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Implementation of Membrane Condenser for Water Recover From Humidified Ambient Air Using Chilled Water as a Coolant

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ABSTRACT
The potential utilization of a membrane condenser for dehumidification of water from humid ambient air is studied in this paper. In this study, the membrane condenser is integrated with a heat exchanger which has a purpose of cooling down the humid ambient air with cooling chilled water, to lower the temperature of the humid air so that it will be in super-saturated state with regard to its humidity, then the super-saturated air is directed to the membrane condenser for separation of water from the air. In this study; the influence of heat exchanger effectiveness on the water recovery rate is investigated. Furthermore, the effect of feed temperature of the humid air as well as the inlet temperature of the cooling water of the heat exchanger, on the water recovery rate of the membrane condenser system is presented.
Keywords-membrane condenser, heat exchanger, humid ambient air.

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I. INTRODUCTION

Water scarcity is a major issue of our continent. More than 1.2 billion peoples are suffering from water shortages, which is more than fifth of the population of the world leave in geographic areas where water is physically scares, and 500 million more people are approaching to the scarce situation, another 1.6 billion of people are living under economic shortage of water as a result of luck of the appropriate infrastructures to utilize water from aquifers and rivers. Water scarcity is one of the main difficulties which have to be faced by many countries of the world in the current 21st century. Due to the advancement of technology and development in living standards of societies water use has been increasing more than twice the rate of population growth [1].

The use of membranes for water treatment is already matured technology, which had been advanced with the development of polymeric technology after the World War II. Currently the reverse osmosis technology is one of the widely used membrane technology used water to recover water from sea water and brackish water [2-4]. The driving force for RO membrane process is pump pressure. A membrane water treatment process which have the highest potential in recovery of water from sea water is membrane distillation (MD), where a driving force in MD based membrane process is a vapor pressure which results a mass transport of water vapor through pores of the membrane. MD has been utilizing for desalination process [5–7] and to treat water from non-volatile particles such as drinking water purification, waste water treatment, chemical production, increasing the concentration in fruit juice of food processing industries, in removing water from blood etc. The implementation of MD for water treatment and recovery is reported on many literatures [8-17].

Membrane condenser is a recent advancement in the field of membrane technology which was recently suggested by Drioli and his colleagues [18-21]. The membrane condensers are manufactured from micro-porous hydrophobic polymers, for recovery of water from industrial waste gas through condensation process. When an air or a gas with supersaturated state or with higher humidity level, is admitted to the membrane surface, their hydrophobic characteristics avoids the penetration of the liquid into the pores which allows the dehumidified gases to stream through the membrane [22]. As a result, the liquid water is clogged and recovered at the retentate side, while the dehumidified gases flows to the permeate side of the membrane unit. The key benefits of membrane condenser are: the process does not involve corrosion, it has lower energy consumption, and it is a clean operation. The volume of recovered water is depends on the cooling process of the gaseous stream which is feed to the membrane condenser. [23].

The use of membrane condenser to recover water from humidified ambient air is rare in the ligatures. Hence, the objective of this paper is to study the utilization of membrane condenser for dehumidification of ambient air.

II. Modeling of the membrane dehumidification system

Fig. 1 presents a schematic depiction of a membrane based dehumidification system, which is designed to recover water from humid ambient air. The system can be effective to work on humid climate geographic location such as Jeddah city. The system comprises components such as heat exchanger and a membrane condenser. Inside the heat exchanger the humid air is cooled down to a lower temperature with chilled cooling water. As a result the humid air will leave the heat exchanger as super-saturated state due to lower temperature (i.e., at point 3). The membrane condenser dehumidified the super-saturated air and the air leaves the membrane condenser as permeate after the dehumidification process.

