2021 International Nuclear Atlantic Conference - INAC 2021
Virtual meeting, Brazil, November 29 - December 2, 2021

ISBN: 978-65-594-1256-3

Modelling and Simulation of DCMD Shell and Hollow Fibre Module for Seawater Desalination

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1. Introduction

Fresh water scarcity is a concerning issue in a world facing rapidly growing population. The development of desalination technologies can help to mitigate the problem by means of producing fresh water from seawater [1]. Membrane distillation (MD) is an emerging desalination technology which is becoming increasingly attractive for its adequacy to use low-grade waste heat from power plants or from renewable energy sources. In this work we address the Direct Contact Membrane Distillation (DCMD) concept, where the feed and the permeate flows are separated by a hydrophobic porous membrane. The driving force for mass transfer is the difference of vapour pressure between the hot and cold sides of the membrane [2-3]. After evaporating at the feed side, water vapour crosses the membrane and condenses at the permeate side. In this work, analytical solutions of the mass and heat transfer across the membrane are combined with finite volume discretized equations describing heat and mass conservation for the feed and permeate streams. An iterative scheme is devised to solve the model equations in order to determine the flow and temperature variables in the DCMD module. The computational model predictions show good agreement with experimental data available in the literature.

2. Physical Model

The DCMD module considered here is a cylindrical shell, with internal radius R_s, which is occupied by n_f hollow fibres. The hollow fibres internal and external radii are a and b, respectively. Note that a detailed 3D modelling of the flow inside the shell would render the analysis cumbersome and computationally expensive. Here we adopt a simplified one-dimensional model based on defining an equivalent channel for the shell flow surrounding a single representative hollow fibre. The equivalent channel is chosen as the annulus, with internal radius b and external radius c, having the same equivalent diameter as the original configuration i.e. the shell filled with n_f hollow fibres. We recall that the equivalent diameter is defined as $4A/\Gamma$, where A is the cross-sectional area of the flow and Γ is the part of the perimeter of the cross-section where mass and heat transfer take place. Thus, it is easy to verify that, in order to preserve the same equivalent diameter of the shell side flow, the external radius of the equivalent channel is $c = R_s/\sqrt{n_f}$. Figure 1 depicts the shell cross section and the equivalent channel discussed above. A multiscale approach is needed to address the problem. It includes modelling of the vapour flux through the micro/nano porous membrane and models for the mass and energy conservation at the scale of the DCMD module. We employ the Dusty Gas Model to describe the vapour diffusion through the membrane pores. A sustained heat flow is the mechanism responsible for maintaining the required temperature difference between the two sides. The present model accounts for all the relevant heat transfer processes. These include convective heat transfer, latent heat transport by the vapour crossing the membrane pores, and conductive heat transfer through the membrane matrix.

3. Discretization and Numerical Solution

Analytical solutions of the mass and heat transfer across the membrane are combined with finite volume discretized equations describing heat and mass conservation for the feed and permeate streams. Both countercurrent and cocurrent configurations of the feed and permeate streams are considered. Figure 2 illustrates the discretization adopted. It comprises N finite volumes and $N+1$ nodes. The finite volumes are represented by $I = 1, N$ and the nodes by $i = 1, N+1$. Finite volumes and nodes are numbered following the axial direction x. A general finite volume I has node i as its first node and node $i+1$ as its second node. It is also important to locate where the variables are defined in the discretization. The radial mass fluxes, G_{ml} and G_{ms}, and the temperatures at the membrane walls, T_{ml} and T_{ms}, are cell centered i.e. defined at the center of each segment. On the other hand, the temperatures of the shell and lumen flows, T_s and T_l, and the axial mass fluxes, G_s and G_l, are defined on the nodes. These nodal values are used to set piecewise linear approximations for T_s, T_l, G_s and G_l (linear on each finite volume/segment). All variables characterizing the DCMD operation are connected, either directly or indirectly. The radial mass fluxes across the membrane depend on the temperatures at the membrane walls, T_{ml} and T_{ms}. These, in their turn, and together with the heat fluxes q''_{ml} and q''_{ms}, depend on the radial mass fluxes and on the temperatures in both lumen and shell. Finally, the temperatures T and T_s, together with the axial mass fluxes G_l and G_s, depend on the radial mass and heat fluxes. In order to tackle this coupled and non linear problem, we devised an iterative solution strategy for updating all relevant variables, starting from a initial guessed solution.

4. Comparison with Experimental Data and Concluding Remarks

We have compared our computational model predictions with the experimental data presented in [4] and [5]. In reference [4] the feed flows in the shell and the operation is in cocurrent mode. Figure 3 shows the excellent agreement between our simulation and the experiments presented in [4]. On the other hand, the experiments in reference [5] have the feed flowing inside the hollow fibres and the operation is in countercurrent mode. Again we observe the good agreement between our model and the experimental data from [5], as shown in Figure 4.

