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Experimental Investigation of Vacuum Membrane Distillation (VMD) Performance Based on Operational Parameters for Clean Water Production.

Faisal Iqbal[*], *Muhammad Asif, Ali Turab Jafry*, *and Wajeeha Bibi*

Faculty of Mechanical Engineering
Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, Topi, Sawabi Pakistan

Abstract

Freshwater shortage is an ongoing concern across the world, due to increasing populations and climate change. Vacuum membrane distillation (VMD) is a viable approach for producing fresh water to meet the needs of society. In the current study, an experimental investigation has been conducted on a laboratory-scale single-stage module to explore the impact of operational parameters such as feed temperature, vacuum pressure, and feed salinity on the performance of vacuum membrane distillation (VMD), including permeate flux, gained output ratio, and specific thermal energy consumption. Results show that increasing the feed temperature and feed flow rate, and reducing the salinity, increases the permeate flux. As the feed temperature rises from 60 to 70°C, the permeate flux increases from 1.90 to 4.36 kg/m²h at a permeate pressure of 12 kPa and salinity of 30 g/L. Similarly, increasing the vacuum pressure from 12 to 18 kPa reduces the permeate flux. As a result, the specific thermal energy consumption increases from 728 to 803 kWh/m³. From experimental findings, it was observed that the rejected brine from VMD retains sufficient energy that could be utilized in another desalination system.

Keywords: Desalination, Vacuum membrane distillation (VMD), Permeate flux, Gain output ratio (GOR), and Specific thermal energy consumption (STEC)

1 Introduction

Vacuum membrane distillation (VMD) stands as one of the most prominent desalination methods within the domain of membrane distillation, with a primary focus among researchers on its optimization. Its significance in the field of membrane desalination arises from its high energy efficiency throughout the process [1]. This efficiency is primarily attributed to the vacuum maintained on the permeate side, where minimal energy transfer occurs from the feed side to the permeate side through conduction across the membrane, thus reducing

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[*] Corresponding author: gme2262@giki.edu.pk

wastage [2]. Moreover, the pore size of VMD membranes exceeds that of alternative membrane distillation techniques such as direct membrane contact distillation (DCMD), sweep air gas membrane distillation (SGMD), and air gap membrane distillation (AGMD). As a result, this leads to an increase in permeate flux [2], [3].

In the vacuum membrane distillation process, vacuum pressure is applied to the permeate side, keeping it below atmospheric pressure and the saturation pressure of salt water in the intake feed stream. This pressure difference generates a significant vapor pressure gradient between the entrance of hot saline water feed and the permeate side, which is the primary driving factor for water vapor transport across a membrane from the feed side to the permeate side. Following this, a condenser is used to convert the vapors into liquid, producing clean water [4]. Numerous studies have investigated the impact of various operational factors and membrane features on system performance, such as permeate flow, gain output ratio, and specific thermal energy consumption [5]. Asif et al. conducted an experimental study to explore how variations in feed flow rate affect the permeate flux of VMD. Their findings demonstrated that with an increase in feed flow rate from 1000 to 4000 L/h, while holding the feed temperature constant at 80°C, the permeate flux rose from 4 to 25 kg/m^2 [6][7]. Similarly, Alklaibi et al investigated the influence of feed temperature on permeate flux, revealing that a rise in feed temperature from 40 to 80°C resulted in a 12% increase in permeate flux [8]. Furthermore, Termpiyakul et al. examined the impact of feed salinity on permeate flux, noting that increasing salinity from 0 to 2 M led to a 12% decrease in productivity [9]. Additionally, several other researchers have investigated the impact of membrane characteristics on VMD performance. It has been concluded that increasing membrane porosity and mean pore size while decreasing membrane thickness enhances system performance [10].

This research work investigates the effect of operational parameters, such as feed temperature, feed flow rate, salinity, and vacuum pressure, on the performance of VMD by experimental analysis. The study evaluates key factors such as permeate flux, gain output ratio, and specific thermal energy consumption. These investigations were conducted using a laboratory-scale single-stage module.

2 Experimental Setup

The experiments have been conducted on a small-scale single-stage VMD module as shown in Figure 1. The membrane characteristics of the setup are mentioned in Table 1. The feed seawater used in the experiments was prepared in the lab by adding salt to tap water, maintaining its salinity equal to standard seawater, which is 30 g/L. The device used for measuring salinity was the HI98319 digital salinity tester, waterproof and pocket-sized, manufactured by HANNA Instruments, Romania. This tester can measure the salinity of brackish or saltwater in three different units: ppt, PSU, and S.G., with an accuracy of ±1.0 ppt for solutions ranging from 0.0 to 40.0 ppt and an accuracy of ±2.0 ppt for solutions ranging from 40.0 to 70.0 ppt. The flow rate, feed temperature, and vacuum pressure were measured using a flow meter and an absolute pressure gauge mounted on the setup, as shown in the figure. Each experiment was repeated three times, and the data were recorded.

