# The Heat and Mass Transfer Phenomena in Vacuum Membrane Distillation for Desalination

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*Abstract*—Vacuum membrane distillation (VMD) process can be used for water purification or the desalination of salt water. The process simply consists of a flat sheet hydrophobic micro porous PTFE membrane and diaphragm vacuum pump without a condenser for the water recovery or trap. The feed was used aqueous NaCl solution. The VMD experiments were performed to evaluate the heat and mass transfer coefficient of the boundary layer in a membrane module. The only operating parameters are feed inlet temperature, and feed flow rate were investigated. The permeate flux was strongly affected by the feed inlet temperature, feed flow rate, and boundary layer heat transfer coefficient. Since lowering the temperature polarization coefficient is essential enhance the process performance considerable and maximizing the heat transfer coefficient for maximizes the mass flux of distillate water. In this paper, the results of VMD experiments are used to measure the boundary layer heat transfer coefficient, and the experimental results are used to re-evaluate the empirical constants in the Dittus- Boelter equation.

*Keywords*—Desalination, heat and mass transfer coefficient, temperature polarization, membrane distillation

## I. INTRODUCTION

MEMBRANE distillation (MD) is a hybrid of thermal distillation and membrane process. The possible application of MD for desalination has been examined by some researchers [1]-[5]. MD offers various advantages in comparison to the traditional distillation and pressure driven membrane processes [6]. MD for water desalination is a membrane technique for separating water vapor from a liquid saline aqueous solution by transporting through the pores of hydrophobic membranes, made mainly of polypropylene (PP), polytetrafluoroethelyne (PTFE), polyvinylidenefluoride (PVDF) and polyethylene (PP). Various types of methods may be employed to impose a vapor pressure difference across the membrane to drive a flux. The permeate side may be a cold liquid in direct contact with the membrane, called direct contact membrane distillation (DCMD) or a condensing surface separated from the membrane by an air gap called air gap membrane distillation (AGMD) or a sweep gas blown across the membrane called sweep gas membrane distillation (SGMD) or vacuumed called vacuum membrane distillation

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(VMD). Because AGMD and DCMD do not need an external condenser, they are best suited for applications where water is the permeating flux. SGMD and VMD are typically used to remove volatile organic or dissolved gas from an aqueous solution [5], [7]-[10].

VMD is a kind of MD process; it is an evaporative process and in recent years, it has received attention as a means for efficient removing trace amount of volatile organic contaminants from water [7], [8]. VMD can be characterized by the following steps: vaporization of the more volatile compounds at the liquid-vapor interface and diffusion of the vapor through the membrane pores according to Knudsen mechanism [8]-[12]. VMD is also useful tool for measuring the boundary layer effects with in a membrane module. In this paper, the results of VMD experiments for desalination process are used to measure the boundary layer heat transfer coefficient within the membrane module, and experimental results are used to evaluate the empirical constants of the heat transfer correlation. Then, using a heat- mass transfer analogy, the boundary layer mass transfer coefficient are calculated and used along with the complete VMD model to predict the performance of VMD of salt water feed [8]-[12]. An examination of the literature permits to assert that the DCMD has been the configuration more studied, as apposed with VMD, which has deserved less attention.

## II. THEORY

In MD processes mass transport and heat transport are coupled. This study proposes VMD process, in which a feed solution is brought into contact with one side of a micro porous membrane and vacuum is pulled on the opposite side. In these conditions, a transmembrane water vapor pressure difference is created. The driving force for mass transfer in MD systems is the difference in the partial pressure of water vapor across micro porous hydrophobic membrane. The recognized transport mechanisms for mass transfer across the membrane are usually molecular diffusion and Knudsen diffusion and, sometimes, viscous flow. Molecular diffusion has a partial pressure difference as driving force and non-identical molecules that are in the way form the resistance to mass transfer. The driving force for Knudsen diffusion is also a partial pressure difference, but in this case molecules bounces into the membrane matrix, which form the resistance to mass transfer. Knudsen diffusion is thus important for small pores and / or low pressure. Finally, viscous flow has a total

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pressure difference as driving force, and the membrane matrix forms the resistance against it [8]-[12]. In a VMD configuration, the molecular diffusion is not adequate due to the very low value of the partial pressure of the air inside the pores. Consequently, the Knudsen and viscous flow diffusion should be a chosen as more appropriated [13]-[15].

