contained in the retentate by more than 10%. This indicates higher efficiency of the membrane filtration and a decrease in fouling. Changes in the characteristic parameters of the helical configuration allow to tailor the efficacy of the filtration, where the number of turns is the most influencing parameter. A higher filtration performance was obtained for water with a Reynolds number of 250 flowing inside a helical tube with 3 turns, a tube and coil radius of 20.2 and 120 mm, respectively, and a patterned membrane with a membrane-non membrane length ratio of 0.5. An efficiency of 32% was achieved for the lower base footprint helical tube configuration, when 60% of the inlet fluid is filtered.

In conclusion, modulating the membrane module's geometry in a nature-inspired way was established as an efficient anti-fouling strategy, where the membrane positions and addition of curvature are highly influential factors.

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