Table 1: Properties of the Hollow Fiber Membrane Module

Parameters on the shell side	Values and attributes
d_s (mm)	90
Length of the membrane module (mm)	1225

Material	Acrylonitrile butadiene styrene
Fiber parameters	**Values and attributes**
d_o (mm)	1.6
d_i (mm)	0.9
δ_m (mm)	0.35
Pore size (µm)	0.5
Material	PTFE

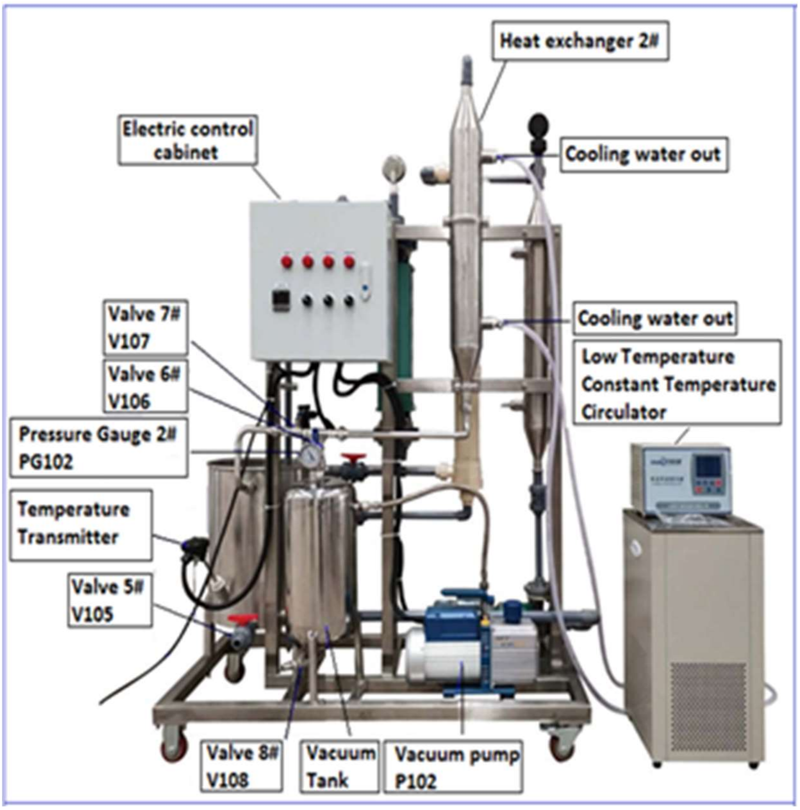


Figure 1: Experimental setup of single-stage lab scale module

3 Result and Discussion

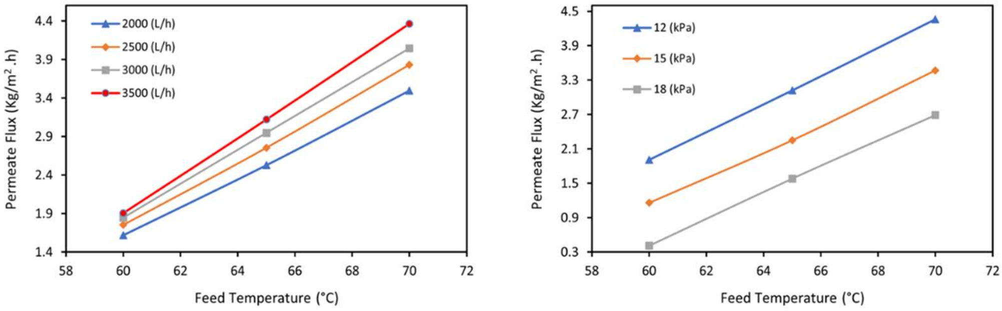
The results and discussion section contains the experimental results of vacuum membrane distillation (VMD). Experiments were performed on a single-stage lab-scale VMD system by varying various operational parameters, including inlet temperature, vacuum pressure, flow rates, and salinity, to investigate these parameters' effect on VMD performance. The evaluation process considered performance parameters such as permeate flux gain output ratio, and specific thermal energy consumption. The experiments were conducted using the lab-scale VMD apparatus. A hollow fiber membrane module, where fibers were packed together in a shell and oriented vertically, was employed for the experiments. Feed water flowed on the shell side from the top of the membrane module and exited at the bottom of the shell. The vapors produced on the membrane surface of the feed side traversed through the membrane pores to the lumen side (permeate side) and condensed outside the membrane module in the condenser unit. The experimental operational parameters are outlined in Table 2.