The model suggests a linear relationship between the water flux, N, and the water vapor pressure difference between evaporating and condensing surface.

$$N = K_M \Delta P_V = K_M (P_V - P_0) \quad (1)$$

Where $K_m$ is called MD coefficient, $P_0$ is the pressure in the vacuum side and $P_v$ is the water vapor pressure in the membrane surface at the temperature $T_w$. Coefficient $K_m$ depends on temperature as well as on some geometric characteristics of the membrane. Based on the Kinetic Theory of Gases or the Dusty Gas Model, suggest that there is a Knudsen type diffusion of water molecules through the membrane pores and the permeation flux, N, was written [13], [15], [16]:

$$N = 1.0638 \frac{r\varepsilon}{\tau} \left( \frac{M}{RT} \right)^{1/2} \frac{\Delta P_V}{\delta} \quad (2)$$

Where r is the pore size, $\varepsilon$ is the fractional void volume of the membrane, $\delta$ is the membrane thickness, $\tau$ is the pore tortuosity, M is the water molecular mass and R is the gas constant.

As it is well known, the water vapor pressure at liquid – vapor interface (in Pa) may be related with the temperature (in K), by using the Antoine's equation [12]:

$$P_V = \exp(23.1964 - \frac{3816.44}{-46.13 + T}) \quad (3)$$

VMD is a thermally driven process, heat and mass transfer are involved simultaneously and boundary layers are formed near the membrane surface. Consequently, there is a decrease of the driving force due to polarization effects of both temperature and concentrations [6]. When a molecular mixture is brought to the membrane surface by the driving force action, some molecules will permeate through the membrane whilst others will be retained. This leads to an accumulation of the retained components and a depletion of the more permeating components in the boundary layer adjacent to the membrane surface. This phenomenon is referred to as concentration polarization.

In VMD process, there is a heat transfer occurs by two major mechanisms: (i) the latent heat transfer accompanying the transmembrane vapor flux, and (ii) heat transferred by conduction through the membrane matrix [13], [15]. Consequently, there is rather complex relationship between both heat and mass transfer. This is related and involved with the presence of an unstirred boundary layer that adjoins the

membrane at the feed side. The temperature at the membrane surface is lower than the corresponding value at the bulk phase. This creates temperature gradients in the liquid film adjoining the membrane. This phenomenon is called temperature polarization [13]-[15], [17], [18].

Heat transfer across the boundary layers in a MD module is often the rate limiting step for mass transfer, because such a large quantity of heat must be supplied to the vapor liquid interface to vaporize the liquid. The heat transfer coefficient of the VMD feed side boundary layer, $h_f$, is defined by [8]:

$$Q = h_f \Delta T_f \quad (4)$$

Where Q is the rate of heat transfer across the boundary layer and $\Delta T_f$ is the temperature drop across the boundary layer. In VMD, the conductive heat transfer across the membrane is negligible because of the low pressure on the permeate side of the membrane [8], [13]; therefore, the heat transferred through the liquid boundary layer and the energy transported through the membrane for VMD [8], [12]:

$$h_f \Delta T_f = N \Delta H_V \quad (5)$$

where $\Delta H_v$ is the latent heat of vaporization of water.

