

Numerical modeling and optimization of vacuum membrane distillation module for low-cost water production

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Abstract

A two-dimensional numerical model, involving energy conservation, momentum transport and continuity equations, was developed to provide the profiles of temperature, velocity and pressure of vacuum membrane distillation (VMD) process using hollow fiber module. The theoretical prediction was in good agreement with the experimental results from literature. Four design and operation variables, including feed temperature, hollow fiber length, feed volume flow rate and vacuum pressure, were optimized to minimize water production cost (WPC) using genetic algorithm (GA). A case study shows that the WPC can be decreased by 38.1% in comparison with the non-optimized VMD process. Meanwhile, a general guidance for reducing the WPC was also provided. The feed temperature should be adopted as high as possible, while the hollow fiber length cannot be too long to result in a decrease in water flux and an increase in pressure drop. The flow rate is recommended to take a lower bound value and the moderate degree of vacuum is preferable. This study indicates the importance of VMD system optimization to minimize water production cost.

Keywords: Vacuum membrane distillation; Numerical modeling; Optimization; Low-cost water production

1. Introduction

Membrane distillation (MD) is a thermally-driven process, which utilizes water vapor pressure gradient to drive the water vapor across a hydrophobic microporous membrane [1]. In general, it is composed of three heat and mass transfer steps: the water vapor evaporates at the membrane surface in the hot feed side, passes through the membrane pores and finally condensates at the other side of the membrane. MD has been considered as a promising technology because of its moderate operating temperature, which means that low-grade heat can be utilized as the heating source. In addition, it is capable of treating high concentration brines without serious performance deterioration [2], enabling it to be incorporated with other processes such as reverse osmosis (RO) and crystallization [3]. Furthermore, it produces high purified permeate water, suggesting its potential for applications in medical and food industries.

Based on different condensation methods, there are mainly four types of membrane distillation configurations: direct contact membrane distillation (DCMD), sweeping gas membrane distillation (SGMD), air gap membrane distillation (AGMD) and vacuum membrane distillation (VMD) [4]. Among the four configurations, VMD has been proved to be the most energy efficient due to its insignificant temperature polarization effect, relatively high mass flux and energy efficiency [5, 6]. However, the disadvantage of VMD lies in the fact that it requires an external vacuum pump to facilitate the transfer of the permeate water vapor across the membrane, causing extra energy consumption [7]. Thus, it suggests that

more intensive efforts should be made with respect to the optimizations of the design and operating conditions of VMD process.

In order to make VMD process more economic for desalination, many investigations have been carried out in recent years [8-11]. VMD using flat sheet membrane module was preferred because of its relatively easy fabrication [12, 13], while some studies also reported hollow fiber VMD modules, given its large specific membrane surface area in comparison with the flat sheet membrane module, as well as its easily scalable potentiality [5, 7]. However, to our best knowledge, there is no report on the economic analysis in terms of module design and the optimization of operating conditions for hollow fiber based VMD process, probably due to the fact that VMD requires external vacuum pump consumption in comparison with DCMD, making it unclear to estimate the overall energy cost.

To achieve the goal of VMD system optimization, appropriate modeling of VMD process is required. As a conjugate heat transfer process, VMD essentially features two-dimensional (2-D) heat and mass transfer in both the flow channel and membrane matrix. Therefore, the distributions of temperature, velocity and pressure along the longitudinal (z-axis) and transversal (r-axis) directions are of the concern, as a thorough understanding of the heat and mass transfer inside the VMD module cannot be attained until the profiles of these parameters are determined. Nevertheless, at present, most of the modeling studies still adopt the approach of analytical one-dimensional (1-D) modeling based on energy balance for the control volume by applying empirical heat and mass transfer equations, which were derived

from non-porous and rigid heat exchangers [5, 6, 13], whereas the 2-D modeling employing Navier-Stokes equations as governing equations, which can provide more reliable and comprehensive information, are not commonly applied for investigation. To bridge the gap, some researches utilized commercial program packages such as FLUENT to simulate the flow condition and achieved satisfactory simulation results by comparing with the experimental data [14, 15]. However, the computation speed of the commercial program packages is rather slow even with high performance computers. It is widely acknowledged that the numerical methods using scientific programming language (e.g. FORTRAN) or mathematical software systems (e.g. MATLAB) are superior to the commercial program packages (e.g. FLUENT) in terms of computation speed and efficiency [16]. It seems the commercial program packages are more suitable for the cases which have very complex boundary geometries and require extremely high accuracy.

