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Performance of Vacuum Membrane Distillation for Water Flux Enhancement by Recirculated Air

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ABSTRACT

At present, converting seawater or saltwater is employed to change to more freshwater to help meet the problem of shortage of freshwater. Membrane distillation is a process for desalination in which only water vapor is passed through a porous hydrophobic membrane. The modules used in this experiment are tubular. Vacuum membrane distillation supplemented by humid air recirculation (RVMD) is introduced to enhance the efficiency of the vacuum system for water productivity enhancement. This study examined the operating conditions of the system, that affect the performance of the system which consists of cooling water temperature hot feedwater temperature, transmembrane pressure, and transmembrane temperature. The results showed that when increasing feed water temperature with the increase in the water flux. The maximum flux value was 2.97 L/m²hr at the feed water temperature of 50°C, transmembrane pressure -60 kPa, and cooling water temperature of 30ºC.

1. INTRODUCTION

Water is essential to human life, especially freshwater. The shortage of fresh water in the dry season is a yearly occurrence and is a concern in many countries. On our planet, there are only 37 million cubic meters of freshwater, 2.5% of which are 97%. covered by seas and oceans, and moreover, 2.5% of that freshwater source is polar ice, and only 1% can be used to sustain the life of animals and humans [1], [2]. Desalination of seawater for drinking water is also an interesting solution in many countries that have a shortage of fresh water. Reverse osmosis (RO) process and thermal evaporation process It is the technology of desalination used today, and since 2001, the RO process has been used by more than 60% as a technology used to manage freshwater from seawater [3].

Membrane distillation (MD) is an alternative technology used to improve the quality of seawater to become freshwater. Membrane distillation uses a hydrophobic membrane and allows only water vapor molecules to pass through to separate liquid and vapor. In which only water vapor can penetrate through the membrane. Other liquids and solutions dissolved components are confined to the other side of the membrane [4].

The advantages of the membrane distillation process compared to the traditional distillation process can be summarized as follows able to run the system at low temperature and pressure and temperature, and the operating cost is lower. The quality of distilled water is of high quality. It can use low-grade waste heat or couple with a solar power system which makes it attractive for brackish drinking water production in arid regions [5], [6]. It is an alternative to traditional separating processes such as distillation and reverses osmosis (RO). However, when comparing RO and MD systems, MD systems have disadvantages, for example, low flux and high thermal consumption [7], [21].

The operation of the VMD system consists of two aspects: the feed side and the permeable side-feed water is pumped from the tank into the top of the module and the end of the module is connected to the vacuum pump and is in vacuum condition. The vacuum pump carries out the vapor that has penetrated through the membrane and cannot be condensed to continue condensing in the condenser. If the non-condensing gas is taken out Accumulation of steam or non-condensable gas in the module will result reduce the heat and mass transport. Thus, vacuum pumps can reduce heat loss and enable a higher flow rate of vapor pressure through the membrane [8].

Such a limited number of research papers refer to the recirculating VMD process. This is due to the complexity of performing and experimenting. The complexity is the result of a wide range of operation changes and parameters, such as reduced feed vapor pressure. Increased feed viscosity and penetrating pressure decrease the evaporation efficiency [9].

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However, only a small percentage of the studies on the VMD distillation process was found that mentions circulating air or moisture back into the module. Kaewseng [10] had a comparison of conventional vacuum membrane distillation (CVMD) and result of a wide range of operation changes and parameters, such as reduced feed vapor pressure. Increased feed viscosity and penetrating pressure decrease the evaporation efficiency [9]. However, only a small percentage of the studies on the VMD distillation process were found that mentions circulating air or moisture back into the module. Kaewseng [10] had a comparison of conventional vacuum membrane distillation recirculation vacuum membrane distillation (RVMD) with tubular modules. From the experiments, it was found that the recirculating distillation process yielded higher flux production than the traditional distillation system. There is very little writing on VMD that mentions looping the moisture air back into the module. Mostly in the VMD system, the release of air after condensation is discussed. In a VMD system, the humid air released into the atmosphere is a by-product, returning it to the module improves the temperature inside the module, helping to differentiate the temperature inside the module and at the membrane surface thereby helping the flux content. that happened to flow well [11], [12].

