

Flux Prediction in Direct Contact Membrane Distillation

Dahiru U. Lawal and Atia E. Khalifa

Abstract—Membrane distillation (MD) is a potential mean of water desalination. MD is a thermally driven desalination technology that has been employed in four basic configurations. One of these configuration is Direct Contact Membrane Distillation (DCMD). In DCMD, both hot and cold solution is maintained in direct contact with micro porous hydrophobic membrane material. Heat and mass transfer analysis was performed on DCMD. Based on Kinetic theory of gas, the performance of different models of membrane permeability (coefficient) was investigated under different DCMD operating parameters (feed temperature, coolant temperature and feed flow rate). Knudsen number provides the guideline in identifying the type of model of mass transfer to be considered under any given experimental conditions.

Results revealed that for a given pore size under the same simulation and experimental conditions, Transition (Knudsen-Molecular diffusion) type of flow model predictions is in good agreement with the experimental results. Hence the best model to be consider for flux prediction in DCMD. The effect of membrane pore size was also studied. Results showed that permeate flux increases with increase in pore size up to the critical pore condition where the flux prediction remain constant (unchanged).

Index Terms—Desalination, direct contact membrane distillation, flux prediction, hydrophobic membrane material.

I. INTRODUCTION

Membrane distillation (MD) is an emerging technology for desalination. It is a thermally driven separation process in which separation is achieved as a result of phase change. Membrane distillation is a process that applied differences in vapour pressure to permeate water vapour through hydrophobic membrane sheet and reject non-volatile component present in the water. A.S Jonsson *et al.* [1] stated that Findley was the first to link the separation techniques now known as membrane distillation (MD). Membrane distillation differs from other membrane technologies since the driving force for desalination is not the total pressure of water through the membrane but the difference in vapour pressure of water across the membrane.

The membranes materials usually employed for MD are hydrophobic in nature. Four basic configurations are usually employed in MD [2]. These are the vacuum membrane distillation (VMD), direct contact membrane distillation

(DCMD), sweeping gas membrane distillation (SGMD) and air gap membrane distillation (AGMD). In all these MD configuration, membrane coefficient (permeability) limit the performance of MD system. Membrane permeability is a function of applied temperature, membrane thickness, pore sizes, tortuosity, porosity, physical properties of fluid, the geometry and its dimension, and the average velocity of the fluid.

In DCMD, evaporation occurs at the hot feed solution when the vapour pressure at the hot side is greater than the vapour pressure at the coolant side of the membrane. The vapourized gases then passes via the pores of membrane and condensed in the flowing coolant solution.

MD can utilizes waste heat to enhanced mass transfer through a hydrophobic, micro porous membrane material. MD operates at low temperature (below boiling point of water). This process was introduced in the late 1960s but has not yet gets to the commercial market. Perhaps, this is due to lack of membranes that have the characteristics most suitable for the process performance, especially at reasonable prices [3].

MD offer some advantages over other desalination techniques like reverse osmosis (RO). The advantages includes but not limited to [4]; (a) Low energy consumption (b) Membrane fouling in MD is less of a problem (c) Lower operating temperatures (temperature as low as 30 °C have been used) (d) High rejection factors achieved (e) No Extensive pre-treatment is necessary as required in reverse osmosis (f) Possibility of using waste heat and renewable energy. However, MD have some shortcoming which may include: (a) Lack of membranes and modules designed specifically for MD (b) Permeate flux decay with time due to fouling, membrane deterioration (c) Risk of membrane pore wetting (d) Commercial membrane modules are still expensive.

L. Martinez and F. J. Florido Diaz [5] developed a model which is based on a dusty gas model of gas transport through porous media. A direct contact membrane distillation experiment was conducted using two flat sheet membrane material. Two experiment were carried out, in the first experiment, GVHP22 membrane was used while HVHP45 membrane material was employed in the second experiment. The output results show that the developed model prediction were in good agreement with the experimental results.

Jian-Mei Li *et al.* [6] investigated experimentally the influence of feed flow and feed temperature on distil pure water flux in direct contact membrane distillation (DCMD) and vacuum membrane distillation (VMD) using an aqueous solution of about 35g/l NaCl. Different types of membrane material were compared and there result shows that for both DCMD and VMD, Polyethylene (PE) membrane material produces higher water flux when compared to

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polypropylene (PP) membrane material.