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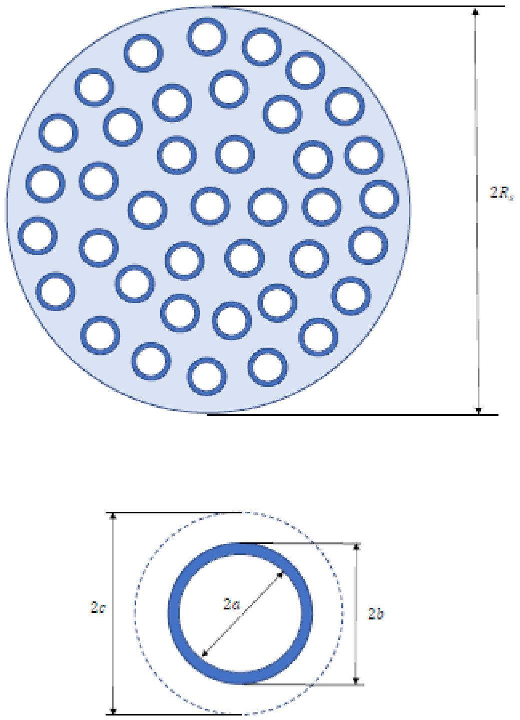

Figure 1: Shell cross section (top) and equivalent channel (bottom).

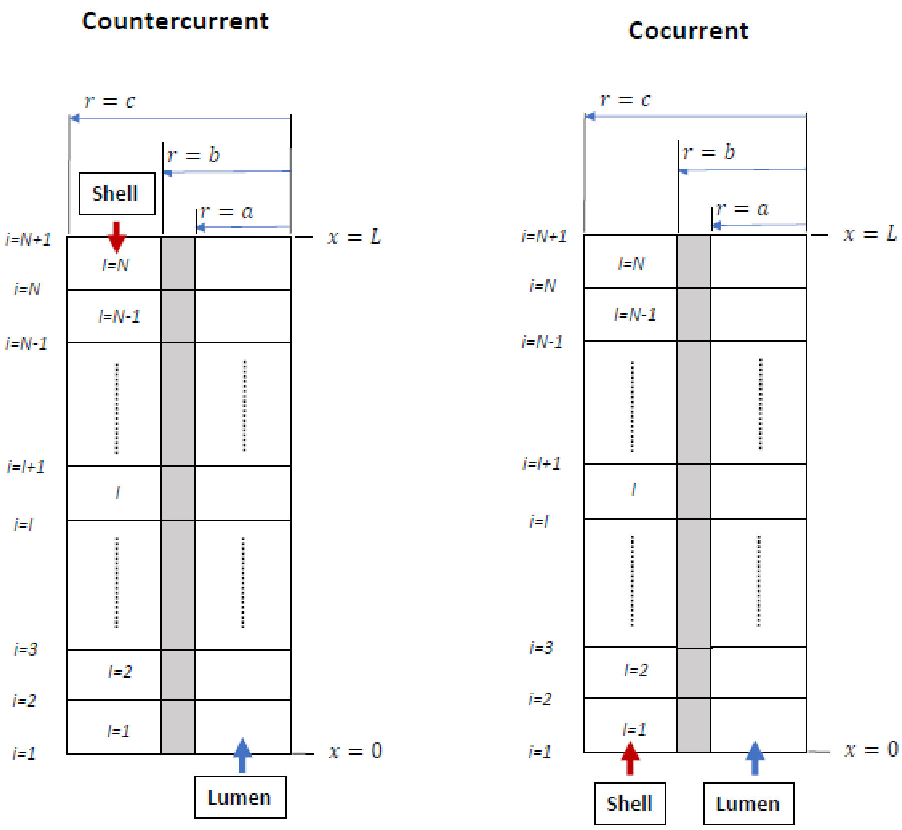

Figure 2: Discretization: Finite Volumes and Nodes.