This paper's main purpose is to modify a vacuum membrane distillation for water productivity enhancement by recirculated air and study the performance of the new system of VMD. In this experiment, the focus was on the effect of various factors effect on the increase in the flux of the Recirculation VMD system by studying the feedwater temperature, cooling water temperature, different pressure, and transmembrane temperature in the system.

2. MATERIALS AND METHODS

2.1 Materials

In the study, micro-porous hydrophobic polyolefin was used for the vacuum membrane distillation module. The characteristics of the micro-porous hydrophobic polyolefin sheet are listed in Table 1. The net area of the membrane used to make the module was 0.45 m^2.

Table 1. Properties of the polyolefin membrane.

Parameter	Results	Analytical Instrument
Contact angle	124.3°	Rame-hart contact angle- goniometer
Pore Size	67.42%	Mercury Porosimetry
Porosity	0.014 µm	Mercury Porosimetry
Thickness	0.30 mm	Vernier

2.2 Apparatus and Method

Figure 1 is a schematic diagram of a recirculating vacuum system with humidity which consists of 4 main parts: the feed part, the permeate part, the condensation part, the polyolefin module membrane, and a thermostatic hot water bath (SH-BW20L), circulating pump (single phase 110-220V), flow meter (TT Z-3001), thermometer and humidity meter (ASAIR AM2302). The pressure gauge and pressure regulating valve are integrated on the hot side. The vacuum side is equipped with a vacuum pump (DAA-V507-GD) Erlenmeyer flask collecting freshwater and electronic scales (WT20002N).

The feed side is connected to a hot water tank (1) with a thermostatic bath as a heating element and can adjust the temperature. Controlling the flow rate with a flow meter. After the feed water is pumped up from the hot water tank to enter the hydrophobic microporous membrane modules (2). The module is responsible for separating water vapor and liquids and solutions dissolved components. The resulting water vapor is then sucked up by a vacuum pump and condensed to the condenser (3 and 4). Condensation and heat exchange within the condenser is carried out using tap water supplied by variable cooling water. The hot water feed is pumped by a circulating pump (single phase 3000-3600rpm) located in the hot water tank into the top of the module from which vapor is generated. The vapor generated inside this module is sucked out from the bottom of the module by a vacuum pump (DAA-V507-GD).

The condensed water vapor is stored in a rose-shaped flask and its volume is measured by weighing from a balance digital. The vacuum pressure adjustment applied in the system is adjusted through a vacuum valve and thereafter at the end of the tube. The supply side of the pump recirculates the air into the upper module.

In the laboratory scale the variables were:

(a) Hot feed water Temperature (T_f) - In the experiment, distilled water was used to run the system. The temperature of the distillate solution used in the system was set the temperature to 30, 40, and 50°C respectively.

(b) Cooling Temperature (Tc) - Condensation and heat exchange within the condenser is carried out using tap water supplied by variable cooling water, whose temperature ranged from 10, 20, and 30°C respectively.

(c) Vacuum pressure ΔP - In this study, the vacuum pressure was variable at -20, -30, -40, -50 and -60. kPa, respectively. To investigate the influence of vacuum pressure on the system's permeate flux.

(d) Flow rate – In the experiment, the system flow rate was constant throughout the experiment at 1.5 L/min.