The empirical correlation like a Dittus-Boelter equation gives the value of $h_f$ for turbulent liquid flow written in the simplified form [8]:

$$hd/k_T = Nu = a \, Re^b \, Pr^c \quad (6)$$

Where d is the effective tube diameter, $k^T$ is the thermal conductivity of the water, Nu, Re and Pr are the Nusselt, Reynolds and Prandtl numbers respectively, and a, b and c are characteristic constants of the module design and liquid flow regimes. The viscosity correction factor normally associated with the Dittus-Boelter equation $(\mu / \mu_{wall})^{0.14}$, is negligible for MD application [8].

When both heat and mass transfer are occurring simultaneously, the mass and heat transfer coefficients may be related by the Reynolds analogy [19].

$$\frac{h_f}{k_f} = \rho C_P \left( \frac{Sc}{Pr} \right)^{2/3} \quad (7)$$

Where $k_f$ is the mass transfer coefficient of boundary layer, $\rho$ is the density of water, $C_p$ is the specific heat, and Sc is the Schmitt number. From (7), the mass transfer coefficient can be calculated once the heat transfer coefficient is known

### III. EXPERIMENTAL

Experiments were performed using a micro porous hydrophobic PTFE flat membrane (Millipore). The typical characteristics of the membrane are summarized in Table I. In

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all experiments, the aqueous feed solution of about 25000 to 35000 mg/l NaCl in pure water was prepared and continuously circulated through the membrane module from the vessel by a feed flow pump. A flow rate of feed water was measured by the Rotameter connected in between the pump and module. A vacuum pump was connected to the permeate side of the membrane module to remove the water vapor flux. Cold trap was used to condense and recover the water permeating vapor. The condensed pure water was collected to calculate the distillate flux. Calibrated vacuum gauge was used to measure the pressure at the permeate side of the module. A schematic view of the setup is presented in Fig. 1. The feed temperature and feed flow rate was varied respectively between 40 and 60 $^0$C, and 30 and 54 l/h. The vacuum pressure was kept 3 kPa in all the experiment. The process was allowed to run for approximately 1 to 2 h.

TABLE I
MEMBRANE CHARECTRISTICS

| Material | Hydrophobic PTFE |
|---|---|
| Pore size, μm | 0.22 |
| Porosity, % | 70 |
| Thickness, μm | 175 |
| Membrane area, cm$^2$ | 3.6 |

During the experiment, the level in the feed tank was maintained by adding measured amounts of feed water to the feed tank every 15 to 20 min. The flux was calculated by plotting the cumulative volume added to the feed versus time, and taking the slope. The membrane wetting or fouling was not observed during the experiment, because the volume versus time data did not fall on a straight line. The total volume of water added to the feed tank was compared to the volume of permeate collected at the end of experiment. Apparatus leaks or excessive evaporation from the feed tank did not seem to a problem with this experimental setup.
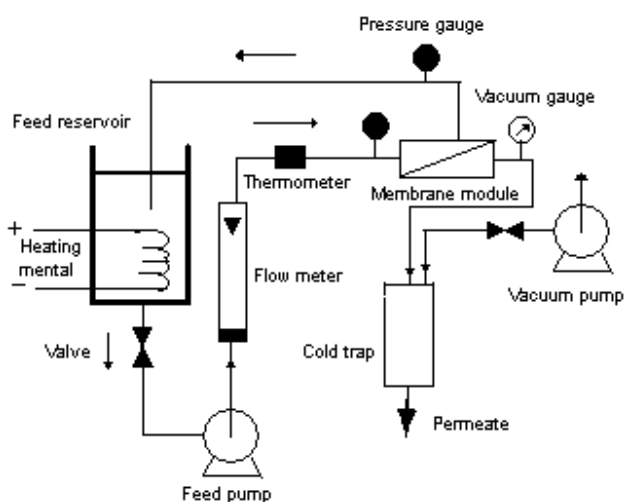


Fig. 1 Experimental setup.

