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Review Article

A Review & Studies on Design Parameter of Membrane Distillation Process for Water Treatment

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Abstract - *Membrane Distillation is an Advance Separation Technique, where we exploit the attributes like the selective nature of the membrane. That provides an advantage over conventional technology. It also has low energy consumption and initial investment cost over conventional technology. This paper reviews Design Parameters of Membrane Distillation Process for Water Treatment (Desalination). As MD has four major types, this paper focuses on Direct Contact MD due to simple design and low operation energy requirement, general mitigation technique & different foulants and fouling mechanism. MD can concentrate feed solutions to their saturation point without negligible flux decline; MD Technique reduces capital and operation costs by using low-grade waste energy or solar energy.*

The practical large-scale application of membrane distillation is mainly obstructed by a few issues like High energy requirement, membrane fouling & scaling causing wetting of pores of the membrane, and this paper gives a review on some of the solutions on optimizing MD system concerning thermal efficiency and membrane fouling and scaling for Desalination.

Keywords - *Desalination of water, Membrane Distillation Thermal Separation, Method, Parameters of MD, Water treatment process, Direct Contact Membrane Distillation.*

I. INTRODUCTION

In history, the method of Membrane distillation was termed by various names like capillary distillation, osmotic distillation, pre-evaporation, trans-membrane distillation etc. A committee was formed at the Workshop on Membrane distillation Rome-1986 to standardize the terminology describing the MD process.

Smolders and Franken later compiled the nomenclature defined by that committee into 'Terminology for Membrane Distillation', an excerpt of which is presented here to define the scope of this review. the name 'membrane distillation' should be applied for membrane operations having the following characteristics:

- The membrane should be porous.
- Membrane wetting should not occur by the process of liquids.
- No capillary condensation should take place inside the pores of the membrane.
- the membrane must not alter the vapour-liquid equilibrium of the different components in the process liquids.
- At least one side of the membrane should be in direct contact with the process liquid.
- A partial pressure differential in the vapour phase is the driving force behind each component's membrane operation.

Conventional distillation is the process that helped coin the term Membrane Distillation. Conventional distillation & MD rely on vapour-liquid equilibrium as a basis for Separation, and both processes require that the latent heat of vaporization be supplied to achieve the characteristic phase change [1].

The desalination process can be achieved mainly by two techniques, first is distillation (Thermally) and the Separation with the help of membrane. We can obtain fresh water from many types of saline sources of water mainly sea, as we are observing that many natural freshwater sources are gradually decreasing.

Desalination has become a major process to reach the ever-growing demand for water, as saline water sources are limitless. in recent years we have observed many advancements in the Desalination of water.

The data published by the world health organization (WHO) states that 1billon people currently do not have access to clean water. It is estimated to reach 3.5 billion by the year 2025. 80% of diseases in humans are caused by polluted water. We mainly use groundwater and lake, river water as a source of freshwater due to contamination of these sources. [2] Thus, there is a need to find alternative water sources as freshwater sources are rapidly decreasing due to high demand from commercial and domestic sectors. the ever-growing rise in population and pollution is also responsible for the current water crisis. [3]

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A. Techniques for Desalination

As discussed earlier, the two major techniques for Desalination of water are:

- Distillation
- Membrane-based separation method

Both of these techniques have their own set of advantages and disadvantages, such as in the case of distillation, as it is a thermal separation technique, it can only be used where the energy is at reasonable rates to make the process economic. in member separation, the saline water has to be pre-treated first to use this method. Sometimes this pre-treatment can be quite expensive. (RO) Reverse osmosis is one of the major membrane methods used for Desalination. It has less thermal requirement than that thermal distillation. Nevertheless, even RO needs pre-treatment of feed before use due to the issue of fouling; above this, RO has expensive MOC (Material of construction) like duplex stainless steel to withstand the high pressure created by the electric pumps and also to avoid corrosion caused by seawater. Thus, it is only feasible for a large scale process.