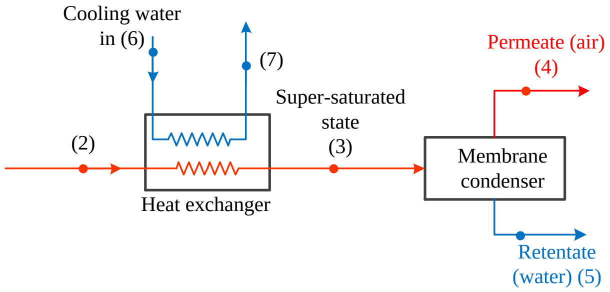


Fig. 1 Model used to analyze water recovery of membrane condenser

2.1. Thermal analysis of the heat exchanger

The heat exchange rate between the humid ambient air and the chilled water (Q_{Hx}) can be related in terms of the heat exchanger effectiveness with Eqn. (1) [24].

$$\varepsilon_{Hx} = \frac{Q_{Hx}}{Q_{Hx,max}} = \frac{Q_{Hx}}{(\dot{m}C_p)_{min}(T_{hot,in} - T_{cold,in})} = \frac{Q_{Hx}}{(\dot{m}C_p)_{min}(T_2 - T_6)}, \quad (1)$$

Where (Q_{Hx}) is the actual heat exchange rate by the working fluids of the heat exchanger, (ε_{Hx}) is effectiveness of the heat exchanger, $(\dot{m}C_p)_{min}$ the lower thermal capacitance of the two fluids.

The temperature of the humid air and the chilled water at the exit of the heat exchanger can be given with Eqn. (2).

$$Q_{Hx} = \dot{m}_{air}\, C_{p,air}\,(T_2 - T_3) = \dot{m}_{wat}\, C_{p,wat}\,(T_7 - T_6), \quad (2)$$

Rearranging Eqn. (2), the temperature of the humid air at the exit of the heat exchanger (T_3) can be given with Eqn. (3).

$$T_3 = T_2 - \frac{Q_{Hx}}{\dot{m}_{air}\, C_{p,air}}, \quad (3)$$

The pressure drop of the humid air inside the heat exchanger is the difference in pressure of the humid air at the inlet and exit of the heat exchanger as presented with Eqn. (4).

$$\Delta P_{Hx} = P_2 - P_3, \quad (4)$$

Rearranging Eqn. (4), the pressure of the humid air at the exit of the heat exchanger can be given with Eqn. (5).

$$P_3 = P_2 - \Delta P_{Hx}, \quad (5)$$

2.3 Thermal analysis of the membrane condenser

The recovery rate of the membrane condenser can be given with Eqn. (6) [19].

$$Rec = \frac{n_{v,2} - \frac{P_{g,3}(n_{tot,2} - n_{v,2})}{P_3 - P_{g,3}}}{n_{v,2}}, \quad (6)$$

Where $n_{v,2}$ is number of moles of the water vapor in the humid air at the feed or point 2, $n_{tot,2}$ is the total number of mole of the humidified air at the feed, $P_{g,3}$ the saturated pressure of the water vapor, P_3 is pressure of the humidified air at the exit of the heat exchanger.

Table 1 shows the modelling parameters which are used in the analysis.

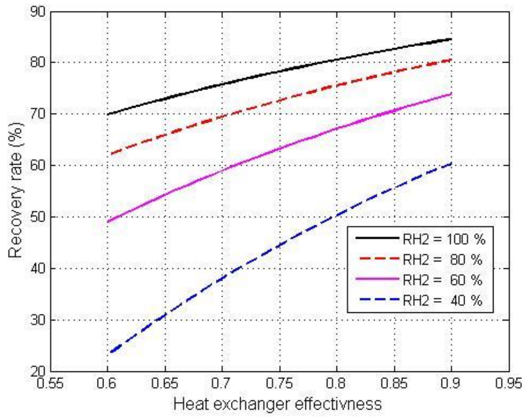
Table 1. Modelling parameter used in this study

Parameters	Value
Inlet pressure of the humid air at inlet of the heat exchanger, P_2	2 bar
Inlet temperature of the humid air at inlet of the heat exchanger, T_2	5 to 40 ^oC
Inlet temperature of cooling chilled water to the heat exchanger, T_6	4 to 8 ^oC
Mass flow rate of the humid air	4 $kg.s^{-1}$
Mass flow rate of the cooling water	1 $kg.s^{-1}$
Effectiveness of the heat exchanger	0.6 to 0.9