Robert W. Field *et al.* [7] developed a model for the overall mass transfer coefficient for direct contact membrane distillation. The developed models revealed that membrane effective thickness is the sum of the actual thickness. Their investigation revealed that at a typical conditions, the sum of the additional terms exceeds 100 μ m, which shows that the flux is not inversely proportional to membrane thickness. The sum of the additional terms depends on the heat-transfer coefficients of the films but typically exceeds 100 μ m. They also shows that the thermal efficiency does not depend on membrane thickness. The traditional method for combining the Knudsen diffusion coefficient and the molecular diffusion coefficient overestimates the resistance and at the same time underestimates the permeate flux.

Tzahi Y. Cath *et al.* [8] experimentally investigate a new membrane module and new membrane distillation configurations. In a turbulent flow regime and with a feed water temperature of only 40 °C, the performances of three hydrophobic micro porous membranes were evaluated. Result revealed that reduction in temperature polarization and permeability obstructions in the DCMD of salt solutions could be obtained simultaneously by careful design of a membrane module and configuration of the MD system. Result shows that there was a substantial improvement in mass transfer of water vapour for the new method as compared to that of the available literature. It was shown that the permeate flux obtained for the new approach can be more than twice of the traditional mode of DCMD when operating at relatively low temperatures. In investigating the performance of the new configuration, both NaCl and synthetic sea salt feed solutions were used. Salt rejection was greater than 99.9% in all the cases. Economic aspects of the improved DCMD process was discussed and the new enhanced DCMD process was compared with the reverse osmosis (RO) process for desalination.

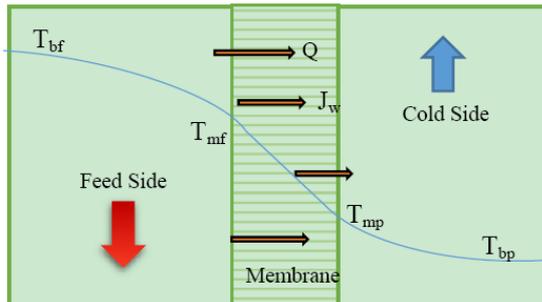


Fig. 1. Schematic diagram of Heat and mass transfer across MD membrane.

II. THEORY

The system considered in this study is as depicted in Fig. 1. It consists of feed chamber and coolant chamber separated by a hydrophobic porous membrane material. In this system (DCMD), heat and mass transfer occurs simultaneous. The feed temperature T_{bf} decrease over the feed side boundary layer to T_{mf} at the membrane surface. Part of the water evaporates and diffuse through membrane pores. At the same time, heat is conducted through membrane to the cold chamber. The cold flow temperature T_{bp} rises across the

cold boundary layer to T_{mp} at the membrane surface to the cold chamber as vapour condenses into the fresh water [2]. The driving force is hence the vapour pressure difference between T_{mf} and T_{mp} , which is less than the vapour pressure difference between T_{bf} and T_{bp} . The process is otherwise called temperature polarization [9].

A. Mass Transfer

Mass transfer in MD takes place by convection and diffusion of vapour through the micro porous membrane sheet [10]. In DCMD, both heat and mass transfer process takes place through the membrane as shown in figure1. The water permeate flux (J_w) obtained depends on the membrane characteristic and the established driving force.

The mechanism of mass transfer in the membrane pores is guided by three basic process. These are the Knudsen-diffusion (K), Poiseuille-flow (P) and Molecular-diffusion (M) or a combination between them known as the transition mechanism. The general expression for mass transfer in MD is [11];

$$J_w \propto \Delta P_m \quad (1)$$

$$J_w = C_w \Delta P_m \quad (2)$$

where C_w is the overall mass transfer coefficient (membrane permeability) which is the reciprocal of an overall mass transfer resistance and $\Delta P_m = P_{mf} - P_{mp}$ is the transmembrane vapour pressure difference (the driving force).

$$J_w = C_w (P_{mf} - P_{mp})$$

For pure water, P_m is determined by Antoine equation [2];

$$P_m = \exp\left(23.328 - \frac{3841}{T_m - 45}\right)$$

Khayet *et al.* [12] suggested that the permeate flux has a linear relation with the partial pressure difference through the membrane pores when the feed is water and the temperature difference through the membrane is low.