For strategic Separation of saline water, we can use Membrane Distillation (MD), i.e. small-scale Desalination of water near remote coastal areas where we can't set up a distillation column or RO plant. Membrane Distillation (MD) is a thermally driven membrane separation process; by the name, we can say it has thermal distillation and membrane separation properties. in MD, it is necessary to have a porous hydrophobic membrane; MD has 3 major stages: Evaporation, Transfer, Condensation.

a) Evaporation

The feed solution is evaporated from the hot side of the membrane.

b) Transfer

Evaporated solution vapours passes through the pores of the hydrophobic membrane.

c) Condensation

Permeated vapours are condensed on the other side of the membrane.

The hydrophobic membrane should only allow the water vapour to transfer to the other side to activate this. in addition to this, the membrane should also have high thermal stability and low thermal conductivity to withstand the high temperature and reduce the loss of heat (Energy) to surrounding and across the membrane.

Membrane distillation has a significant edge over other membrane separation techniques.

- The simple design of hardware compared to distillation and RO setup.
- The purification percentage is as high as 90% and more in membrane distillation for metal salts, thus a great alternative for water desalination.
- MD can also be used for non-volatile components where the traditional distillation fails.
- Relative to distillation, it has low operating temperature and pressure.

An MD process can be divided into four main configurations, each of which has a significant impact on separation efficiency and cost [4] [5] [6] [7].

B. Membrane Distillation Applications

- Desalination of seawater: MD is not highly affected by salt concentration in saline feed solutions, and hence, this technology can achieve good quality distillate with minimal brine discharge
- Desalination of brackish water: Membrane distillation (MD) provides a low recovery rate for geothermal brackish water desalination; however, combining MD with reverse osmosis (RO) can increase the output rate.
- Treatment of process water: the MD method has several advantages for treating textile wastewater, including minimal area coverage, high efficiency, ease of implementation, scalability, and dye recycling from concentrate. More crucially, given the temperature of the textile wastewater discharge (50–80 °C), the MD process can directly access the wastewater without additional energy for the heating stage.
- Purification of water, Removal and concentration of ammonium as a resource.

Membrane distillation (MD) is a novel water purification process investigated worldwide as a low cost, energy-saving alternative to conventional separation processes, such as distillation [8].

II. CONFIGURATION OF MEMBRANE DISTILLATION

A. Direct Contact Membrane Distillation (DCMD)

A high-temperature liquid phase (feed) is in direct contact with the hot side of the membrane surface, while a cool aqueous phase is in direct contact with the permeate side in the simplest MD setup. As a result, volatile chemicals evaporate at the feed side's heated liquid/vapour interface. the vapour phase will condense in the cool liquid/vapour interface on the permeate side after passing through the membrane pores.

The temperature differential across the membrane causes the vapour pressure difference, and the hydrophobic property of the membrane prevents the feed from passing through the membrane.

Despite its simplicity, this technique has a higher rate of conduction heat loss than alternative setups. Shell-and-tube or plate-and-frame membrane modules could be used in DCMD for cross-flow or longitudinal flow [9] [10] [11] [12].

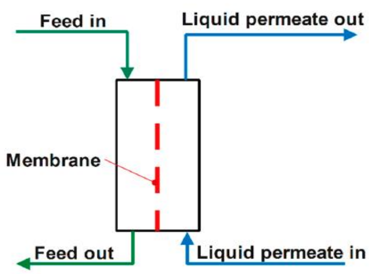

Fig. 1 Direct Contact Membrane Distillation (DCMD) [13]

B. Vacuum Membrane Distillation (VMD)

A pump establishes a vacuum on the membrane module's permeate side in the VMD arrangement. If the permeate stream is the product, an external condenser is employed as with AGMD.

