Development of a CFD modeling approach applied to gas separation in hollow fiber membrane module: Pt. 1 - Analysis of fluid flow

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Abstract

Computational simulations have a wide range of applications across various industry sectors. Gas separation is crucial in the oil and gas field, and membrane processes constitute a fundamental part of industrial production [1]. Despite the usage of numerical simulation to represent the membrane separation processes that have already been extensively covered in the literature [2], integral models have been used as tools within process simulators. This modeling approach cannot predict the flow and mass dynamics inside the equipment. This work presents the development of a Computational Fluid Dynamics (CFD) model approach [3] to represent the flow over the hollow fibers as a porous media region, and the mass transport through the membrane is represented as a volumetric sink term. Simulation tests were performed to analyze the fluid flow on an arbitrary membrane module considering different pressure drops.

Introduction

A geometry representing the spatial description and its discretization in non-overlapping volumes, named computational mesh, is required to perform CFD simulations. If each fiber is represented, geometry and mesh would be very complex for a hollow fiber membrane module. Therefore, a porous media modeling approach is employed to capture the effect of a pack of fibers in each volume of the mesh. In all, the model development is divided into two scale sizes. The macroscale deals with species transport through the porous media from the flow perspective using CFD conservation equations. The porosity affects the flow resistance and can be related to the number of fibers and the surface area available for mass transfer. The mesoscale deals with the volumetric sink term to account for the mass transfer to the interior of the hollow fibers. This work explores the compressibility effects and flow patterns inside the equipment for different pressure drops, which can provide modeling recommendations.

Flow models and simulation settings

Considering a homogeneous fiber packing in the module, the flow porosity, ε, and flow permeability, K, are constant and can be obtained as an equipment parameter. In addition, the flow resistance due to the presence of the pack of fibers can be modeled following Darcy's law [4]. The mass that transfers from the module to the hollow fiber's interior, S_m, is modeled through a volumetric sink term. For steady flow, Eqs. (1) and (2) show the continuity and momentum conservation equations where $\underset{\sim}{v}$ is the velocity, p is the pressure, and μ is the dynamic viscosity. The mass transfer to the interior of the fibers is not considered in this work ($S_m = 0$).

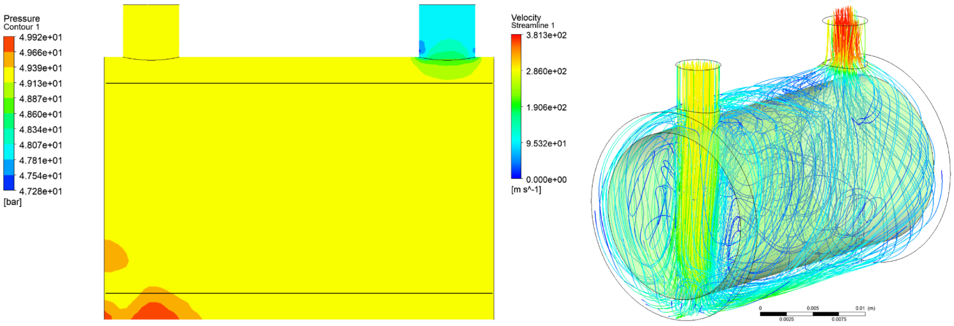
$$\boldsymbol{\nabla} \cdot (\rho \underset{\sim}{v}) = S_m \tag{1}$$

$$\boldsymbol{\nabla} \cdot (\rho \underset{\sim}{v} \underset{\sim}{v}) = -\boldsymbol{\nabla} p + \mu \left(\boldsymbol{\nabla} \underset{\sim}{v} + \boldsymbol{\nabla} \underset{\sim}{v}^{t} \right) - \frac{\varepsilon \, \mu}{K} \underset{\sim}{v} \tag{2}$$

The ANSYS CFD package was used to prepare the geometry and mesh and numerically solve the flow in a fictitious cylindrical membrane module. The hollow fiber region is centralized in the module, and the porosity and flow permeability were set as 0.5 and 4.74 x 10^{-9} m^2, respectively. The inlet was set as pure carbon dioxide, and no mass transfer between the module and the fibers was considered. Both incompressible and compressible flows were simulated using different pressure drops between the inlet and outlet regions.

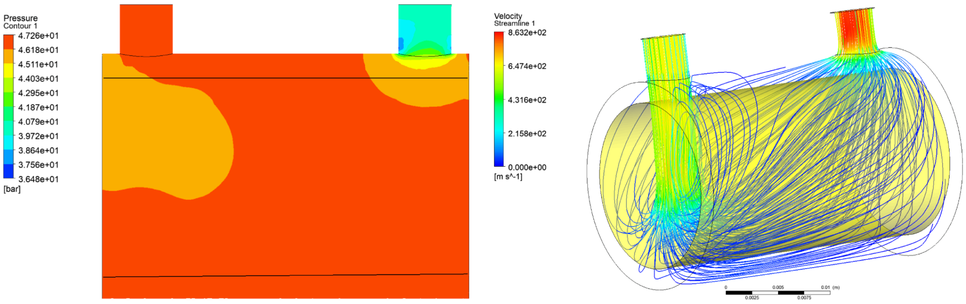
Results

It is important to note that all shown results in this section passed on mesh convergence and residual tests (10^{-5}). Figures (1) and (2) show the contour plots for pressure and velocity streamlines for incompressible flow using 2 and 10 bar pressure drops as boundary conditions. It can be noticed that there is a recirculation flow pattern for a lower pressure drop, where the fluid shows a tendency to flow directly to the outlet for a higher pressure drop. The pressure drop is most relevant at the outlet region in both cases. It may indicate that the pressure is nearly constant in the hollow fiber region.



(A) (B)

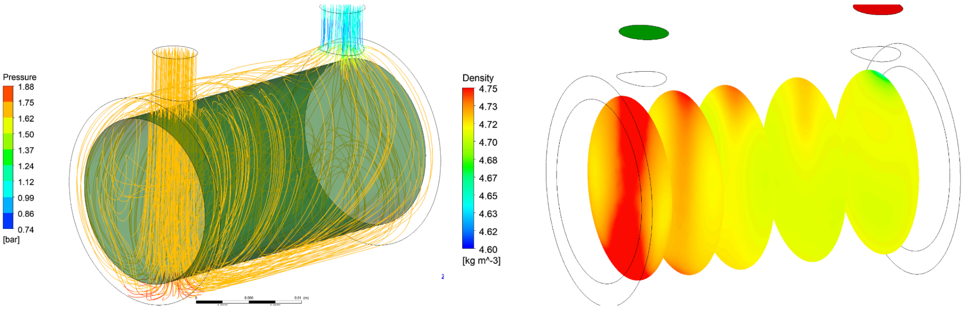
Figure 1: (A) pressure contour and (B) velocity streamline plots for incompressible flow and 2 bar pressure drop.



(A) (B)

Figure 2: (A) pressure contour and (B) velocity streamline plots for incompressible flow and 10 bar pressure drop.

To check the compressibility effects, Fig. (3) presents the velocity streamline and cut planes of density contour along the membrane module using an ideal gas compressible model solution for 2 bar pressure drop. It can be noticed that the recirculation flow is attenuated but still satisfactory. In addition, the density varies by nearly 5% in absolute values, which indicates that an incompressible approach may be sufficient to represent the lower-pressure drop case.



(A) (B)

Figure 3: (A) velocity streamline colored by pressure and (B) density contours on the porous region plots for compressible flow and 2 bar pressure drop.

Acknowledgments

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