The Partial pressure difference is obtained as;

$$P_{mf} - P_{mp} = \left(\frac{dP}{dT}\right)_{T_m} (T_{mf} - T_{mp}) \quad (3)$$

Substitution of Eq. (3) into (2) leads to

$$J_w = C_w \left(\frac{dP}{dT}\right)_{T_m} (T_{mf} - T_{mp}) \quad (4)$$

where P_{mf} and P_{mp} , are the transmembrane vapour pressure at the feed and permeate sides respectively while T_{mf} and T_{mp} are the transmembrane temperature at the feed and permeate sides respectively.

Combination of Clausius–Clapeyron equation and the Antoine equation gives the expression for evaluating $\frac{dP}{dT}$ [2];

$$\left(\frac{dP}{dT}\right)_{T_m} = \frac{\Delta H_v}{RT_m^2} \exp\left(23.328 - \frac{3841}{T_m - 45}\right) \quad (5)$$

and

$$\Delta H_v = 1.7535T + 2024.3 \quad (6)$$

where R is the gas constant equivalent to 8.314472 J/mol.K, T_m is the mean temperature in kelvin (k) given by $T_m = \frac{T_{mf} + T_{mp}}{2}$ and ΔH_v is the heat of vapourisation of water.

B. Membrane Permeability (C_w)

Just like how Reynolds number is used as a guide line in identifying if a flow is laminar, turbulent and transitional, Knudsen number (K_n) is the governing quantity which provide the guideline in identifying which type of mechanism of mass transfer to be considered under the given experimental condition. Based on kinetic theory of gases, the mechanism for mass transfer through DCMD membrane is by Knudsen model or ordinary molecular diffusion or the poiseuille (viscous) flow model or combination of two or more of the models.

In DCMD, the viscous flow model is usually neglected because both feed and permeate solutions are in direct contact with membrane material under atmospheric. The total pressure is constant at atmospheric leading to negligible viscous kind of flow [10], [13], [14]. Knudsen number is expressed as;

$$K_n = \frac{\lambda_w}{d_p} \quad (7a)$$

where λ_w is the mean free path of the water molecule and d_p is the pore size (diameter). The mean free path of the water molecule is given by;

$$\lambda_w = \frac{K_B T}{\sqrt{2} \pi P_m (2.641 \times 10^{-10})^2} \quad (7b)$$

where K_B is the Boltzmann constant, P_m is the mean pressure within the membrane pores, T is the absolute mean temperature in the pores (Kelvin).

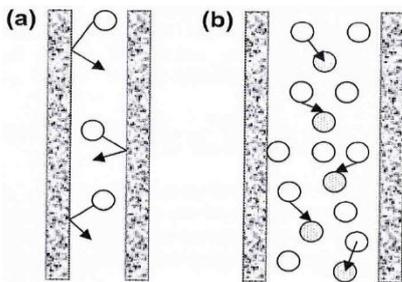


Fig. 2. (a) Knudsen type of flow and (b) Ordinary molecular type of flow [2].

When membrane pore size is low in comparison with mean free path of the water molecules in vapour state ($K_n > 10$ or $d_p < 0.1\lambda_w$), then the molecule-pore wall collisions preside over the molecule-molecule impact, so the Knudsen kind of flow is responsible for the mechanism of mass transfer through the membrane pores as shown in the Fig. 2a. In other word, when the ratio of pore radius to the mean free path is lower than 0.05 ($\frac{r_p}{\lambda_w} < 0.05$), then Knudsen kind of flow model is employed. The membrane permeability (C_w^K) in Knudsen region is given as [2], [7], [15], [16];

$$C_w^K = \frac{2\pi}{3} \frac{1}{RT} \left(\frac{8RT}{\pi M_w} \right)^{1/2} \frac{r_k^3}{\tau \delta} \quad (8)$$

when the membrane pores is assumed to have a uniform size, then the average pore radius is used and it's given as [2], [16], [17];

$$C_w^K = \frac{2}{3} \frac{\varepsilon \bar{r}_k}{RT \tau \delta} \left(\frac{8RT}{\pi M_w} \right)^{1/2} \quad (9)$$

when the mean free path of the transported water molecules in vapour state is less than the membrane pore size ($K_n < 0.01$ or $d_p > 100\lambda_w$), then the molecule-molecule collision is predominant over the molecule to pore wall, so ordinary molecular diffusion is responsible for the mass transfer in the continuum region which is cause virtually by stagnant air inside the membrane pores due to the low solubility of air in water. In this case, the expression below may be adopted to evaluate the membrane permeability [2], [16];