Furthermore, the vapour pressure differential is created by constantly removing the vapour permeate from the vacuum chamber. the produced vacuum must be less than the saturation pressure of volatile compounds in the aqueous feed to provide the driving force. Conduction heat loss is low in the VMD design, and membrane wetting is avoided [3] [14][15, 16].

a) Disadvantages

- Pore wetting risk
- Higher fouling
- Vacuum pump and external condense

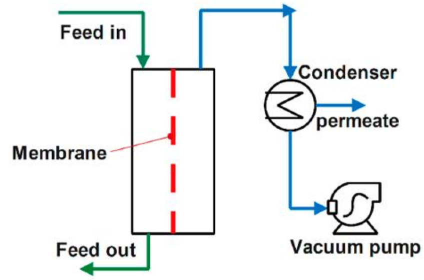

Fig. 2 Vacuum Membrane Distillation (VMD) [13]

B. Sweeping Gas Membrane Distillation (SGMD)

An inert gas (stripping gas) is delivered to the permeate side of the membrane as a carrier to sweep the vapour or gather vapour molecules from the membrane surface in SGMD, also known as air stripping membrane distillation. A gas barrier, like AGMD, reduces heat loss while dramatically increasing mass transfer, making SGMD a process with bright prospects [17] [18]. SGMD, on the other hand, produces a tiny amount of permeate vapours while requiring huge volumes of sweep gas and external condensers, resulting in additional costs.

As a result, compared to other MD setups such as DCMD [19] [20], the method has gotten minimal attention.

a) Disadvantages

- Due to the small volume of permeate diffuses in a large sweep gas volume, a large condenser is needed.
- Low flux

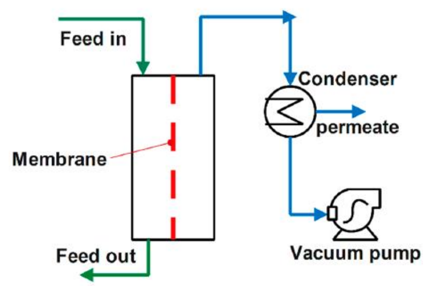

Fig. 3 Sweeping Gas Membrane Distillation (SGMD) [13]

C. Air Gap Membrane Distillation (AGMD)

The evaporator channel in this arrangement is comparable to DCMDs. However, an air gap between the membrane and the cooled surface is a controlling element for heat and mass fluxes.

The evaporated volatile compounds flow through the membranes and the air gap before condensing on the cold surface. the condensation surface distinguishes the permeate (distillate) from the cold liquid, an important feature of this design (coolant).

As a result, the cold liquid could be anything else, such as cold feed water. the AGMD has the maximum energy efficiency among the other configurations, and the membrane used can be a flat sheet or hollow fibre.

a) Disadvantages

- Creation of additional resistance to mass transfer.
- Hard module designing.
- Lowest gained output ratio.

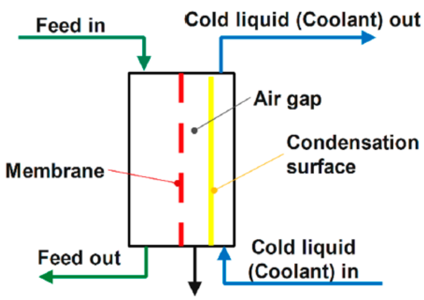

Fig. 4 Air Gap Membrane Distillation (AGMD) [13]

III. TEMPERATURE AND CONCENTRATION POLARIZATION

The MD process is plagued by temperature and concentration polarization effects [21] [22]. MD is a non-isothermal separation process in which heat and mass transport happen simultaneously and are linked [21]. the MD process consists of three primary steps: (1) feedwater vaporization at the liquid-vapour interface in the feed channel, (2) water vapour transport across the membrane pores, and (3) water vapour condensation into distillate in the permeate channel. Heat is removed from the feed and permeate sides of the membrane at the liquid-vapour interfaces at the same time as water is transferred. As a result, temperature and salt concentrations at liquid-vapour interfaces differ from those in bulk feed and permeate, forming boundary layers on both sides of the barrier. These occurrences are known as Effects of polarization due to temperature and concentration. the polarization effect of temperature produces the temperature difference between the two sides of the membrane, which is smaller than the temperature difference between the two sides. the process water flux is reduced by separating the feed and distillate (or coolant) streams.