In addition, the conventional optimization strategy for a system was mainly single variable dependent, with other variables fixed [17]. This kind of optimization procedures may require a large amount of experiment designs to correlate the object functions and decision variables, which can hardly reflect the interaction of the multi-variable dependent process. Intuitively, the most accurate way of the optimization is to try out all possible conditions and compare the target functions to ultimately identify the optimized match. However, this type of clumsy method is rather time consuming and extremely low efficient, especially for some complicated problems of multi-variables with a large value domain and the requirement of high accuracy.

Genetic algorithm (GA) is one of the advanced numerical methods that mimic the Darwin's natural selection and evolution, so that a better match (offspring) may probably be generated regarding to the requirement (object function). It is able to significantly scale down the choices of the match and facilitate the generation of the desired design and operating conditions from a series of combination of the match rather than from a huge number of the possibilities. Recently, Cheng *et al.* used the genetic algorithm to perform the optimization of DCMD and AGMD systems with two and three variables based on their 1-D modeling, respectively [18, 19], but limited works on multi-variable optimization of VMD process based on 2-D modeling have been reported.

In current study, we intend to optimize the module design and operating conditions of the VMD process. The aim of the study is to develop a VMD system with the lowest water production cost based on the economic analysis of the optimized system. Specifically, a 2-D model was firstly built up for hollow fiber VMD membrane module and solved using finite element method (FEM), which led to the acquirement of the distribution profiles of temperature, velocity and pressure in the membrane module. The objective function was established to minimize water production cost by investigating four variables, including feed temperature, hollow fiber length, volume flow rate and vacuum pressure. The genetic algorithm was applied to seek the best design and operation conditions. A case study was performed to provide guidance for a VMD system with membrane area of 0.1m^2 .

2. Theory and methodology

2.1 VMD model development

- *Governing equations*

The schematic of a VMD hollow fiber module is shown in Fig. 1a, which represents the 2-D model simulating the main configuration of the VMD module. The feed stream flows into the lumen side, while the shell side is under vacuum. N represents water flux across the membrane; q_f is the volumetric flow rate of the feed stream. L is the length of the hollow fiber and membrane module. The r - and z -coordinates are perpendicular and parallel to the hollow fiber membrane surface, respectively.

In principle, the steady state heat transfer in the MD module includes the convective and conductive heat transfer of the feed flow in the lumen side, the latent heat transfer associated with water vapor transport across the membrane pores, and the conductive heat transfer in the polymer membrane matrix. To define and simplify the model, some assumptions were made as follows: (1) the feed stream is a steady-state flow; (2) the flow pattern is within laminar flow region; (3) the feed stream has constant physical properties; (4) only z -axis velocity exists and r -axis velocity is assumed zero; (5) the temperature profile has no influence on the velocity profile; (6) there is no slip condition at the boundary. By considering these assumptions, the model equations of the feed flow can be expressed according to the Boussinesq approximation [20]:

$$\rho_f C_p \mathbf{u} \cdot \nabla = \nabla \cdot (k_f \nabla) \quad (1)$$

$$\rho_f \mu_f \cdot \nabla u = - \nabla p + \nabla \cdot \left[\mu \left((\nabla u + (\nabla u)^T) - \frac{2}{3} \nabla u I \right) \right] + \rho_f g \quad (2)$$

$$\nabla \cdot u = 0 \quad (3)$$

where ρ_f , C_f and k_f are the feed flow density, heat capacity and thermal conductivity, respectively; T is the local temperature of the feed flow; u is the local velocity of the feed flow; p represents the local pressure; r is the local position in radial direction; μ is the viscosity of the feed flow. The boundary conditions at the membrane surface for the energy conservation Eqn. (1) are provided by following equations

$$-k_f \frac{\partial T}{\partial r} \Big|_{r=d_i/2} + N \cdot \frac{k_m \cdot (T_{fm} - T_{pm})}{\delta} \quad (4)$$

$$T(r, 0) = T_0 \quad (5)$$

$$\frac{\partial T}{\partial r}(0, z) = 0 \quad (6)$$

$$u(r, 0) = u_0 \quad (7)$$

$$\frac{\partial u}{\partial r}(0, z) = 0 \quad (8)$$

Where d_i and δ are the inner diameter and thickness of the hollow fiber; N and H are the mass flux and evaporation enthalpy of water; T_0 and u_0 are the inlet temperature and velocity of the feed stream. Given that a high degree of vacuum exists in the shell side of the VMD membrane module, the conductive heat flux across the membranes can be neglected for further simplification [5]. Therefore, the Eqn. (4) can be expressed by the following equation:

$$-k_f \frac{\partial T}{\partial r} \Big|_{r=d_i/2} = N \cdot \frac{k_m \cdot (T_{fm} - T_{pm})}{\delta} \quad (9)$$

