Journal of Membrane Science 513 (2016) 260–269

Contents lists available at ScienceDirect

Journal of Membrane Science

journal homepage: www.elsevier.com/locate/memsci

Novel method for the design and assessment of direct contact membrane distillation modules

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ARTICLE INFO

Article history:
Received 13 August 2015
Received in revised form
29 March 2016
Accepted 3 April 2016
Available online 5 April 2016

Keywords:
Membrane distillation
Direct contact
Module performance
Module sizing
Process design

ABSTRACT

An equivalent effectiveness-number of transfer units (ε-NTU$_{MD}$) method was developed for direct contact membrane distillation. Efficient performance rating and design sizing for individual DCMD modules can be rapidly made based upon limited experimental data. Using this method, the construction of a specific finite element model and their associated costs, involving both time and expenditure, are avoided. Instead the module performance or sizing requirements can be estimated efficiently using a set of expressions based on the conventional ε-NTU expressions used for the design of heat exchangers. The outlet temperatures are also predicted which is useful for the design of the overall DCMD process and module cascading networks. The ε-NTU$_{MD}$ method was validated against an experimentally validated discretized model of a flat sheet DCMD module, built using MATLAB. A correction function is included in the ε-NTU$_{MD}$ method proposed which results in 100% of the derived data being accurate within 6% of model results. Method validation was done for both co- and countercurrent flow, with a range of module dimensions, flowrates and membrane permeabilities.

1. Introduction

Membrane distillation (MD) has become a popular research area in recent years, particularly for desalination. It has the potential to tackle the shortage of potable water while using relatively small amounts of high grade energy; the main energy supply for MD is low grade heat [1]. Compared to other established desalination processes, MD has the advantages of: (a) ambient operational pressure; (b) minimal chemical interactions; (c) 100% (theoretical) rejection of ions; and (d) ability to process highly concentrated feed [2–4]. There are four commonly acknowledged MD configurations, namely, direct contact membrane distillation (DCMD), air-gap membrane distillation (AGMD), vacuum membrane distillation (VMD) and sweeping gas membrane distillation (SGMD). They are named accordingly to and differentiated by the media adjacent to the permeate side of the membrane. With the simplest design, the main disadvantage of DCMD is the relatively high conductive heat loss due to the direct contact between both fluids and the membrane [5]. Compared to DCMD, heat loss is reduced in AGMD. The stagnant air however increases the mass transfer resistance and the transmembrane flux is then limited by diffusion across the air gap and evaporation through the pores [6,7]. As a result the permeate flux of AGMD is significantly less than that of DCMD [8]. In VMD, a low pressure or vacuum is applied on the permeate side for a higher permeate flux [9]. Yet this sometimes gives rise to a more severe problem of membrane wetting compared to other configurations [10]. An external condenser is required to collect the permeate in SGMD which is less desirable due to additional complexity and higher expense. Heat recovery is also difficult in this configuration [11]. While each configuration has its merits and disadvantages, DCMD is the most considered configuration out of the four. It has the simplest design, with a higher permeate flux compared to AGMD, achieving less aggressive membrane wetting compared to VMD and without the complication of a condenser compared to SGMD.

The governing equations adopted for DCMD [12–14] are very similar to those used in heat exchangers [15] but instead of mere heat conduction across the fluids contact surface, an additional term is required as heat is also carried through the membrane via the permeate flux. With other membrane contactor processes, the key performance indicators are usually: transmembrane flux, overall module permeation and separation ratio [16]. However due to the thermal-driven nature of membrane distillation and the resultant coupled heat and mass transfer across the membrane [12], thermal efficiency is also an important parameter in design and evaluation of DCMD systems [17,18].

Due to its robustness, the effectiveness-number of transfer units ε-NTU method, popularised by Kays and London [19] has for

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http://dx.doi.org/10.1016/j.memsci.2016.04.009
0376-7388/

Table 1
Key features of the ε-MTU model for PRO and RO.