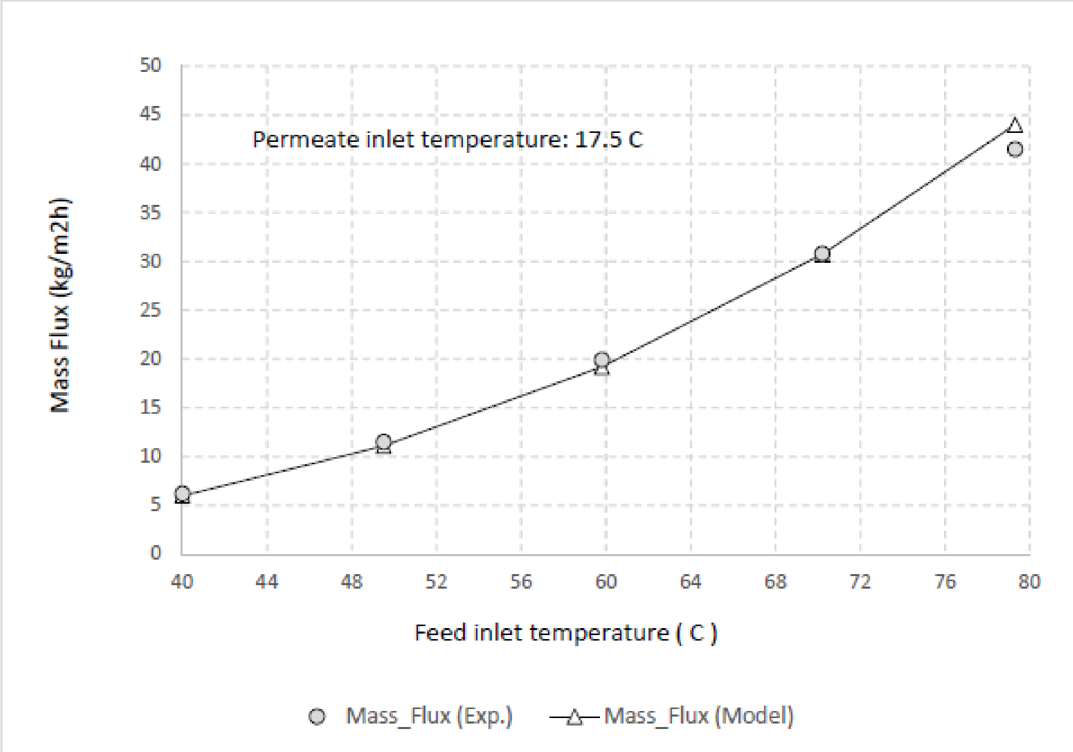

Figure 3: Predicted mass flux compared with experimental data from [4].

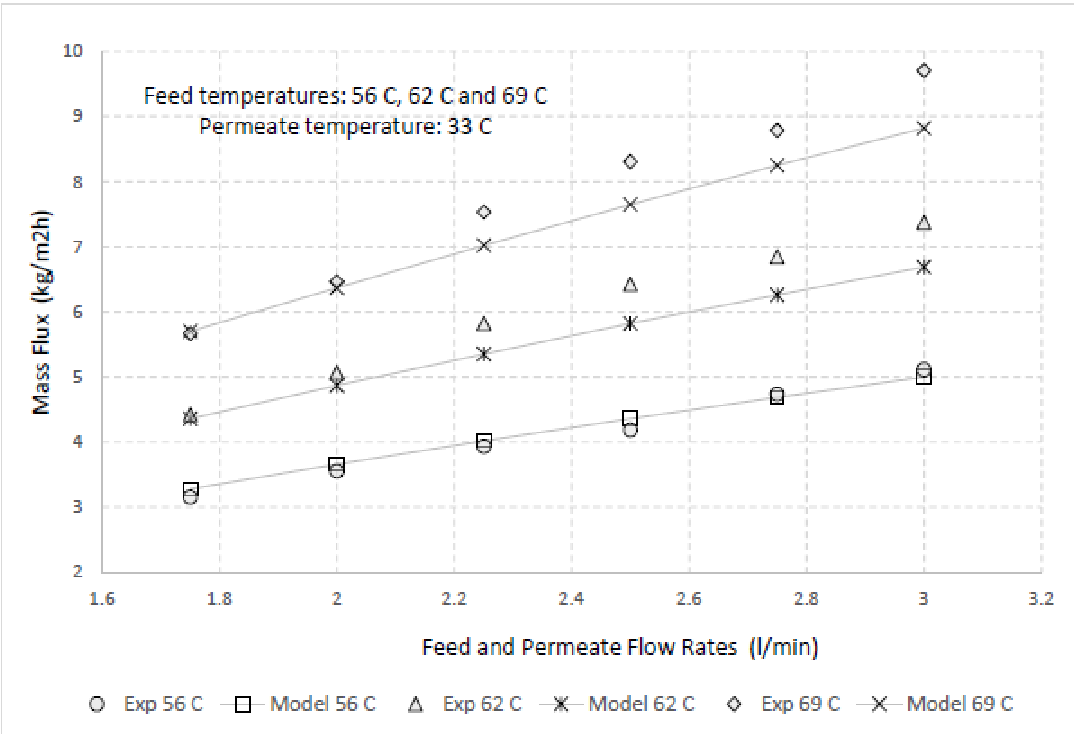

Figure 4: Predicted mass flux compared with experimental data from [5].