- *Mass transfer in VMD process*

Although various mathematic models such as Knudsen, Poiseuille and molecular diffusion models have been developed for the prediction of mass flux, it was generally accepted that the water flux across the membrane can be expressed empirically as:

$$N = C(p_{fm} - p_{pm}) \quad (10)$$

where, C is the membrane distillation coefficient of the membrane and dependent on the membrane geometry and operating conditions [21]. The subscript fm and pm represent the membrane surface in the feed side and permeate side, respectively. It is believed that the three mechanisms of Knudsen diffusion, molecular diffusion and Poiseuille flow transition model are helpful in prediction of the MD mass flux [1, 21-23]. In this study, the Knudsen model was to be applied as the molecule-pore collision mechanism was dominant in the mass transfer of VMD process [24]. The membrane distillation coefficient C can be written as [1, 7]:

$$C = 1.064 \frac{D\varepsilon M}{\delta\tau RT} \left(\frac{D\varepsilon M}{\delta\tau RT} \right)^{0.5} \quad (11)$$

where, D is the membrane pore size; ε the porosity of the membrane; τ the membrane pore tortuosity; M the mass molecular of water and R the gas constant.

In the VMD process, the vapor pressure difference arisen from the temperature difference between the membrane surfaces was the driving force for water vapor transfer across the membrane. The partial pressure can be determined by correlating with the membrane surface temperature according to Antoine equation:

$$p = \exp\left(23.20 - \frac{3816.44}{T+226.87}\right) \quad (12)$$

where, p and T are the water vapor pressure and membrane surface temperature at the feed side, respectively. The units of pressure p and temperature T are Pa and °C, respectively.

- *Finite element method for numerical solutions of VMD model*

In this study, Galerkin finite element method (FEM) as a standard strategy was applied to provide numerical solutions based on the boundary conditions Eqns. (5) ~ (9). To solve the 2-D model of the flow in the lumen side, the domain of interest was heterogeneously divided by the free quad elements with the maximum element size of 5×10^{-3} m and minimum element size of 1.4×10^{-4} m. The number of the elements in the feed flow channel was set to be 4661, as it was found that no distinct higher accuracy can be achieved with more elements. The element distribution became reasonably denser towards the boundary in order to achieve a better computing accuracy due to more severe change approaching the membrane surface. A detailed distribution of the elements in the lumen side of the membrane module is shown in Fig. 1b.

After meshing the flow channel inside the hollow fiber, the PDE governing equations for energy, momentum and continuity were discretized and solved by Galerkin FEM. As the temperature profile did not significantly influence the hydrodynamic condition according to the model assumptions, it can be computed after the velocity profile was determined. The iteration procedure to solve the coupled equations in the governing equation is shown in Fig.

2. The VMD module dimensions and the operating conditions were initially provided as the

parameters. In addition, the boundary conditions were also specified as introduced previously in Eqns. (5) – (9). The governing equations, together with the boundary were finally reduced to the algebraic equations for solution by standard Galerkin FEM using the FAESOR package. The MATLAB source codes were developed by Pkrysl from University of San Diego (http://hogwarts.ucsd.edu/~pkrysl/faesor/faesor_publish.html).