Model	ε-MTU for Ideal PRO [24]	ε-MTU for RO [25]
Simplifications and assumptions	• Idealized model • Concentration polarization effects are neglected • Presser drop through flow channel is negligible • 100% salt rejection rate • Within the salinity range, the osmotic pressure follows van't Hoff's law, i.e. linearity between osmotic pressure and salinity • The PRO membranes can withstand arbitrary net driving pressures	• Membrane permeability is constant and independent of feed salinity • Concentration polarization effects are incorporated via use of a dimensionless correction factor (Tables of correction factor are provided for feed concentration) • Hydraulic pressure drop along the flow channel is negligible • 100% salt rejection rate • Osmotic pressure follows van't Hoff's law, i.e. linearity between osmotic pressure and salinity[a]
Key analogy and modification to conventional ε-NTU for heat exchangers	• Instead of temperature difference, the driving potentials are the concentration and pressure differences • Effectiveness is expressed as the recovery ratio achieved and the maximum recovery ratio of the system • Four dimensionless groups were introduced to express the recovery ratio of the membrane	• Instead of temperature difference, the driving potentials are the concentration and pressure differences • Effectiveness is expressed as the recovery ratio achieved and the maximum recovery ratio of the system • Four dimensionless groups were introduced to express the recovery ratio of the membrane • A correction factor is introduced into the model to allow for the effects of concentration polarization and nonlinearity between osmotic pressure and salinity
Model validation	• Results were validated using a numerical model that includes the nonlinear function for the osmotic pressure • Error percentage of approximately 5% reported for the calculations of recovery ratio and effectiveness. • Maximum error of 20.3% is reported when evaluating feed stream concentration in the case of power production using counter flow module	• Results were compared with literature data, with the assumption that the mass transfer coefficient is held constant throughout the exchanger • With the incorporation of the correction factor, a mean error of 7.8% and a maximum of 29.3% were found

[a] Only for initial development, adjustment were made to improve the model by introducing a correction factor.

many years been the industrial standard for designing heat exchanger systems and networks [20–23]. As a design tool, the ε-NTU method can be used to calculate the rate of heat transfer in heat exchangers when the temperature profile is unknown and thus there is insufficient information to obtain the log-mean temperature. It can also be used to determine the required surface area of a heat exchanger for a fixed effectiveness and given set of inlet conditions. Recently, different researchers have used the backbone of the original version of ε-NTU, which originally only applies to heat exchangers, for various mass transfer systems. Sharqawy et al. [24] has developed the effectiveness-mass transfer units (ε-MTU) for pressure retarded osmosis (PRO) membrane mass exchanger and similarly, Banchik et al. [25] has developed ε-MTU for reverse osmosis (RO). Some key features of these two models are presented in Table 1. Others have also looked into the use of ε-NTU in dehumidification, which is a conjugate heat and mass transfer system. [26, 27].

Aiming to provide a similar ε-MTU method for DCMD, this paper adopts the derivation of the conventional ε-NTU method but with modifications which accommodate the conjugate heat and mass transfer in MD. In this present work, a set of ε-NTU expressions are developed specifically for DCMD. These ε-NTU expressions can provide good and robust estimations for the outlet temperatures, thermal efficiency of individual modules and the amount of transmembrane flux with a straightforward algorithm. This reduces the time and computing cost required in cases when finite element models are constructed and used for design purpose. The method has been labelled as **ε**-NTU$_{MD}$.

2. Theory and analytical derivation of the ε-NTU$_{MD}$ method for DCMD

A few assumptions were adopted in the derivation of the ε-NTU$_{MD}$ method; as with the work from MIT on PRO and RO [24,25], the aim has been to develop a robust method. Thus for the designing or rating of a DCMD module, the following approximations are reasonable:

(1) Low salinity in the feed solution i.e. around that of seawater or lower. In this case, the effect of concentration polarization is negligible [28] and chemical potential of water is approximated to unity (in reality the activity coefficient of seawater at 298 K is 0.98 [29,30]).
(2) Kinetic and potential energy effects are negligible.
(3) The effective membrane permeability, K_{eff} and overall heat transfer coefficient, U (Eq. (6) and (9) below) are, as suggested in [13], taken to be invariant with position. This is consistent with the classical approach to the design of heat exchangers.

Fig. 1 shows the schematic drawings of the two DCMD configurations. The symbols used are conventional and a list is given at the end of the paper. The governing equations of the heat and mass transfer across the membrane of DCMD are given as:

$$q = h_f(T_f - T_{fm}) \tag{1}$$

$$q = h_p(T_{pm} - T_p) \tag{2}$$

$$q = N\lambda + \frac{k_m}{\delta}(T_{fm} - T_{pm}) \tag{3}$$

and the transmembrane flux, N, is given as:

$$N = \frac{K}{\delta}\left(P_{fm} - P_{pm}\right) \tag{4}$$

or in terms of temperature, as suggested in [13]

$$N = K_{eff}\left(T_f - T_p\right) \tag{5}$$

where K_{eff} is given as:

$$K_{eff} = \frac{K^*}{\delta + \frac{k_m}{U_L} + \frac{\lambda K^*}{U_L}} \tag{6}$$

where