On the other hand, the concentration polarization effect causes the salt concentrations at the membrane to rise. Surface concentrations versus bulk feed concentrations. the influence of concentration polarization on water flux in MD desalination of seawater or other saline feed waters with similar feed salinity is minor compared to the temperature polarization effect [23] [24].

The concentration polarization effect can considerably reduce water flux and boost the process propensity for membrane scaling in the MD process of hypersaline feeding. the unfavourable effects of temperature and concentration polarization on MD water flux are particularly severe for the process operating at high temperature and low feed velocity. Negative flux can develop due to polarization effects at extreme settings [21]. As a result, temperature and concentration polarization effects are considered a disadvantage of MD and should be minimized [25] [26]. To offset the impacts of temperature and concentration polarization on MD performance, several approaches such as using spacers, applying turbulent flow, transverse vibration, and aeration, and employing microwave irradiation have been used [27] [28] [29] [30].

The temperature polarization coefficient τ can be used to calculate the magnitude of the temperature polarisation effect. Eq. can be used to compute for the DCMD process. the value depends on the fluid dynamics of the process and can range from 0.4 to 0.7 [26].

$$\tau = \frac{T_h - T_c}{T_{hm} - T_{cm}}$$

This represents the loss of thermal driving force due to the thermal boundary layer.

The concentration polarization coefficient φ is also used to evaluate the concentration polarisation effect, and it is calculated as:

$$\varphi = \frac{x_h - x_c}{x_{hm} - x_{cm}}$$

IV. DCMD MODELLING

A. Membrane Material

We choose membranes based on a set of criteria. High hydrophobicity, low mass transfer resistance, resistance to liquid chemical absorbents, and high surface porosity are the most commonly used membrane features for MD applications. in general, thick membrane surfaces provide fractional resistance to mass transmission, whereas pore diameter merely provides fractional resistance. the relationship between membrane resistance and overall mass transfer is explained by Atchariyawut et al. With an increase in membrane surface pore size, the ratio of these two increases, implying that membrane resistance increases [31].

Young Laplace has proposed equation (1) to reflect the effect of pore size on membrane wettability. As pore size rises, liquid entrance pressure falls, indicating higher membrane wettability.

$$\Delta p = \frac{4\sigma\cos\theta}{d_{max}} \quad \ldots (1)$$

Where□□ is the contact angle between the liquid and membrane surface, σ is the liquid surface tension, d_{max} is the maximum pore diameter in the porous membrane.

Thus, the pore size is always the membrane's deciding factor, which is of membrane wettability concern.

MD can only work with hydrophobic membranes. Commercially available membranes that meet these requirements are made of polytetrafluoroethylene (PTFE), polypropylene (PP), and Polyvinylidene difluoride (PVDF) and are typically flat sheet or capillary in shape. [21] Only a few researchers considered creating or changing the membranes utilized in this study [32]. Lawson and Lloyd (1997) used modified membranes with a hydrophobic layer, hydrophilic layer, or hydrophobic layer sandwiched between two hydrophilic layers.

After reviewing over 40 articles, we discovered that the membrane produced by Zhang and Wang changed the surface of a polyetherimide hollow fibre membrane with a fluorinated silica layer to overcome the wettability problem and meet the criteria as mentioned above. Increased surface roughness and decreased surface energy of the membrane resulted in a substantial rise in hydrophobicity of the membrane.

Trans-membrane flux and membrane characteristics can be related as [21]

$$N \propto \frac{r^{\alpha}\varepsilon}{\tau\delta_m} \quad \ldots (2)$$

Where ε is the membrane porosity, r^{α} is the average pore size for Knudsen diffusion,τ is the membrane tortuosity, δ_m is membrane thickness.

B. Membrane Pore Size Optimum

a) Membrane Pore Size

Greater distillate volume is always the most important aspect of a membrane distillation; more distillate volume can be accomplished by a larger pore size [33], which lowers the liquid entry pressure (LEP). If the feed pressure is higher than the liquid entrance pressure, our liquid will infiltrate the membrane through the pore, causing hydrophobicity to be lost [34].