2.1 Optimization strategy for low-cost water production

- *Economic analysis of the VMD system*

The total cost (TC) of the VMD system comprises two major parts: (1) the membrane material cost (MC); (2) the operation cost (OC). To make a valid economic analysis, several assumptions were also made in the following: (1) the membrane life time was 5 years; (2) the system availability was 90%; (3) the maintenance cost was not considered; (4) the interest rate was 5%. Therefore, the MC and OC would be formulated by the following equations [25]:

$$MC = P_m A \frac{i(I+i)^n}{(I+i)^n - I} \quad (13)$$

$$OC = P_e W_e t + P_s W_s t \quad (14)$$

where, A , i and n are the membrane area, the interest rate and life expectancy of the membrane, respectively. P_m , P_e and P_s refer to the costs of unit membrane area, electricity and steam respectively. W_e and W_s indicate the work of electricity and waste steam heat. t is the system operating time. The OC here mainly comprises two parts: the pump energy

consumption (vacuum creation and flow circulation) and the heating of feed solution by waste heat steam. To simplify the calculation, the sufficient supply of waste heat was assumed and the costs of different grade waste heats were not differentiated in the current study. The individual cost of all the items used in the VMD system for the TC calculation is listed in Table 1.

- *Objective function for optimization*

In the study, two constraints were considered to ensure that a certain scale of VMD membrane module was maintained for water production, and the pressure drop in the tube side of the hollow fiber module did not go beyond a reasonable value. Therefore, either the membrane area smaller than the process requirement or the pressure drop in the tube side over the maximum allowable value would be eliminated during the optimization process. As such, the water production cost (WPC) was set as the objective function with two constraints for optimization:

$$\text{Min. } WPC = TC / N \cdot A \cdot t \quad (15)$$

$$\text{Subject to } A \geq A_{\text{required}}$$

$$\Delta P_t \leq \Delta P_{tp} \quad (16)$$

where the TC is the total cost of the VMD system; N and A are the mass flux per unit membrane area and membrane area, respectively; P_t and ΔP_{tp} are the real pressure drop and permitted pressure drop in the tube side of the hollow fiber.

The TC and N are associated with the module design and operating variables of the VMD systems. Four key parameters, including the feed temperature, hollow fiber length, vacuum pressure and the feed flow rate with certain boundaries, were taken into consideration, and the ranges of these parameters are listed below:

- 1) The feed temperature was ranging from 50 °C to 90 °C.
- 2) The length of the hollow fiber was from 0.25 m to 0.50 m.
- 3) The flow rate of the feed stream varied from 1.2 LPM to 6.0 LPM.
- 4) The vacuum pressure was taken from 2 kPa to 10 kPa.

- *The genetic algorithm for optimization*

The optimization was conducted using the genetic algorithm. With four design and operation variables in consideration, millions of combinations were possible options. For a large-scale discrete optimization problem, the genetic algorithm is able to determine the optimal designs. A detailed description of the genetic algorithm could be found in literature [26].

Fig. 3 presents the schematic diagram of the genetic algorithm optimization procedure. Since the genetic algorithm was a numeric search method based on the theory of stochastic probability, it was difficult to set a criterion of convergence as the traditional search methods. Here, the genetic algorithm procedure was terminated after 300 consecutive generations if no improvement of the best design occurred.

- *Sensitivity analysis*

In order to further elucidate the optimization results, sensitivity analysis involving the investigation of the impacts of selected design variables (feed temperature (x_1), hollow fiber length (x_2), flow rate (x_3) and vacuum (x_4)) and their second-orders as well as their interaction terms on the objective function of WPC was also provided. The quadratic model for the VMD system can be formulated as the following equation [27]:

$$WPC = C_0 + \sum_{i=1}^4 C_i x_i + \sum_{i=1}^4 C_{ii} x_{ii}^2 + \sum_{i=1}^4 \sum_{j=1}^4 C_{ij} x_{ij} + \omega \quad (17)$$

where, C_i , C_{ij} and ω are the first-order coefficient, symmetrical interaction coefficient and random error respectively. To determine the coefficients in Eqn. (17), a multiple linear regression (MLR) was applied, and then the least square method was used to determine the coefficients. Analysis of variance was performed by applying Minitab software package.

3. Results and discussion

3.1 Verification of cross-flow VMD model

Fig. 4 depicts the mass flux as a function of the feed temperature ranging from 35 °C to 65 °C with the feed flow velocity of 0.6 m/s in a cross-flow MD module obtained by the 2-D modeling in the present work and the experiment reported in the literature [7]. Basic characteristics of the membrane module used for the simulation are listed in Table. 2. It can

be seen that the simulated results were in good agreement with the experimental data under the same conditions. This suggested that the 2-D model was valid to **predict** the performance of VMD modules in the cross-flow configuration.