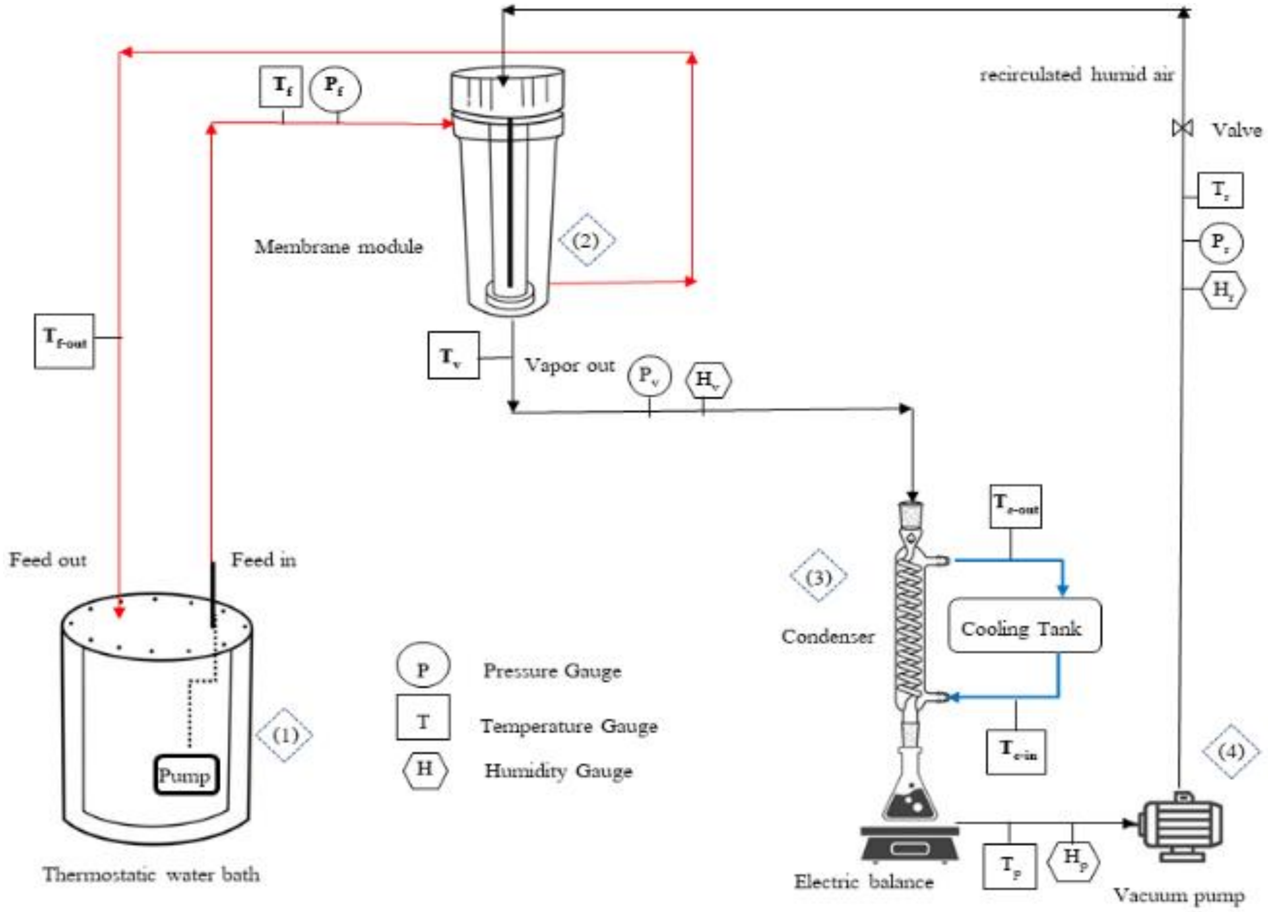


Fig. 1. The schematic diagram of recirculation vacuum membrane distillation.

According to theory, the distillation flux is directly proportional to the difference in vapor pressure between the hot side and the cold side. [13] Water distillate flux (J) in the VMD process is proportional to the vapor pressure difference membrane between the hot feed side and permeate side [14], [15].

Average water distillate flux was calculated based on the amount of condensate collected in each experimental run. The weight of collected freshwater from module membranes within a measured time and registered every hour using a digital balance was calculated as [10].

$$J = \frac{V}{A.t} \tag{1}$$

when J = water flux (L/m^2.hr), V = the volume of water collected in the container (L), A = the total distillation surface area (m^2), and t is the time for running the system and collecting water (hr). The driving forces of membrane pressure differences can be divided into [16].

$$\Delta P = P_{fm} - P \tag{2}$$

where ΔP = the difference in vapor pressure on the hot water side and the permeate side

From Equation 3, it is Antony's equation that relates the temperature at the membrane surface (T_{fm}) and the vapor pressure at the membrane surface (P_{fm}) used to calculate the vapor pressure of pure water [17].