## IV. RESULTS AND DISCUSSION

In this work, the MD flux has been measured for different values of the feed flow rate and temperature of the feed at the inlet of the membrane module. This was measured at constant vacuum pressure in the permeate side. Fig. 2 show the experimental values of the MD flux as function of the water flow rate, with the water inlet temperature as parameter. The feed flow rate was varied between 30 and 54 l/h for each one of the following water inlet temperature: 313, 323 and 333 K. The Reynolds's numbers range from 14521 to 26363. In this case, the MD flux increases with the feed flow rate because of increased Re and decreased boundary layer resistances. At higher Re, high heat transfers from the bulk feed to the membrane surface approaches to the corresponding temperature in the bulk phases leading to grater MD flux.
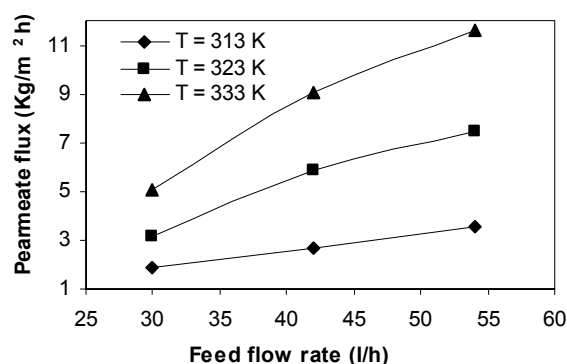


Fig. 2 Effect of feed flow rate at feed salt conc. = 30000 mg/l, and permeate pressure = 3 kPa.

Fig. 3 shows the experimental values of MD flux as function of the water inlet temperature, with feed flow rate as a parameter. Again the MD flux increases with both the feed flow rate and water inlet temperature. This effect can be attributed to the higher water vapor pressure sensitivity at higher temperatures. The feed temperature was varied between 313 and 333 K at 54 l/h feed flow rate and 3 kPa vacuum pressure at permeate side to give Pr ranging from 3.71 to 2.69.
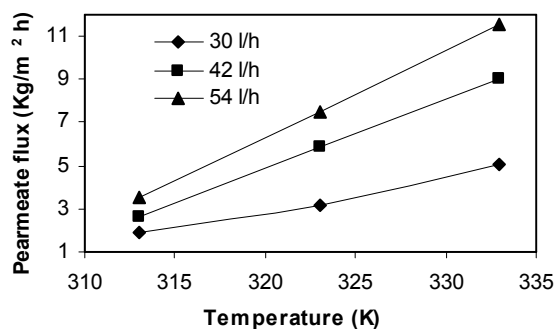


Fig. 3 Effect of feed temperature at feed salt conc. = 30000 mg/l, and permeate Pressure = 3 kPa.

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According to (4), the values of heat transfer coefficient of water feed boundary layer was calculated. It was observed that an increase in the water feed flow rate is accompanied by an increase in the MD flux and corresponding increase in the heat transfer coefficient. This can be attributed to a reduction in the temperature polarization effect. As the heat transfer coefficient increases, the temperature at the membrane surface approaches to the bulk temperature and the vapor pressure driving force increases.
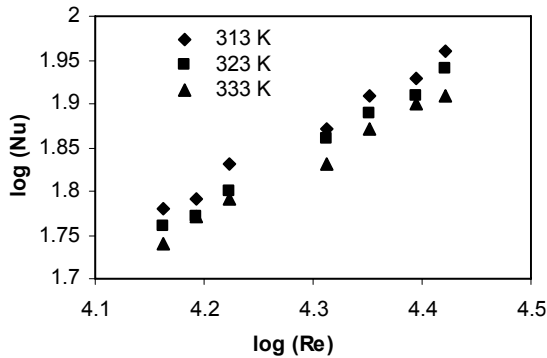


Fig. 4 log (Nu) versus log (Re) at constant feed inlet temperature, feed flow rate = 54 l/h, Permeate pressure = 3 kPa, and feed salt conc. = 30000 mg/l.