$$C_w^D = \frac{\pi}{RT} \frac{P D_w}{P_a} \frac{r_D^2}{\tau \delta} \quad (10)$$

when the membrane pores is assumed to have a uniform size, then the average pore radius is used and it's given as [2], [16];

$$C_w^D = \frac{\varepsilon}{\tau \delta} \frac{P D_w}{P_a} \frac{M_w}{RT} \quad (11)$$

where P_a is the air pressure in the membrane, P is the total pressure inside the membrane pore and D_w is the diffusion coefficient which can be determined from the expressions below [2], [4], [17], [18];

$$\begin{aligned} P D_w &= 1.895 \times 10^{-5} T^{2.072} \\ P D_w &= 1.19 \times 10^{-4} T^{1.75} \\ P D_w &= 4.46 \times 10^{-6} T^{2.334} \end{aligned} \quad (12)$$

where $P D_w$ is in Pa.m²/s

Transition region occurs when we have $0.01 < K_n < 10$ ($0.1\lambda_w < d_p < 100\lambda_w$). In this case, the molecules of liquid water collides with each other and diffuse through the air molecules. For transition region, combined Knudsen - ordinary molecular diffusion type of flow is responsible for the mass transfer. The membrane permeability for this case is determined using the relationship below [2], [16];

$$C_w^C = \frac{\pi}{RT} \frac{1}{\tau \delta} \left[\left(\frac{2}{3} \left(\frac{8RT}{\pi M_w} \right)^{1/2} r_t^3 \right)^{-1} + \left(\frac{P D_w}{P_a} r_t^2 \right)^{-1} \right]^{-1} \quad (13)$$

when the membrane pores is assumed to have uniform size, then the average pore radius as expressed below is used [2], [16], [17];

$$C_w^C = \frac{1}{RT \delta} \left[\frac{3}{2} \frac{\tau}{\varepsilon r} \left(\frac{\pi M_w}{8RT} \right)^{1/2} + \frac{P_a \tau}{\varepsilon P D} \right]^{-1} \quad (14)$$

Membrane tortuosity can be estimated using the correlation suggested by Macki–Meares [19];

$$\tau = \frac{(2 - \varepsilon)^2}{\varepsilon}$$

where ε and τ are the membrane porosity and tortuosity respectively.

C. Heat Transfer

Heat transfer in (DCMD) involved three (3) steps as depicted in Fig. 1. The steps are;

Convection heat transfer in the feed boundary layer (Q_f) given by [2];

$$Q_f = h_f (T_{bf} - T_{mf}) \quad (15)$$

Heat transfer across the membrane sheet (Q_m) which is the summation of latent heat of vaporization (Q_v) and conduction heat transfer through the membrane material and the gas filling pores (Q_c). Hence heat transfer mechanism through membrane is as given in Eq. (16) [2];

$$Q_m = Q_c + Q_v \quad (16)$$

where

$$Q_v = J\Delta H_v = C_w \left(\frac{dP}{dT}\right)_{T_m} (T_{mf} - T_{mp}) \Delta H_v \quad (17)$$

$$Q_c = -K_m \frac{dT}{dx} = \frac{K_m}{\delta} (T_{mf} - T_{mp}) \quad (18)$$

Combining Eqs. ((16), (17) and (18)) leads to

$$Q_m = \left(\frac{K_m}{\delta} + C_w \left(\frac{dP}{dT}\right)_{T_m} \Delta H_v\right) \Delta T_m \quad (19)$$

where $\Delta T_m = T_{mf} - T_{mp}$

Heat transfer in the permeate boundary layer (Q_p) which is given by;

$$Q_p = h_p (T_{mp} - T_{bp}) \quad (20)$$

Different models has been employed in estimating thermal conductivity of the membrane material, but the following sets of equation is often employed [2];

$$K_m = \varepsilon K_g + (1 - \varepsilon)K_p \quad (21)$$

The Isostress model is used in most of MD studies and is known to gives better estimation of K_m [2], [17];

$$K_m = \left[\frac{\varepsilon}{K_g} + \frac{(1-\varepsilon)}{K_p}\right]^{-1} \quad (22)$$

where K_p and K_g are the thermal conductivity of the membrane material and that of the gas filling the membrane pores respectively.