Table 2: Experimental conditions for seawater.

Operational Parameters	**Range**
Feed water temperature (˚C)	60, 65, 70
Feed flowrate (L/h)	2000, 2500, 3000, 3500
Salt concentrations (g/L)	30, 35, 40
Vacuum pressure (kPa)	12, 15, 18
Cooling water temperature (˚C)	20

3.1 Effect of feed temperature on the permeate flux.

Figure 2 (a) illustrates the impact of different feed temperatures on permeate flux across various permeate pressures, ranging from 2000 to 3500 L/h. As the feed water temperature rises from 60 to 70 ˚C, there is an improvement in permeate flux, resulting in increments from 1.62 to 3.5 kg/m^{2}h, from 1.75 to 3.83 kg/m^{2}h, from 1.85 to 4.04 kg/m^{2}h, and from 1.90 to 4.36 kg/m^{2}h at flow rates of 2000 L/h, 2500 L/h, 3000 L/h, and 3500 L/h, respectively. Throughout these changes, the feed salinity and vacuum pressure remained constant at 30 g/L and 12 kPa, respectively. Conversely, an increase in vacuum pressure results in a reduction in permeate flux, while maintaining a constant feed flow rate and salinity at 3500 L/h and 30 g/L, respectively, as shown in Figure 2 (b).
The decrease in permeate flux resulting from an increase in feed temperature can be attributed to the exponential relationship between feed temperature and vapor pressure, as demonstrated by Antoine's equation. This equation illustrates that an increase in the temperature of the feed leads to a corresponding increase in the vapor pressure of the feed solution, which in turn leads to a higher permeate flux.

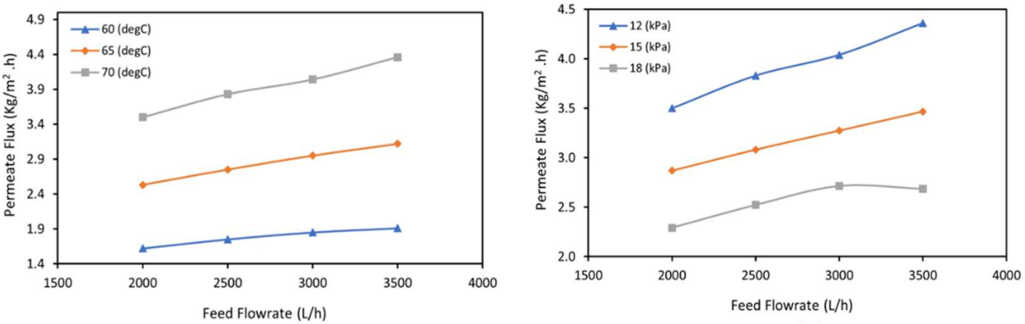


(a) **(b)**

*Figure 2: **(a)** Impact of feed temperature on permeate flux at varied feed rates (2000, 2500, 3000, and 3500 L/h) with a vacuum pressure of 12kPa and feed salinity of 30 g/L. **(b)** Impact of feed temperature on permeate flux at varied vacuum pressure (12, 15, and 18kPa) with a fixed feed flow rate of 3500 L/h and feed Salinity of 30 g/L.*

3.2 Effect of feed flow rate on the permeate flux.

Figure 3 (a) depicts the impact of varying feed flow rates on permeate flux across a range of feed temperatures ranging from 60 to 70 °C. This was achieved while maintaining a constant salinity of 30 g/L and a vacuum pressure of 12 kPa. Upon analysis, it was noted that elevating the inlet feed rate augments circulation velocity, thereby increasing the heat transfer coefficient (HTC). Consequently, the temperature at the membrane interface aligns with the bulk temperature, resulting in a significant difference in vapor pressure across the hydrophobic membrane and thus, a noteworthy increase in permeate flux.
As the feed flow rate escalates from 2000 L/h to 3500 L/h, the permeate flux undergoes enhancements from 1.42 to 1.9 kg/m²h, from 2.42 to 3.22 kg/m²h, and from 3.41 to 4.41 kg/m²h at permeate pressures of 60 °C, 65 °C, and 70 °C, respectively. The rise in feed flow rate is directly associated with an increase in permeate flux. Conversely, as vacuum pressure increases, the permeate flux decreases, as shown in Figure 3 (b).