The value of vapor pressure can be calculated as follows.

$$P_{fm} = exp\left[23.1916 - \frac{3816.44}{Tfm + 273.15 - 46.13}\right] \tag{3}$$

3. RESULTS AND DISCUSSION

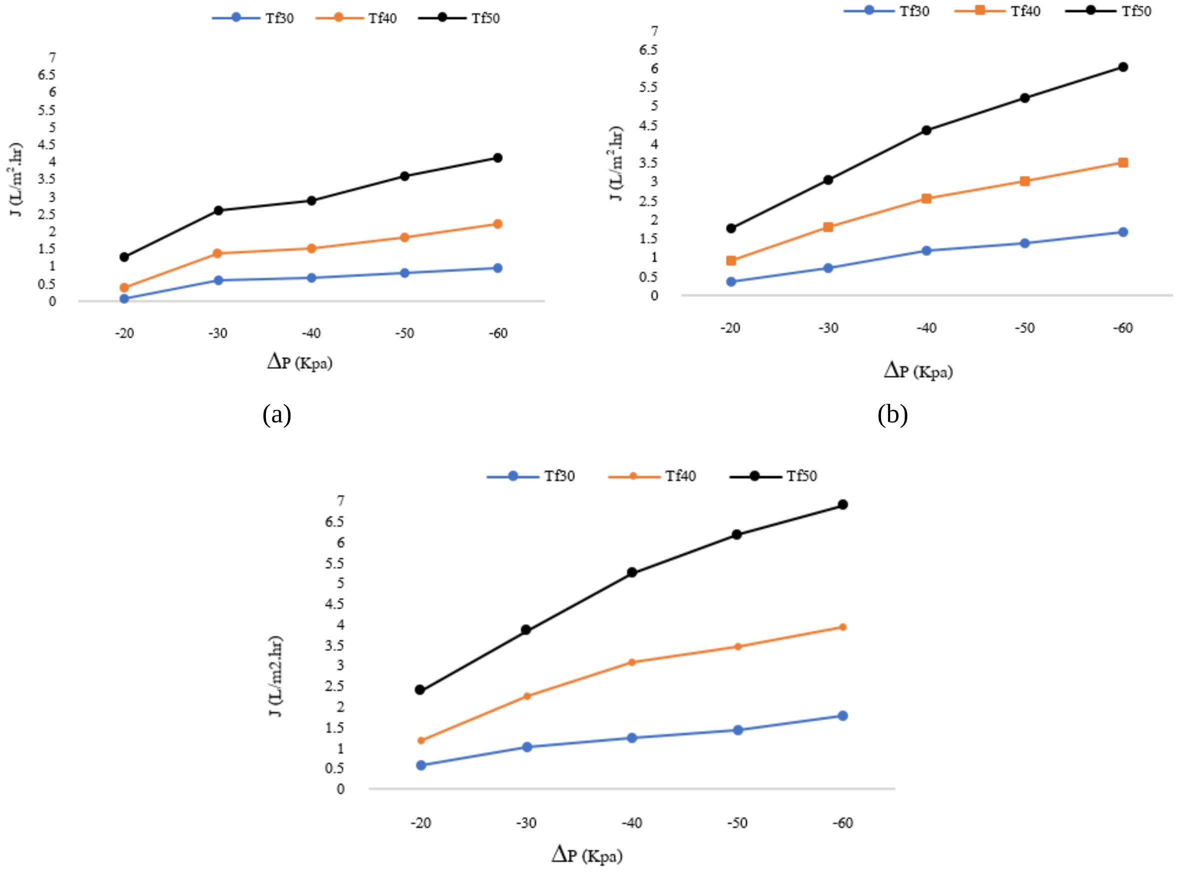
Optimization of operating parameters on recirculation VMD. The effect of various parameters on system performance has been extensively studied. and in this study to find the optimal operating conditions for the best working conditions. The performance of the recirculation VMD system can be summarized as follows.