At steady state, the overall heat transfer through the DCMD system is express as shown below;

$$Q = Q_f + Q_m + Q_p \quad (23)$$

Combination and manipulation of Eqs (15) to (20) leads

to;

$$T_{mf} = \frac{\frac{K_m}{\delta}(T_{bp} + \frac{h_f}{h_p}T_{bf}) + h_f T_{bf} - J_w \Delta H_{vw}}{\frac{K_m}{\delta} + h_f \left(1 + \frac{K_m}{\delta h_p}\right)} \quad (24)$$

$$T_{mp} = \frac{\frac{K_m}{\delta}(T_{bf} + \frac{h_p}{h_f}T_{bp}) + h_p T_{bp} + J_w \Delta H_{vw}}{\frac{K_m}{\delta} + h_p \left(1 + \frac{K_m}{\delta h_f}\right)} \quad (25)$$

Heat transfer coefficients (h_f and h_p) can be estimated by means of dimensionless Nusselt numbers given by [15];

$$Nu_i = \frac{h_i d_i}{k_i} \quad \text{where } i = f, p \quad (26)$$

where k is the thermal conductivity of the fluid, d is the hydraulic diameter, h is the heat transfer coefficient and f is the feed and p is the permeate.

For laminar flow, the following empirical correlation can be used [19], [20];

$$Nu = 1.86 \left(Re Pr \frac{d}{L}\right)^{0.33} \quad (27)$$

For turbulent flow correlation below may be used [21];

$$Nu = 0.023 Re^{0.8} Pr^{0.33} \left(\frac{\mu}{\mu_s}\right)^{0.14} \quad (28)$$

where Pr and Re are the Prandtl and Reynolds numbers respectively and they are given by;

$$Pr = \frac{\mu C_p}{k} \quad , \quad Re = \frac{\rho u d}{\mu} \quad (29)$$

where C_p , ρ , u , and μ are the specific heat capacity, density, average velocity and viscosity of the liquid respectively.

For feed solution containing dissolve salt, P_{mf} may be estimated using the Raoult's law which is given as [22];

$$P_{mf} = (1 - CM_{NaCl})P_m \quad (30)$$

where CM = mole solute concentration.

D. Procedure for Flux Prediction (J_w)

For flux prediction, an iterative method was adopted. Guessed values were assumed for membrane surface temperatures (T_{mf} and T_{mp}) as initial guess, the guessed values were then utilized to estimate permeate flux (J_w) as given in Eqs. ((4), (5), (6), (9), (11) and (14)). The current flux (J_w) value is then utilized to estimate heat transfer coefficient at average membrane surface temperatures ($\frac{T_{bf} + T_{mf}}{2}$ and $\frac{T_{mp} + T_{bp}}{2}$) in accordance with Eqs. ((26)-(28)). Eqs. ((24) and (25)) is then used to estimate the membrane surface temperature, the output results was compared with the initial assumed (guessed) values of membrane surface temperature. The above procedures was repeated until the difference between assumed membrane surface temperature and calculated one is less than 0.1% (until the assumed values for T_{mf} and T_{mp} concurred with the calculated ones

with the relative error of less than 0.1%).

III. RESULTS AND DISCUSSIONS

Prediction of permeate flux was conducted using developed Matlab codes. The results obtained were validated against the experimental work of T.Y. Cath *et al.* [8] and O. Andrjesdóttir *et al.* [23] to testify the best theoretical model to be employed in DCMD under the given experimental conditions. Results of prediction for different models of membrane permeability were depicted in Figs. 3-7.

TABLE I: MEMBRANE PROPERTIES AND GEOMETRICAL CONSTANT USED [8], [23]

Symbol	Values as used in	
	[8]	[23]
δ	175 μm	140 μm
ε	0.7	0.88
K_g	0.029W/mK	0.029W/mK
K_p	0.259W/mK	0.259W/mK
d_p	0.45 μm	0.20 μm
R	8.314J/Kmol	8.314J/Kmol
L	200mm	120mm
W	2mm	104mm
H	3mm	5.2mm
A	$6 \times 10^{-4} \text{m}^2$	$5.408 \times 10^{-4} \text{m}^2$
d_h	$2.4 \times 10^{-3} \text{m}$	$9.905 \times 10^{-3} \text{m}$