(a) **(b)**

*Figure 3: **(a)** Impact of feed flow rate on permeate flux at varied feed temperatures (60, 65, and 70°C) with feed salinity of 30 g/L and vacuum pressure of 12 kPa. **(b)** Impact of feed flow rate on permeate flux at varied vacuum pressure (12, 15, and 18kPa) with feed temperature of 70°C and feed salinity of 30 g/L.*

3.3 Effect of vacuum pressure on the permeate flux.

Figure 4 (a) illustrates how the permeate flux is affected by vacuum pressure when the salinity ratio varies between 30 and 40 g/L. The feed temperature remains constant at 70°C and the feed flow rate is set at 3500 L/h. Upon investigation, it is clear that as the vacuum pressure increases from 12 to 18 kPa, the permeate flux decreases from 4.42 kg/m²/h to 2.72 kg/m²/h. In addition, it is observed that higher salinity causes a slight decrease in the rate at which the liquid passes through, but the effect is minimal. Furthermore, as shown in Figure 4 (b), increasing the feed flow rate enhances the permeate flux significantly.

The decrease in permeate flux with increasing vacuum pressure (low vacuum) is due to the reduction in the driving force required for VMD mass transfer. The difference in vapor pressure across the input side and the vacuum pressure controls the process of mass transfer in VMD. As a result, the VMD flux increases when the vacuum pressure is higher (vacuum pressure is lower). When the vacuum pressure equals the vapor pressure of water on the feed side, the permeate flux decreases to zero since there is no longer a driving force.

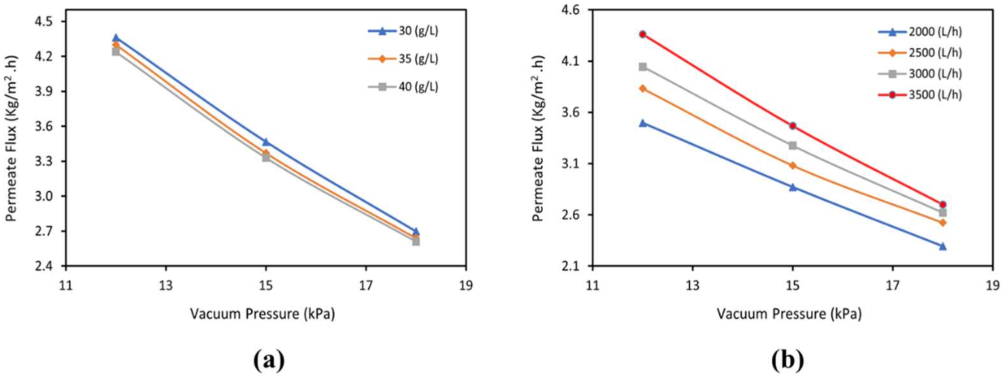


Figure 4: ***(a)*** *Impact of vacuum pressure on permeate flux at varied feed salinity (30, 35, and 40 g/L) with feed temperature of 70°C and feed flow rate of 3500 L/h.* ***(b)*** *Impact of vacuum pressure on permeate flux at varied feed flow rates (2000, 2500, 3000, and 3500 L/h) with feed temperature of 70°C and feed salinity of 30 g/L.*

3.4 Effect of salt concentration on the permeate flux.

Figure 5 (a) depicts the influence of salinity on the permeate flux of VMD (Vacuum Membrane Distillation) for four different feed flow rates, ranging from 2000 to 3500 L/h. Upon analysis, it was seen that as the salinity of the feed increased from 30 to 40 g/L, the rate at which the liquid passed through the membrane reduced from 4.28 to 4.15 kg/m²/hr. This trend remains constant for the other feed flow rates. Nevertheless, the impact of salinity on the permeate flux is negligible. Additionally, it is illustrated in Figure 5 (b) that increasing the vacuum pressure significantly reduces the permeate flux.

The decline in the rate at which liquid passes through a membrane due to an increase in the amount of salt can be explained by the reduction in the pressure exerted by water vapor caused by the higher concentration of salt, as explained by Raoult's Law. The decrease in vapor pressure across the membrane is the driving force for vapor transport, which leads to a reduction in permeate flux [11].