From the experiment to find the steady state (steady state) of the system, distilled water was used to operate the system. The experiments were continuous at 3h. Samples were taken every 10 min for each experiment until the values of the system time and the permeate water weight values after the membrane were passed. The mean was constant over the course of the 180min experiment, which meant that water vapor penetrating through the membrane pores had a constant mass transfer.

3.1 Effect of Operating Different Pressure (ΔP)

Measuring the efficiency of the Recirculation VMD system, the different pressure (ΔP) is one of the measures of system efficiency. Figure 2 illustrates the pressure difference is correlated with the flux generation. At hot feed temperatures of 30, 40 and 50ºC, respectively and at various cooling temperatures starting at 10, 20 and 30ºC, it was found that with increased ΔP, the rate of flux increased accordingly. From the experiment, the highest water production rate was at hot feed water temperature (Tf) 50ºC, cooling temperature 30ºC at a vacuum pressure difference of -60 kPa, the influence of the pressure difference and the hot feed water temperature is it has the same effect on the flux generation rate.

When the vapor pressure between the two sides of the membrane increases. This results in better efficiency of the membrane distillation system. From Figure 3, Yan [18] conducted an experiment and found that the amount of flux generation increases with increasing vacuum pressure.



(a) (b)

(c)

Fig. 2. Effect of vacuum pressure difference on flux (*J*) in recirculation VMD with cooling water temperature (*Tc*) at 10 (a); 20 (b); 30 (c).

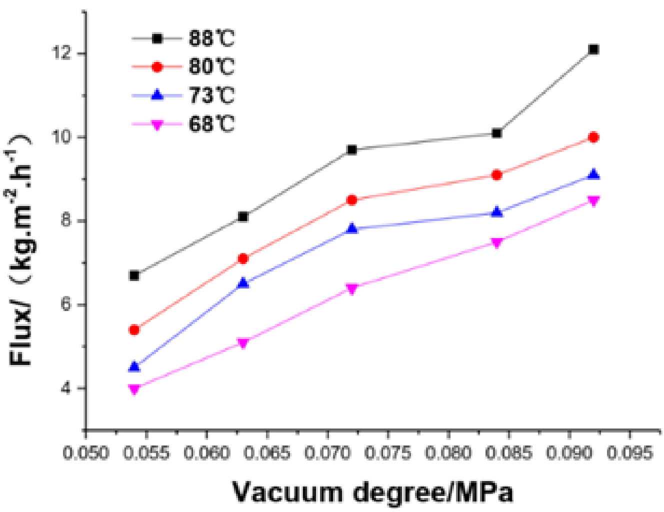
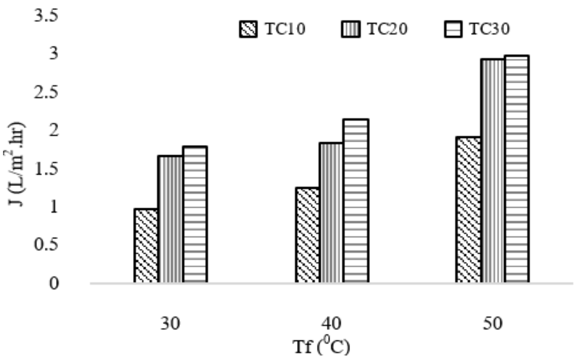
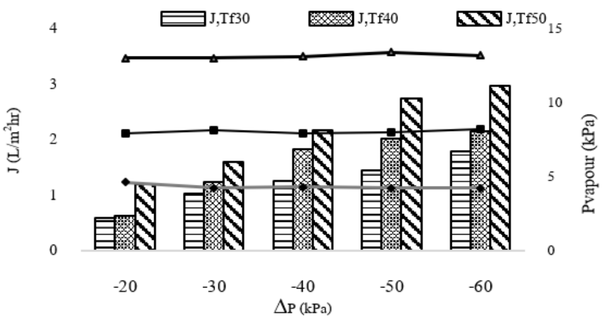


Fig. 3. Effect of vacuum - different hot feed temperatures [16].