For a given pore size, only one type of flow model is good for flux prediction. So we cannot assumed that all the three models of mass transfer coefficient can be utilized simultaneously for a given pore size. The minimum and maximum temperature considered in this work are 15 °C and 60 °C respectively. The estimated mean free path for water molecules in vapour phase at these temperatures are $1.27 \times 10^{-7} \text{m}$ and $1.49 \times 10^{-7} \text{m}$ respectively. For the given pore sizes of $2 \times 10^{-7} \text{m}$ as used by O. Andrjesdóttir *et al.* [23] and $4.5 \times 10^{-7} \text{m}$ as employed by T. Y. Cath [8], the Knudsen number were found to be 0.281 and 0.745 respectively.

The obtained K_n revealed that the flow in DCMD is described by transition model ($0.01 < K_n < 10$) since K_n values falls within the transition region. As such we expect combined Knudsen-molecular diffusion kind of flow model to gives most accurate prediction of flux.

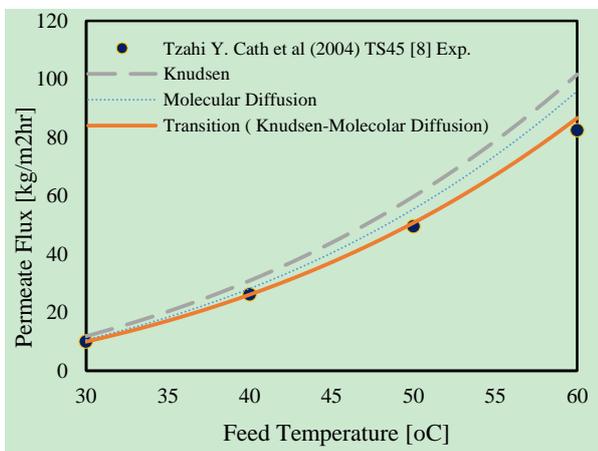


Fig. 3. Flux vs. feed temperature in DCMD for the three models and experimental [8]. Coolant temperature is kept at 20°C, feed and permeate velocities are 1.75 m/s.

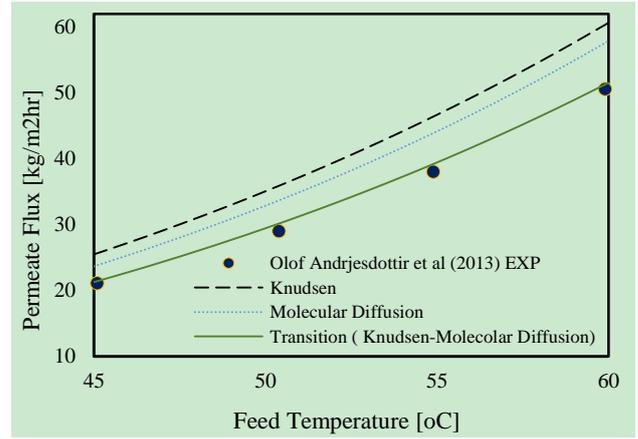


Fig. 4. Flux vs. feed temperature in DCMD for the three models and experimental [23]. Coolant temperature is kept at 21°C, feed flow rate is 12 L/min and coolant flow rate is 4 L/min.

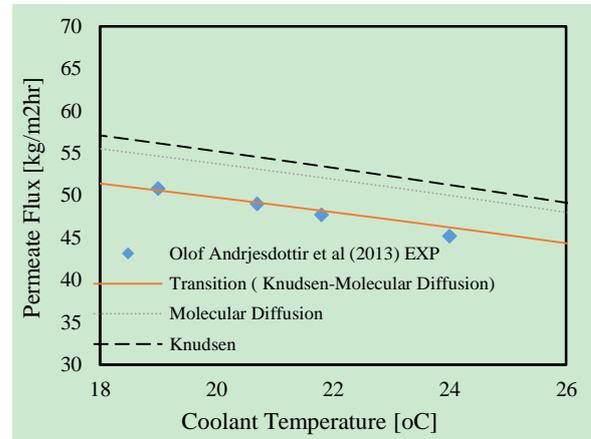


Fig. 5. Effect of coolant temperature on flux for the three models and experimental [23]. Feed temperature is kept at 60°C, feed flow rate is 12 L/min and coolant flow rate is 4 L/min.