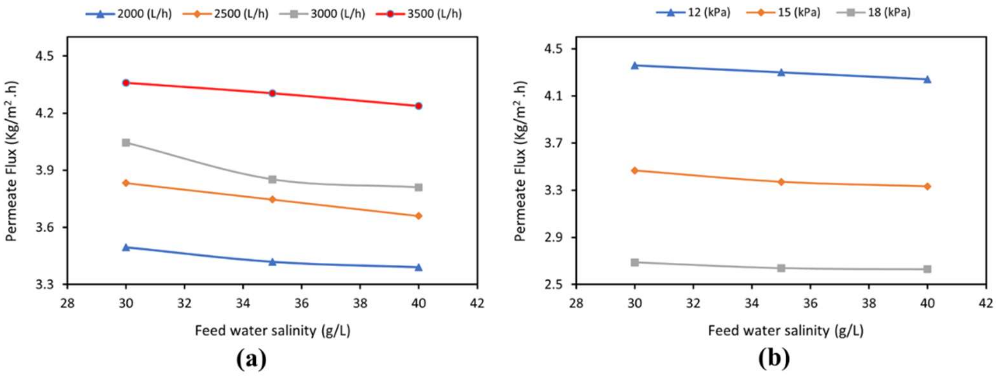


Figure 5: ***(a)*** *Influence of feed salinity on permeate flux at varied feed flow rates (2000, 2500, 3000, and 3500 L/h) with feed temperature of 70°C and vacuum pressure of 12 kPa.* ***(b)*** *Impact of feed salinity on permeate flux at varied vacuum pressure (12, 15, and 18 kPa) with feed temperature of 70°C and feed flow rate of 3500 L/h.*

3.5 Effect of feed temperature on the gain output ratio.

The effect of feed water inlet temperature on the performance of the single-stage VMD setup, evaluated in terms of gain output ratio (GOR), was investigated across a range of vacuum pressures from 12 to 18 kPa, as depicted in Figure 6. The feed temperature ranged from 60 to 70°C. Increasing the feed temperature under different vacuum pressures leads to a rise in the GOR. This trend is attributed to the exponential relationship between temperature and vapor pressure, which optimizes permeate flux. As the GOR reflects the ratio of distillate product to heat input, higher mass production is expected to enhance the GOR. For example, with a rise in feed temperature from 60 to 70°C, the GOR increases from 0.71 to 0.81 for a flow rate of 3500 L/h.

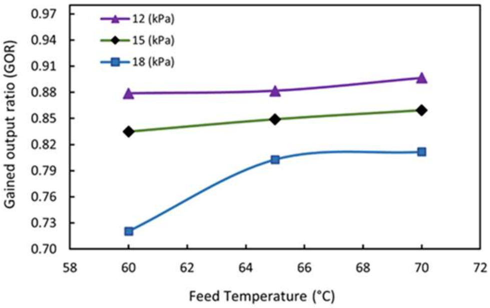


Figure 6: - Impact of Feed Temperature on GOR at varying Vacuum Pressure

3.6 Effect of vacuum pressure on the specific thermal energy consumption.

The impact of vacuum pressure on specific thermal energy consumption is depicted in Figure 7, with consideration to varying feed flow rates. Notably, as vacuum pressure ascends from 12 to 18 kPa (absolute), there's a corresponding increase in specific thermal energy. This is ascribed to the reduction in the driving force, resulting from the decrease in vacuum on the permeate side, which consequently lowers permeate flux, which leads to an increase of specific thermal energy consumption.

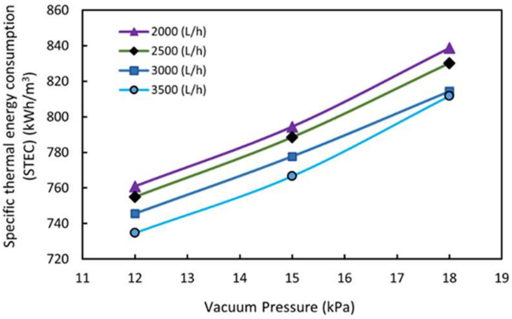


Figure 7: Impact of Vacuum Pressure on Specific Thermal Energy Consumption at Varying Feed Flowrate

4 Conclusion

In this research work, an experimental study has been conducted on the VMD desalination system to investigate the effect of different operational parameters. It has been concluded that increasing the feed temperature and flow rate while reducing the salinity of the feedwater enhances system performance. Specifically, these adjustments lead to an increase in the gain output ratio and a reduction in specific thermal energy consumption.

Furthermore, it was observed that feed salinity has a minimal effect on permeate productivity, while the effects of feed temperature, flow rate, and vacuum pressure are considerable. For instance, increasing the feed temperature from 60 to 70°C resulted in a rise in the gain output ratio from 0.71 to 0.81 for a flow rate of 3500 L/h. Additionally, increasing the vacuum pressure from 12 to 18 kPa led to a decrease in permeate flux.

Consequently, the specific thermal energy consumption increased from 728 to 803 kWh/m³. Overall, these findings highlight the importance of optimizing operational parameters in VMD desalination systems to improve efficiency and productivity. Further research could explore additional factors to enhance system performance even further.

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