3.2 Temperature, pressure and velocity profiles in the flow channel

For a 2-D process, the variation in parameters was featured in both **axial** direction (z -) and radial direction (r -). Fig. 5a shows the temperature profile in the flow channel. To make it clearer in both directions, Fig. 5b shows the temperature profiles in the radial direction at different locations of the flow channel, while Fig. 5c depicts the temperature distributions of the lumen center and membrane surface along flowing direction. From Fig. 5b, it was observed that along the radial direction from the centre of the hollow fiber ($r=0$) to the wall ($r=d_i/2$), the temperature gradually decreased because of the heat transfer through the membrane, which was associated with the mass transfer of the water vapor. In addition, the temperature gradient was relatively small near the centre of the flow channel and increased significantly nearby the membrane surface due to the existence of the thermal boundary layer near the membrane surface.

From Fig. 5c, it can be seen that both of the temperatures decreased along the flow direction due to the loss of the latent heat associated with the water vapor across the membrane. Similar results were also found in the literature [16]. The decrease of membrane surface temperature along flow direction suggests that the membrane length should be optimized as

the mass flux across the membrane would decrease gradually along the membrane module due to reduced driving force for mass transfer. A long membrane module may not be efficient for water production.

Fig. 6 and Fig. 7 illustrate the pressure and velocity profiles in the lumen side of the membrane fiber, respectively. Since it was assumed that only the z -direction velocity existed, the pressure gradient in the r -direction was zero. From Fig. 6, it can be seen that the pressure gradient in the z -direction was **linear**, corresponding to the empirical relationship of pressure drop with the length of flow channel [28]. Along with the flow direction, the pressure gradually drops mainly due to the existence of the shear stress between the fluid and the membrane surface. From Fig. 7, it is observed that the feed flow enters into the hollow fiber with a uniform velocity in the cross section of the flow channel. When the feed flow develops along the hollow fiber, the boundary layer starts to form simply due to the zero velocity of the flow adjacent to the membrane surface when the non-slip boundary is assumed. Based on the profiles shown in Figs. 5 to 7, the VMD performance and related parameters can thus be determined.

3.3 Optimization of module design and operating conditions

To elaborate the optimization process, one case study was performed by taking the basic data from literature [7]. Table 3 **lists the constraints of input parameters for the process**. Table 4 presents optimized design variables and the corresponding values of the objective function of

WPC for VMD membrane module. The variation ranges of the design and operation parameters were also listed in the table. In comparison with the non-optimized VMD configuration (experiment conditions) [7], the optimized VMD tended to adopt a high feed temperature, as it can significantly enhance the water production, but the lower boundary of the hollow fiber length was chosen to effectively reduce the increase of the operation cost caused by the pressure drop. The flow rate was at the lower bound of the domain from 1.2 LPM to 6.0 LPM, indicating that the pressure loss induced operation cost was significant, while the benefit of a larger volumetric flow rate was not enough to offset the increase of the **pumping energy cost**. The vacuum pressure was adopted a moderate value of the domain from 2 kPa to 10 kPa, suggesting the benefit of high vacuum-induced water production not overwhelming the electric cost of the vacuum creation by isothermal compression work.

Fig. 8 shows the convergence of the objective function of WPC with the number of generation. It was observed that the average value of the WPC was higher than the optimum value before 200 generations and then remained the same after 200 generations. It indicated that the **better gene (optimized conditions) was largely shared by the whole community (conditions group) and ultimately the optimized solution (lowest WPC) was ultimately achieved after gene evolution (recombination of conditions)**.

3.4 Sensitivity and effects of four variables to the WPC

One hundred sets of data points were selected to determine the coefficients of Eqn. (17) used for the sensitivity analysis of four variables to WPC. The coefficients and analysis of variance for the quadratic model with 95% of confidence level are listed in Table 5. The F value, which tests the homogeneity of variance, was used to evaluate whether the regression model was adequate to describe the obtained simulation data [29]. And it was observed that the overall F-test for the quadratic regression model was significant with probability less than 0.05, which suggested that WPC was closely related to the four selected design variables, including feed temperature (x_1), hollow fiber length (x_2), flow rate (x_3) and vacuum (x_4). To verify the model, residuals analysis was also performed. Fig. 9a and Fig. 9b present normal probability plot of the studentized residuals and the plot of studentized residuals versus predicted values for the WPC, respectively. It was observed that the majority of the residuals fell around the straight line, indicating that the predicting model was fairly valid. Based on the results listed in Table 5, some of the coefficients are negligible due to lack of close correlation (probability larger than 0.05).