(a)



(b)

Fig. 4. (a) Effect of hot feed water temperature on permeate flux at cooling temperatures of 10, 20, and 30°C at a pressure difference of 60 kPa. (b) Effect of inlet water hot feed water temperature on vapor pressure at cooling water temperatures 30ºC, with a pressure difference of -20, -30, -40, -50, and -60 kPa.

3.2 Effect of Feed Temperature on Permeate Flux

The experimental results are in Figure 4. shows the performance of Recirculation VMD at different feed temperatures (T_f) 30ºC, 40ºC, and 50ºC respectively. Increasing the hot water feed temperature significantly improved the permeate flux. This behavior is as expected. This is because in the VMD process the main driving force is the pressure difference on both sides of the membrane. Hence, according to the Antoine equation, the vapor pressure of the gas-liquid interface on the feed side increases with the water feed temperature increase, it is positively affecting the diffusion process accompanied by a subsequent increase in the driving force of mass transfer, thus increasing the permeate flux [19]. The vapor pressure experiment shown in Figure 5 shows the relationship between vacuum pressure and vapor pressure tested at different hot feedwater temperatures. From the graph, it can be seen that when increasing the vacuum pressure, the value of the vapor pressure does not vary accordingly but at the same time, when the water inlet temperature is increased, the vapor pressure is directly proportional, and the vapor pressure is large when the water temperature is high.

An increase in cooling water temperature results in an increase in water production rates. This is because an increase in cooling water temperature results in an increase in the humidity of the air recirculated into the system. At cooling water temperatures of 10, 20, and 30ºC, the recirculating humidity is approximately 60%, 80%, and greater than 95%, respectively.

The moisture that recirculates in this system will help to cool the inside of the membrane module. As a result, the temperature difference at the membrane's surface and the gap temperature inside the membrane module increased. The rate of water production in the system is therefore higher.

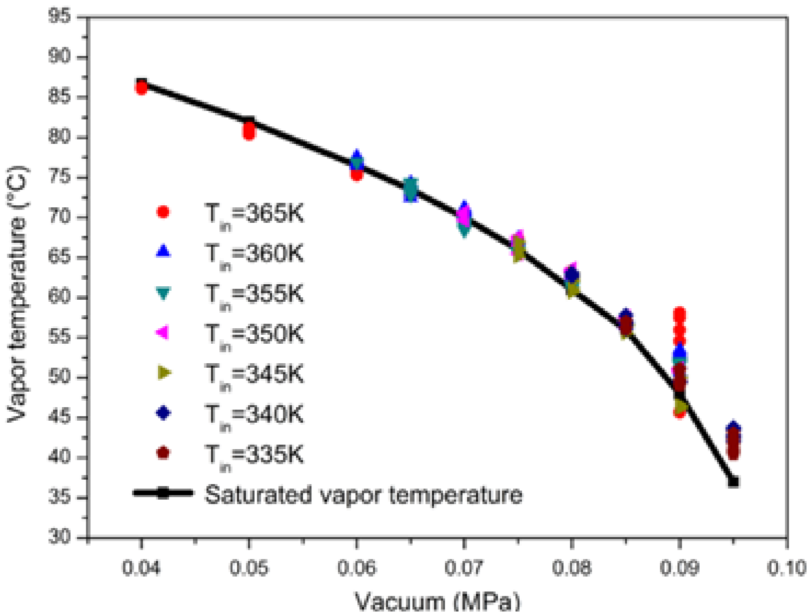


Fig. 5. Relationship between vacuum pressure and vapor pressure at various temperatures [20].

