Desalination 394 (2016) 108–122

Contents lists available at ScienceDirect

Desalination

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

Response surface modeling and optimization of direct contact membrane distillation for water desalination

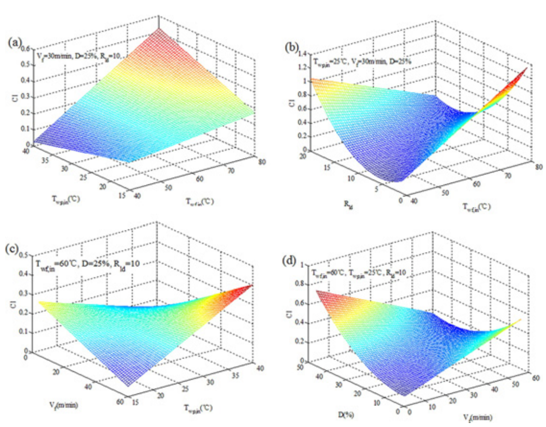
Dongjian Cheng [a], Wei Gong [a], Na Li [a,b,*]

[a] Department of Chemical Engineering, School of Chemical Engineering and Technology, Xi'an Jiaotong University, Xi'an 710049, China
[b] Key Laboratory of Thermo-Fluid Science and Engineering, Ministry of Education, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China

HIGHLIGHTS

- Regression models were established by response surface methodology in DCMD process.
- The models were proved to be able to predict the responses accurately.
- Interaction effects of operational and module-configural factors were investigated.
- Optimal conditions for multi-objectives were determined and confirmed.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 9 January 2016
Received in revised form 18 April 2016
Accepted 29 April 2016
Available online 19 May 2016

Keywords:
Direct contact membrane distillation
Desalination
Response surface methodology
Operating parameters
Module configuration parameters

ABSTRACT

Response surface methodology was applied for modeling and optimization of direct contact membrane distillation (DCMD) for water desalination with PVDF hollow fiber membrane. The optimization objectives included average permeate flux, water productivity per unit volume of module, water production per unit energy consumption, and a comprehensive index to find out a balance among high water flux, high production, and low energy consumption. Effects of both operating parameters and configuration parameters of membrane module, including inlet temperatures of feed and permeate, flow velocity of feed solution, module packing density, and length-diameter ratio of module, on the objectives were investigated. The models for predicting the objectives were developed and statistically validated by analysis of variance. The binary interaction effects of the variables on the objectives were illustrated and discussed. All of the objectives were significantly influenced by the interaction effects of the variables. Under the optimum conditions, 67.1 $kg/(m^2 \cdot h)$ average permeate flux, 4.9825×10^4 $kg/(m^3 \cdot h)$ water productivity per unit volume of module, 2.1839×10^{-4} kg/kJ water production per unit energy consumption, and comprehensive index of 0.7587 were obtained within investigated experimental range. The experimental and predicted results are in good agreement confirming the validity of the models.

* Corresponding author at: Department of Chemical Engineering, School of Chemical Engineering and Technology, Xi'an Jiaotong University, Xi'an 710049, China.
E-mail address: lina@mail.xjtu.edu.cn (N. Li).

http://dx.doi.org/10.1016/j.desal.2016.04.029
0011-9164/

1. Introduction

Membrane distillation (MD) is a thermally-driven process in which vapor molecules evaporate from feed solution and transport through microporous hydrophobic membrane as distillate product. Its driving force is based on the vapor pressure difference generated by temperature gradient between the feed side and the permeate side of membrane [1]. MD process is conducted at lower operating temperatures (30–80 °C) than conventional distillation (>100 °C) and under lower operating pressures (<100 kPa) than conventional pressure-driven membrane processes such as reverse osmosis (RO) (>10 bar). The rejection to non-volatile solute in MD is theoretically 100%. MD system is generally performed in four configurations, including direct contact membrane distillation (DCMD), sweeping gas membrane distillation (SGMD), air gap membrane distillation (AGMD), and vacuum membrane distillation (VMD) [2,3]. DCMD is the most commonly used MD configuration due to its simple operation without the need of external condensers like in SGMD and VMD configurations [3,4], which has been widely applied for fresh water production [5–7], wastewater treatment and reuse [8,9], and food processing [10,11].