Fig. 10a shows the response surface plot of the effects of feed temperature and fiber length on water production cost, while Fig. 10b illustrates the effects of vacuum and flow rate on water production cost. The decrease in feed temperature significantly increased the WPC. This result was in agreement with the general acknowledgement that a high feed temperature can enhance water flux significantly because of the exponential relationship between the vapor pressure and temperature, as shown in Eqn. (12). Obviously, the VMD module should

operate at a feed temperature as high as possible provided that the heating sources are available [30].

Hollow fiber length also played an important role in WPC of the VMD system based on two aspects. On one hand, the driving force was gradually lost because of the development of the thermal boundary layer along the fiber length, as shown in Fig. 5a, leading to a lower average mass flux for a longer fiber. On the other hand, a longer hollow fiber would cause a higher pressure drop as shown in Fig. 5c. Similar finding was also reported in the literature [31]. Therefore, it was necessary to use a shorter fiber in an attempt to reduce the WPC.

With the increase of the feed flow rate, the mass flux across the membrane increased accordingly. The dependence of the mass flux on Reynolds number was due to the heat transfer in the thermal boundary layer in the lumen side. With a higher flow rate, which corresponds to a larger Reynolds number, the heat transfer coefficient was enhanced, leading to the suppression of the temperature polarization, which was one of the most important factors adversely affecting the MD process [31]. Nevertheless, a higher Reynolds number, which benefited the heat transfer within the thermal boundary layer, was actually at the penalty of higher energy consumption. With the increase of the circulation velocity (larger Re), the pressure drop in the lumen side of the fiber was significantly increased. Thus, it was required to balance the benefit of the more mass flux and the penalty of the energy usage.

When the vacuum pressure was increased at the shell side, the mass flux gradually decreased because of the loss of the driving force across the membrane, as indicated by Eqn. (10). It was worth noting that although a higher degree of vacuum can produce more mass flux with the same membrane area, the energy consumption should also be considered due to more work required to maintain the vacuum for water production. In the current study, it seemed the benefit of high water production did not significantly outweighed the electrical cost stemming from the high vacuum, resulting in the choice of a moderate degree of vacuum for the sake of low WPC.

4 Conclusions

In this study, a 2-D heat and mass transfer model for the VMD system was developed and numerically solved. The modeling has been proved to be valid for the prediction of the VMD performance. With the temperature, velocity and pressure profiles obtained from the modeling, four variables, including feed temperature, fiber length, volume flow rate and vacuum pressure as the key design and operating conditions, were optimized for low-cost water production using genetic algorithm.

It was found that the water production cost per ton decreased by 38.1% for an optimized system. It is preferable to adopt a higher feed temperature to produce more water. While for a given membrane area used, a shorter fiber length is favored in order to decrease the pressure-drop induced operation cost. The volume flow rate should be low as a significant pressure

drop is expected, leading to relatively high operation cost. The vacuum pressure should be kept moderate because the increase of water production does not overwhelm the electric cost in the current study.

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Nomenclature

A	Membrane area based on inner diameter, m^2
C	Membrane distillation coefficient, $\text{kg m}^{-2} \text{Pa}^{-1} \text{s}^{-1}$
C_f	Heat capacity, $\text{J kg}^{-1} \text{K}^{-1}$
D	Membrane pore size, m
d_i	Inner diameter, m
N	Mass transfer flux, $\text{kg m}^{-2} \text{h}^{-1}$
L	Length of membrane, m
p	Pressure, Pa
Re	Reynolds number
T	Temperature, $^{\circ}\text{C}$
u	Velocity of fluid, m s^{-1}
M	Mass flow rate, kg s^{-1}
R	Gas constant, $\text{J}/(\text{K}\cdot\text{mol})$
r	Radial distance, m
x	Axial distance, m
ΔH	Latent heat, J kg^{-1}

Greek letters

δ	Thickness of membrane, m
ε	Membrane porosity, %
τ	Membrane pore tortuosity
κ	Thermal conductivity, $\text{W m}^{-1} \text{K}^{-1}$

μ	Viscosity, Pa s
ρ	Density, kg m ⁻³

Subscript

c	Tube centre
e	Electricity
f	Bulk of the feed
fm	Membrane surface at the feed side
in	Inlet
m	Membrane
out	Outlet
s	Steam
0	Inlet side

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