According to the following relation

$$LEP = \frac{-2B\gamma_L \cos\theta}{r_{max}} \quad \ldots (3)$$

Where γ_1 is the liquid surface tension, θ is the liquid-solid contact angle, $_{max}$ is the largest pore radius, and B is a geometric factor determined by pore structure.

The pore size effect becomes more dominant when a solution with low surface tension is employed in md [35]. As a result, we need the pore size to be as small as possible because too small a pore size will affect MD permeability. As a result, we need an optimum pore size value, which is a time-consuming task because we will have to calculate each MD category for each type of feed solution.

b) Membrane Thickness

Membrane thickness has a significant impact on heat and mass transport in MD. Membrane thickness and flux are inversely proportional, i.e., if we keep the thickness to a minimum, we get the maximum flux [36]. To get a higher heat transfer, the membrane should be thick, which would decrease permeability because a thin membrane was necessary.

Gray et al. [37]evaluate the efficacy of several membranes in DCMD under varied circumstances and feed temperatures. A PVDF microfiltration membrane with a non-woven support layer and other membranes were used in his research. the new PTFE membrane in DCMD demonstrated increased flow, improved energy efficiency, and doubled LEP, according to his most groundbreaking conclusion in MD [37].

V. EFFECT OF OPERATING PARAMETERS

A. Feed Temperature

Feed temperature is crucial in MD setup, and it is the most frequently discussed parameter. the feed temperature is usually between 60 and 90 degrees Celsius [21]. in all MD configurations, flux varies exponentially with feed temperature [32] since the driving force for MD is the difference in vapour pressure across the membrane, which is a function of temperature.

B. Feed Concentration

In all md configurations, the driving force is highly influenced by the solute concentration; if it is high, the transmembrane vapour pressure will drop [32]. This is due to the enhanced temperature polarization and the entrance length of CBL at the membrane surface [38].

C. Feed Flow Rate

The influence of the feed flow rate on the permeate flux is generally positive [39] [40]. This is due to the mixing effect caused by increased turbulence inside the feed channel, which re-educates temperature and concentration polarization effects. As a result of the turbulence, the temperature at the membrane surface approaches that of the bulk feed. the effects of flow rate on yield are less than half that of feed temperature [39], and its importance is clear at higher temperatures, especially when combined with a larger trans-membrane temperature drop. [40]. To a certain extent, the connection between trans-membrane flux and feed flow rate is linear. Above that, there will be no effect. [41]

VI. MODELING OF MEMBRANE DISTILLATION

A. Mass Flux

A volatile species are transported in two steps: (1) mass transport from the bulk feed solution to the seed membrane surface, (2) mass transport through the membrane pores, and (3) mass transport from the membrane surface to the permeate bulk liquid [32]. Diffusion through the pores and free Convection in the air gap affects the mass transferred over the membrane in the AGMD arrangement [42].

On the feed side, water and volatiles evaporate from the liquid-vapour interface, diffuse across the membrane, and condense or evaporate from the membrane module as vapour on the permeate side. the fundamental goal of MD process modelling is to predict permeate flux based on membrane properties, module design, and operating circumstances [32].

$$N = K(P_f^{sat} - P_p^{sat}) \quad \ldots\ (4)$$

The letter k denotes the membrane distillation coefficient. the water vapour pressures on the feed and permeate sides of the membrane are represented by p_f^{sat} and p_p^{sat} , respectively. They are the T_{Fm} and T_{Pm} functions, respectively. the Antoine equation is used to compute the water vapour pressure. Because there are dissolved species with a molar concentration of X_{Fsat} the feed side, Raoult's law can be used to explain the decrease in vapour pressure.

The latent heat flow and conduction across the membrane caused by the temperature gradient characterize the transmembrane heat flux. This temperature creates the saturation pressure that guides the flow through the membrane.