The heat transfer coefficient associate with each of the data points was measured and the dimensionless Re and Nu were calculated from the solution properties. Fig. 4 shows the results as a log-log plot of Nu Versus Re is made to estimate the dependence of the heat transfer coefficient on the Re, that is, on the water feed flow rate. These results were used to evaluate the empirical constants b in the heat transfer correlation (6). This plot is made for each water inlet temperature, so the influence of the Pr will be small. The best fit line slope is 0.71 $\pm$ 0.09 which agrees with the Dittus-Boelter value of 0.8. Thus, in the VMD experiments, the Dittus – Boelter value of b = 0.8 is applicable to this work.
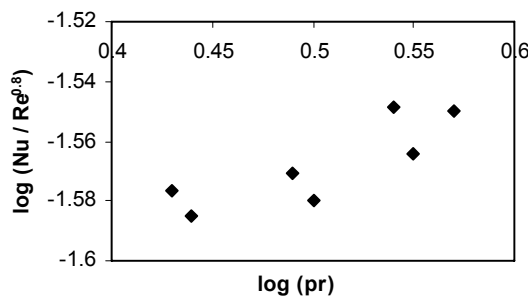


Fig. 5 log (Nu /Re$^{0.8}$) versus log (Pr).

In the Fig. 5, a plot of log (Nu / Re$^{b}$) versus log (Pr) was made on to estimated the empirical constant a and c of (6). The best fit line slope is 0.30 $\pm$ 0.06 and the intercept gives a value of 0.019 $\pm$ 0.008 which corresponds well with the

Dittus-Boelter value of a = 0.023 and c = 0.33. Hence, the experimentally determined empirical constants did not deviate significantly from their Dittus-Boelter values. Thus, (6) can be re-written as:

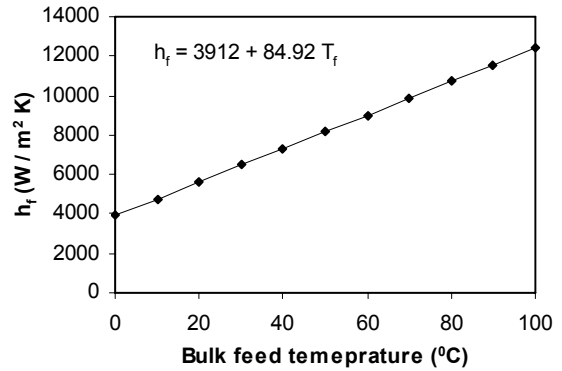$$Nu = 0.023\, Re^{0.8}\, Pr^{0.33} \qquad (8)$$



Fig. 6 Heat transfer coefficient, $h_f$, is a function of bulk feed temperature at feed flow rate = 54 l/h.

The (8) was simplified and calculated the heat transfer coefficient is a linear function of feed temperature. Fig. 6 shows a graph of the heat transfer coefficient over a 0 to 100 $^0$C temperature range at 54 l/h feed flow rate and for 30000 mg/l of salt concentration in feed water. Additionally, the simplified mass transfer coefficient, $k_f$, equation was developed by using the heat-mass transfer analogy as shown in Fig. 7. The following simplified equations (9), (10) of heat and mass transfer are formed, which are used frequently for VMD system ($T_f$ is in $^0$C):

$$h_f = 3912 + 84.92 T_f \qquad (9)$$

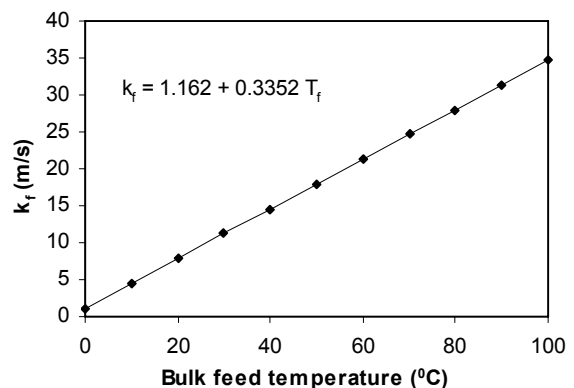$$k_f = 1.162 + 0.3352 T_f \qquad (10)$$



Fig.7 Mass transfer coefficient, $k_f$, is a function of bulk feed temperature at feed flow rate = 54 l/h.