To support the above claim, the developed code was used to predict the permeate flux, the predicted flux were validated against the experimental work of T. Y. Cath *et al.* [8] and O. Andrjesdóttir *et al.* [23] as shown in Figs. (3, 4, 5 and 6) which depicted the effects of increasing feed temperature, coolant temperature and feed flow rate respectively. Results shows good agreement between transition model prediction and experimental results of [23] and [8].

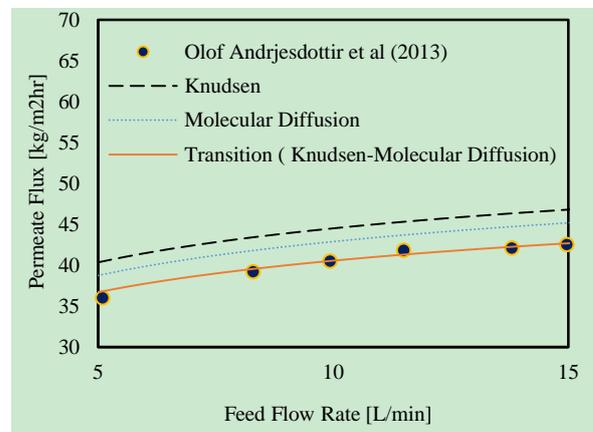


Fig. 6. Effect of flow rate on flux for the three models and experimental [23]. Coolant flow rate is 3 L/min, feed temperature is 60 °C, and coolant temperature is 21 °C.

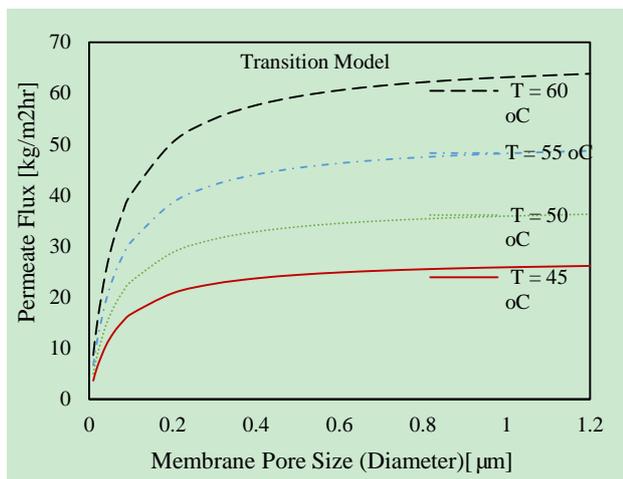


Fig. 7. Effect of pore size in DCMD for combined Knudsen-Molecular diffusion model. Coolant temperature is kept at 21°C, feed flow rate is 12 L/min and coolant flow rate is 4 L/min.

As observed from Figs. 3, 4, 5 and 6, both the Knudsen diffusion model and molecular diffusion model tends to overestimate the permeate flux with Knudsen type of flow model having the highest flux prediction.

Effect of feed temperature on permeate flux was as shown in Figs. 3 and 4. Permeate flux increases with increase in feed temperature. This is in accordance with Antoine equation which shows exponential rise in vapour pressure as the feed temperature increases. This leads to increase in flux production. It can be concluded that the theoretical model used in this study is good in predicting the permeate flux as there is good agreement between the model predictions and experimental results with an error between 0.1 - 4.84 % for [8] and 0.47 - 3.55% for [23]. Molecular diffusion model is second in flux prediction follow by the Knudsen model when they are compare in terms of good agreement with experimental data.

Fig. 5 depicted the effect of increasing coolant temperature for the three models of membrane coefficient. As observed from the figure, the flux prediction decreases with increase in coolant temperature. This is due to the fact that as the coolant temperature increases, there is decreases in the temperature difference between the feed and the coolant chambers which leads to the reduction of permeate flux. The models prediction shows that Knudsen model gives the highest permeate flux prediction (over prediction). Next in flux prediction model closer to the experimental value is the molecular diffusion model. The transition model gives the best predictions against the experimental values with a deviation ranging between 0.20 - 2.16 %.