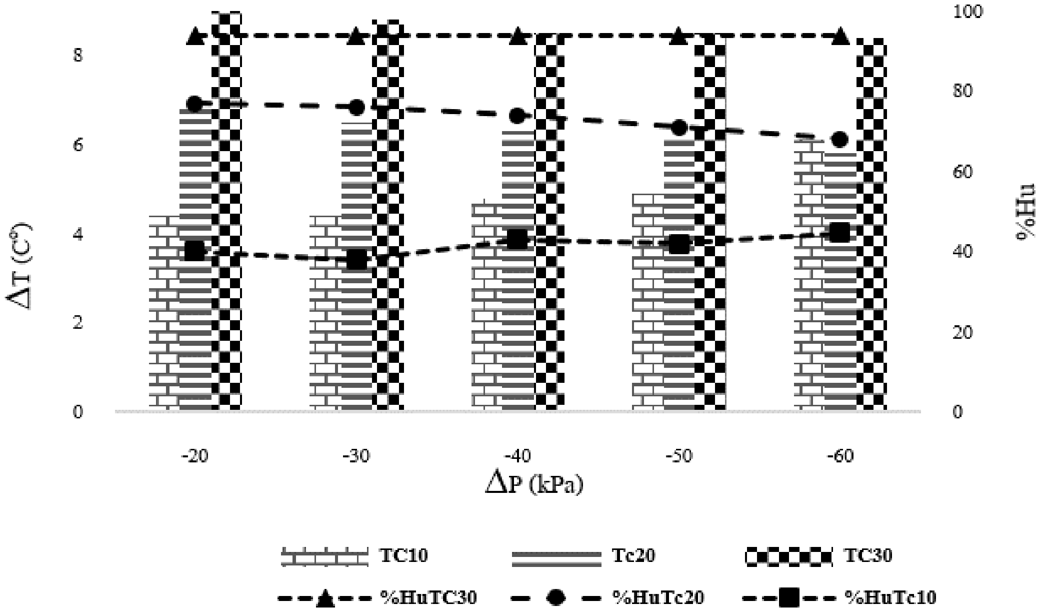


Fig. 6. Effect of recirculating humidity on the temperature difference (TV – Tf, ΔT) of the VMD system at a feed temperature of 50°C, with a cooling temperature of 10, 20, and 30°C.

3.3 Effect of Humid Recirculation

This experiment shows the relationship between ΔT and permeates flux to determine the effect of ΔT on Recirculation VMD processes under conditions. T_f = 50°C Figure 6 illustrated the variations of ΔT, humidity, and JVMD with ΔP. From the picture, it can be seen that when the cooling temperature is increased from 10-30°C, the value of the measured humidity is higher. at a cooling temperature of 10°C Humidity is 40-50%, cooling temperature 20°C, humidity 60-70%, and at cooling temperature 30°C, humidity is 80-90%. not complete, so moisture is left behind when it is discharged from the vacuum pressure pump. At the same cooling water temperature, the inlet temperature increases, (T_f) The results show that the difference between the surface temperature and internal temperature of the membrane unit increases, resulting in a higher water production rate.

The inlet water temperature of 50°C, the water production rate is higher than that of 40 and 30°C, respectively, as shown in Figure 7 is a recirculation of humidity (Hr) back into the module, where Hr is a measure of the moisture content after condensation. The advantage of this reverse humidifier acts as an absorber and a heat sink, resulting in a lower temperature in the Tv module and the difference in membrane temperature increased (ΔT = TV- Tf). These ΔT of RVMD values were further enhanced with the residual H_r values after higher condensation by changing the T_c condition from 10 to 30°C.

3.4 The Rate of Water Production per Energy Used

In the preparation of a vacuum membrane distillation system in this research. As the average ambient air temperature of Thailand is about 27-30°C according to the Thailand's Meteorological Department website, the initial temperature setting of the system in this research (also corresponding to the temperature of the hot water side) was then set at 30°C. The hot water and coolant starting temperature is elected to 30°C so that no energy is required to change the water temperature. This system will benefit tropical countries that do not require energy to cool the coolant above the average air temperature.