Factors affecting the performance of DCMD have been studied extensively, including operating conditions [12–17], module configuration parameters [12–14,18], and membrane properties [12,16,19]. The operating conditions investigated are generally the temperature of the feed and permeate, the flow rate (flow velocity) of feed and permeate, and the feed concentration. Feed temperature has a significant influence on permeate flux. In most cases, increasing feed temperature leads to an exponential increase of permeate flux since water vapor pressure driving force increases exponentially with the increase in temperature according to Antoine equation [12–15,20]. The increase in flow rate of feed and permeate is beneficial for reducing temperature polarization and concentration polarization on membrane surface leading to the increase in permeate flux and thermal efficiency [14]. High feed concentration will cause the decrease in water vapor pressure and the increase in concentration polarization, and lead to a negative effect on permeate flux [13]. However, the influence of feed concentration (activity) on the driving force of MD may not be significant compared to that of temperature difference across the membrane. For instance, Khayet et al. [21] reported that the most significant individual effect upon the permeate flux was attributed to the feed temperature while the feed solute concentration had the lowest individual effect upon the DCMD permeate flux in comparison to the feed temperature and stirring rate. Elzahaby et al. [22] also reported that pure water productivity decreased by only 2.7% with the increase in NaCl concentration from 3 to 50 g/L in DCMD process. As to the module configuration parameters, increasing hollow fiber length will decrease permeate flux due to the reduction of average transmembrane temperature difference [13,14], and will also make the membrane prone to be wet due to the increased hydrodynamic pressure at the same flow rate [3]. The large packing density of membrane in a module is favorable to increase the unit volume productivity, but the increasing channeling and dead zones will reduce mass transfer [18]. The increased packing density of membrane module decreased the ratio of permeate flux to the overall driving force dramatically, due to the uneven flow distribution in the lumen side of the module and the channeling effect [20]. As to membrane properties, the studies on the relationship of DCMD performance with membrane thickness, porosity, tortuosity, pore size, and thermal conductivity have been widely reported [23–24]. The permeate flux increases by increasing membrane pore size and porosity and by decreasing membrane thickness and pore tortuosity [25].

Since the factors influencing MD process are very complicated, conventionally MD research varies one parameter and keeps the others constant. This research method is expensive, laborious and ignores the interaction effects between the independent parameters [21,26–28]. Therefore, a design of experiment allows the simultaneously varying of input parameters, which can reveal their significance and complex interaction under real operation conditions. The response surface methodology (RSM), a collection of mathematical and statistical technique, is one of the most relevant multivariate methods [26]. In RSM, the predicted response is plotted in 3D as a function of two inputs allowing to visualize their contribution and interaction influence [4,28]. RSM method has been applied successfully in MD process in modeling, optimization, and investigation of interactions between several parameters in recent years [21,28–33].

Both single objective [21,28–30] and multi-objective [31–33], such as permeate flux and thermal efficiency, have been investigated with RSM method. The most studied variables for the optimization were operating parameters such as temperatures and flow rates of the feed and permeate, and feed concentration. Khayet et al. employed a central compositional design (CCD) for modeling and optimization of DCMD process [21] and SGMD process [28]. In DCMD, the interaction effect between feed temperature and stirring velocity increased the permeate flux while the interaction effects between stirring velocity and feed concentration and between feed temperature and feed concentration decreased the permeate flux. In SGMD, the significant interactions were observed between the variables such as gas temperature and gas flow rate, feed temperature and gas flow rate, and feed flow rate and gas flow rate. Chang et al. [29] developed quadratic response surface models to predict the performance of DCMD and AGMD in terms of separation efficiency (water production per unit hot fluid flow rate) and heat requirements. The studied factors were flow rates of hot and cold fluids, hot fluid temperature, and membrane thickness in DCMD, and hot fluid flow rate and hot fluid temperature in AGMD. Under the optimal conditions, separation efficiency of 8.2% and 5.8% were obtained for DCMD system and AGMD system, respectively, close to the obtained efficiency of reverse osmosis technology. Boubakri et al. [30] studied the effects of vapor pressure difference, feed flow rate, permeate flow rate, and initial ionic strength on DCMD permeate flux and found the significant interaction between feed flow rate and initial ionic strength. C. Cojocaru and M. Khayet [31] developed RS-models to predict permeate flux and sucrose concentration rate in SGMD as functions of feed inlet temperature, air circulation velocity, and initial sucrose concentration. The interaction effect between air circulation velocity and initial sucrose concentration was more significant than that between feed inlet temperature and initial sucrose concentration, whereas the interaction between feed inlet temperature and air circulation velocity was negligible. He et al. [32] observed the highest positive effect of hot feed inlet temperature on both distillate flux and gained output ratio and a trade-off between distillate flux and gained output ratio by varying cold feed inlet temperature and feed flow rate when keeping hot feed inlet temperature as constant. Zaherzadeh et al. [33] reported the optimization of membrane structural characteristics (pore size, porosity, and contact angle) for increasing permeate fluxes with the influencing factors of membrane synthesis process (temperature, pressure, and polymer concentration).

It has been reported that both operating conditions and membrane module configuration parameters play significant roles in MD performance based on experiments or simulations [12–14,20, 34–36]. However, the study on the optimization of DCMD process considering operating conditions and module configuration parameters simultaneously is few. Cheng et al. [14] applied the genetic algorithm to a two-objective (water productivity and thermal efficiency) optimization of DCMD under different operating conditions and fiber dimensions. They found that thermal efficiency decreased as water production increased and vice versa with the designed variables including inlet cold flow rate, fiber length, and module packing density. In addition, Yu et al. [36] suggested that the simulations of DCMD process could provide qualitative predictions on the effects of operating conditions and module configuration parameters on MD performance, which could guide future study on the hollow fiber module design, module scale-up, and process optimization to facilitate MD commercialization.