Fig. 6 showed the prediction of permeate flux under the influence of feed flow rate. It is seen that flux increases with increase in feed flow rate. This is as a result of higher turbulent that is generated in the feed channel which accelerate higher mixing effect and thus higher flux. The transition models prediction shows good match with experimental data with a minimum deviation ranging from 0.0% to maximum deviation of 0.96 %. The molecular diffusion and Knudsen type of flow model tends to over predict the permeate flux.

To investigate the effect of membrane pore size, membrane pore size were varied from 0.05 µm to 1.2 µm for different feed temperature using transition model. The

selected range of pore size was based on summarized table of commercial membranes commonly used in MD studies [2]. The obtained results was as depicted in Fig. 7. It is obvious from the figure that permeate flux increases with increase in membrane pore size. For instance, for 55°C feed temperature, there was an initial sharp rise in permeate flux from 0.01 µm to 0.4 µm. Further increase in pore size resulted in negligible or little increase in permeate flux. The rise in permeate flux continue to diminishes as the pore size increase until the critical pore size ($0.1 \lambda_w$) where the predicted flux remain constant for any further increment in pore size.

M. Khayet and T. Matsuura [2] stated that to achieve higher permeate flux under some given experimental condition, membrane with pore size smaller than $0.1 \lambda_w$ should be used so that Knudsen type of flow will occur which usually gives higher permeate flux.

IV. CONCLUSIONS

The basic concept of heat and mass transfer analysis been performed to evinced the significant effect of membrane permeability (coefficient) on the mass transfer (permeate flux) in DCMD. The presented models was tested on the effect of increasing feed temperature, feed flow rate and coolant temperature. The predicted flux was validated against the experimental work of T. Y. Cath *et al.* [8] and Olof Andriessdottir *et al.* [23]. For DCMD, Knudsen diffusion, molecular diffusion and combine Knudsen-molecular diffusion models may be used in prediction of permeate flux. In model selection, membrane pore size must be taken into consideration. In most cases, the transition model is adopted for the prediction of flux in DCMD since large portion of membrane area is described by transition model.

Results showed that for membrane pore size of 0.2 and 0.45 µm, transition model is best to be adopted as its flux prediction in all of the cases were in good agreement with the experimental results. Results also revealed that other models for membrane permeability (Knudsen diffusion model and molecular diffusion model) tends to over predict the permeate flux with Knudsen model predicting the maximum flux. These leads to the conclusion that the best model for the prediction of permeate flux in DCMD is the combined Knudsen-molecular diffusion model as most of the region is captured by the model. Increasing the membrane pore size leads to an initial sharp rise in permeate flux production up to the critical pore size where the flux remain constant no matter the increment in pore size.

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NOMENCLATURE

A	Cross sectional area [m^2]
d_p	Pore size [μm]
d_h	Hydraulic diameter [m]
D	Diffusion coefficient [m^2/s]

h	Heat transfer coefficient [W/m ² K]
H_v	Heat of vapourisation [kJ/kg]
J_w	Permeate flux [kg/m ² hr]
K	Thermal conductivity [W/mK]
B_w	Mass transfer coefficient [kg/m ² sPa]
K_m	Membrane thermal conductivity [W/mK]
K_g	Thermal conductivity of gas filling the pores [W/mK]
K_p	Thermal conductivity of membrane material [W/mK]
K_n	Knudsen number [dimensionless number]
M_w	Molecular weight [g/mol]
Nu	Nusselt Number [dimensionless number]
P	Total pressure [Pa]
P_m	Mean Pressure [Pa]
Pr	Prandtl Number [dimensionless number]
Q_s	Sensible heat transfer [W/m ²]
Q_v	Latent heat transfer [W/m ²]
Q_c	Conduction heat transfer [W/m ²]
R	Gas constant [J/Kmol]
Re	Reynolds number [dimensionless number]
Sc	Schmidt number [dimensionless number]
Sh	Sherwood number [dimensionless number]
T	Absolute temperature [K]
Subscripts and Superscripts:	
f	Feed
p	Permeate
m	Membrane
b	Bulk
mf	Feed side of membrane
mp	Coolant side of membrane
bf	Bulk feed
bp	Bulk permeate
c	Coolant side
h	Hot region
Greek Letters:	
δ	Membrane thickness; film thickness [μ m]
ϵ	Porosity [%]
τ	Tortuosity [No unit]
μ	Viscosity [Ns/m ²]
λ	Mean free path [m]
V	kinematic viscosity [m ² /s]
ρ	Density [kg/m ³]

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