From Table 2 it is found that with the initial setting of hot water and cooling water at 30ºC, the maximum water production rate is hot water temperature 50°C coolant temperature 30°C, so the heat energy used to change the water temperature is only used for the hot water temperature. As the coolant side remains at 30°C, reducing the coolant temperature to allow condensation is not always necessary.

4. CONCLUSIONS

In this study, it was found that the optimal operating conditions for the RVMD system were the feed temperature of (T_f) 50°C, the cooling water temperature of (T_c) 30°C, and the vacuum pressure difference of (ΔP) -60 kPa.

This is the one that produces a maximum flux of 2.97 L/m^{2}hr. The conclusion is from the study that increasing the feed temperature significantly improved the permeate flux. The relationship between flux increment and feed temperature can be suitably represented by Antonie equation which indicates the exponential relationship between water vapor pressure and temperature on the membrane surface. As a result of the increase in temperature, more water vapor is produced.

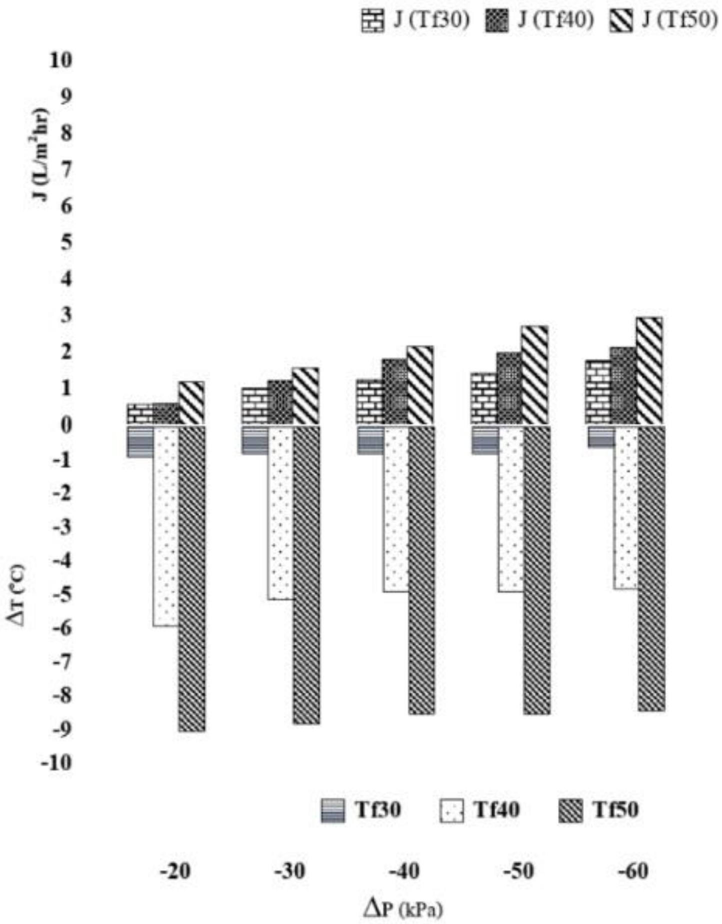


Fig. 7. Effects of temperature difference (TV – Tf, ΔT) on permeate flux (J) with different feed temperature (Tf) at Tc 30°C.

Table 2. The analogy is the rate of water production when changing hot water temperature and coolant temperature.

T_f - T_c (°C)	ΔT (ºC)	flux (L/m^{2}h)				
		ΔP, P_v-P_f (kPa)				
		20	30	40	50	60
30-30	0	0.58	1.03	1.26	1.45	1.79
30-20	10	0.35	0.73	1.20	1.37	1.67
30-10	20	0.06	0.62	0.66	0.80	0.97
40-30	10	0.62	1.24	1.83	2.01	2.15
40-20	20	0.59	1.07	1.36	1.66	1.84
40-10	30	0.34	0.75	0.86	1.02	1.24
50-30	20	1.20	1.59	2.17	2.73	2.97
50-20	30	0.85	1.25	1.81	2.18	2.53
50-10	40	0.88	1.25	1.37	1.78	1.91

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