Within the applied temperature range, this pressure is calculated using Antoine's equation as [30]

$$p_{i(pure)}^{sat} = \exp\left(23.238 - \frac{3841}{T_i - 45}\right),\ i \in \{f, p\} \ldots (5)$$

The above flux equation can be represented in terms of temperature difference.

$$N_A = C\frac{dp}{dT}\left(T_f - T_p\right) \quad \ldots\ (6)$$

The Clausius-Clapeyron equation can be used to express the relationship between vapour pressure and temperature:

$$\frac{dp}{dT} = \left[\frac{\Delta H_v}{RT^2}\right]P \quad \ldots\ (7)$$

Combining both equations 6 and 7

$$N_A = C\frac{dp}{dT}\left[\left(T_{f,m} - T_{p,m}\right) - \Delta T_{th}\right]\left[1 - X_m\right]$$

The above equation is the mass flux of vapour pressure and temperature.

B. Heat Flux

The heat transmission in the DCMD process may be broken down into three steps: feed boundary layer heat transfer, membrane heat transfer, and permeate boundary layer heat transfer [43]. Convection via the feed membrane surface is equated to Convection through the permeate membrane surface, which is also equated to the combined conduction Q_m and latent heat of evaporation across the membrane.

- Convection from the feed bulk to the membrane surface's vapour-liquid interface

$$q_f = h_f(T_h - T_{hm})$$

- Convection to the permeate side from the vapour-liquid interface at the membrane surface

$$q_p = h_p(T_{cm} - T_c)$$

Where h_f and h_p denote the heat transfer coefficients on the feed and cold stream sides, respectively.

- Through the microporous membrane, evaporation and conduction occur.

$$q_m = N_A H_v + h_m(T_{hm} - T_{cm})$$

Where h_m is the conductive heat transfer coefficient, where $K_m$and δ denotes the membrane thermal conductivity and thickness respectively, H_v is the latent water heat.

C. Energy Consumption

The saline feed solution must be heated, and the distillate must be cooled in MD. A chiller was employed as a heat sink in this experiment. in reality, though, seawater at room temperature may be cooled by passing it through a heat-exchanging coil. As a result, cooling energy was not taken into account while assessing the thermal efficiency of the operation.

The specific thermal energy consumption (STEC), which is the thermal energy used per volume unit of produced distillate, can be used to measure the efficiency of a thermal desalination process [44] [45]. STEC (in MJ/l) of DCMD without brine recycling can be computed using a heat and mass balance

$$STEC = \frac{\rho_{f,in} \times F_{f,in} \times C_p(T_{f,in} - T_{sys})}{F_d \times 10^6}$$

The feed's inlet volumetric flow rate (m3/s), inlet temperature ºC, and inlet density (kg/m3) are represented by $F_{f,in}$, $T_{f,in}$ and ρ .in, respectively. the temperature of the saline water in the storage tank (which is assumed to be constant at 25) ºC is T_{sys}, and the specific heat capacity of solutions $\frac{KJ}{Kg}.\,{}^{\circ}C$ is C_p.

VII. CONCLUSION

There are many membrane technology applications in wastewater treatment. This paper is compiled important ones that are used, their advantages and disadvantages, and this paper also studies the parameters which affect Membrane distillation. For Desalination and wastewater treatment MD process is a great alternative compared to conventional distillation and membrane separation process(RO) on a large scale. If it is researched by interdisciplinary field, MD can meet technological, economic and ecological demands in the future.

In this paper, we have summarized equations from various research papers to study the effect of the Temperature concentration of feed on the operation of the process. Different types of Membrane Distillation Configuration are described. Specifically, *Direct Contact* Membrane Distillation is selected out of the four configurations as it is easy to construct and has low operation cost than other MD configurations. To choose a membrane for the DCMD process, various parameters have to be studied like its pore size, membrane material, its wetting properties & its thickness that are elucidated in this paper. Energy consumption, heat flux and mass flux are summarized with their equations. the effect of feed concentration, feed temperature and its flow rate on the operation of MD are studied; the above study helps to Mathematically model membrane distillation system and make the system optimized for large scale treatment of water. the energy consumption discussion helps to find an alternative energy source for this process as it requires less energy than convention distillation. We can use the waste energy from industries or even solar energy for the MD process, thus making it energy efficient.

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