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Attention would be better focused on designing VMD module to provide high heat transfer coefficient practically, if VMD has been used for desalination, it will be operated at low pressures with good membrane permeability to maximize the flux. Therefore, the process will be heat transfer limited. So maximizing the heat transfer coefficient by a good module design maximizes the mass flux.

The effect of boundary layer heat transfer resistance relative to the total heat transfer resistance of the system is given by the (11) of temperature polarization coefficient, θ:

$$\theta = \left(T_f - T_{fm}\right)\big/\left(T_f - T_V\right) \qquad (11)$$

where $T_f$ is the bulk feed temperature, $T_{fm}$ is the feed side membrane surface temperature, and $T_v$ is the vacuum side temperature. The concept of the temperature polarization factor will be used as a tool for evaluating the effect of the input parameters on maximizing the mass flux. When, the value of θ approaches zero for systems, $T_f \rightarrow T_{fm}$ and the process is limited by mass transfer through the membrane and resistance in the liquid phase is negligible. When θ → 1, $T_{fm} \rightarrow T_v$ so the resistance in the membrane is negligible and the process is limited by heat transfer to the membrane surface [18]. The calculated value of θ as a function of feed bulk temperature is shown in Fig. 8. The results indicate that θ increases by increasing bulk feed temperature. Since increasing the bulk feed temperature increases the mass flux that requires sufficient heat of vaporization providing such a heat increases the difference between the $T_f$ and $T_{fm}$, and in turn the polarization factor. It is important to keep θ as small as possible.
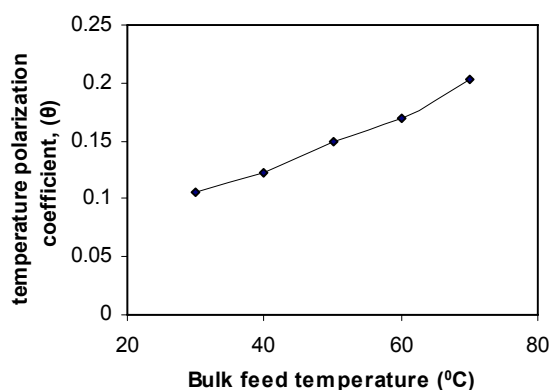


Fig. 8 Temperature polarization coefficient at feed salt concentration = 30000 mg/l, and permeate pressure = 3 kPa.

## V. Conclusions

An experimental study of VMD process was reported for water purification or the desalination of salt water in a flat sheet membrane module configuration. The effect of water feed flow rate and feed inlet temperature on MD flux has been discussed and presented a method to estimate the feed boundary layer heat and mass transfer coefficient from the Dittus-Boelter equation and its mass transfer analogy. The experimental heat transfer coefficients were used to test the applicability of Dittus-Boelter equation to VMD process. The role of heat transfer resistance in the liquid phase and mass transfer resistance in the membrane matrix are more important in the transport mechanism. So in the module design to provide the high heat transfer coefficient for maximize the mass flux of distilled water.

MD flux is strongly dependent on the water feed flow rate and feed inlet temperature. An increase in the water feed flow rate and temperature is a accompanied by an increase in the MD flux and corresponding increase in the heat transfer coefficient in the water feed boundary layer. This can be attributed reduction in the temperature polarization effect. Also, the study undertaken of the effect of bulk feed temperature on the temperature polarization factor and found it increase with increase in bulk feed temperature. Hence, the polarization factor is a major tool for VMD process behavior.

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