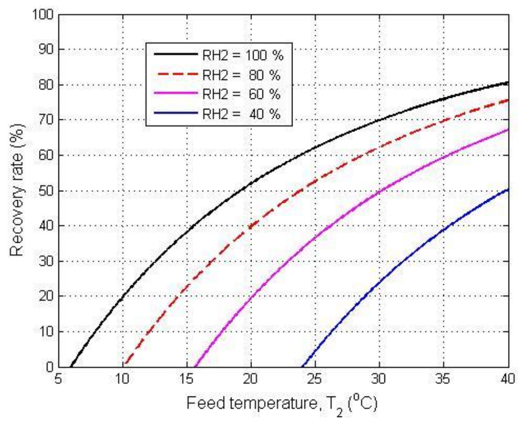
III. RESULT AND DISCUSSION

Fig. 6 shows the relationship between effectiveness of the heat exchanger and recovery rate for different relative humidity of the air at the feed (or point 2). The result is generated for modelling parameters which are presented in table 1, and for 40 ^oC inlet temperature of the humid air at the heat exchanger and 6 ^oC inlet temperature of the cooling water and for zero pressure drop of the humid air at the heat exchanger. From the result it can be understood that as heat exchanger effectiveness increases the recovery rate of the membrane based dehumidifier increases. Furthermore, the increase in relative humidity of the feed increases the increase in recovery rate of the system. For 100 % of relative humidity the recovery rate can be as high as 85 %.

Fig. 7 shows the relationship between feed temperature of the humid air and recovery rate, for different relative humidity of the air at the feed. The result is generated for modelling parameters which are presented in table 1, and for 0.8 effectiveness of the heat exchanger and 6 ^oC inlet temperature of the cooling water and for zero pressure drop of the humid air at the heat exchanger. From the result it can be understood that as the feed temperature increases the recovery rate of the membrane based dehumidifier increases. Furthermore, the increase in relative humidity of the feed increases the increase in recovery rate of the system. For 100 % of relative humidity the recovery rate can be as high as 80 %.

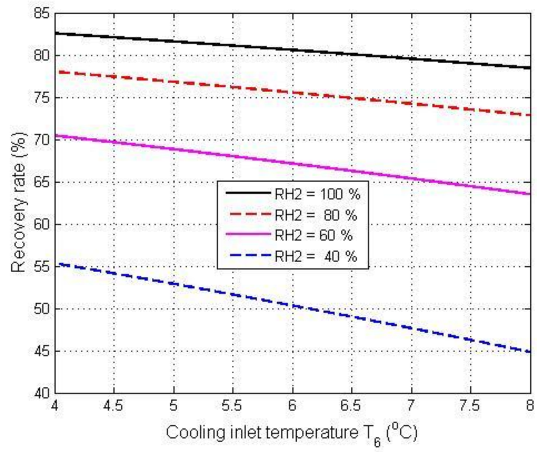


The effect of heat exchanger effectiveness on the performance of the dehumidifying system, for T_6=6 ^oC, T_2=40 ^oC, and for ΔP_{Hx}=0.



The feed temperature on the performance of the dehumidifying system, for T_6=6 ^oC, $\mathcal{E}_{Hx}$ = 0.8, and for ΔP_{Hx}=0.

Fig. 8 shows the relationship between the inlet temperature of the cooling water and recovery rate, for different relative humidity of the air at the feed. The result is generated for modelling parameters which are presented in table 1, and for 0.8 effectiveness of the heat exchanger and 40 ^oC feed temperature of the air and for zero pressuredrop of the humid air at the heat exchanger. From the result it can be understood that as thetemperature cooling water increases the recovery rate of the membrane based dehumidifier decreases.



The feed temperature on the performance of the dehumidifying system, for T_2=40 ^oC, $\mathcal{E}_{Hx}$ = 0.8, and for ΔP_{Hx}=0.

IV. CONCLUSION

This is study is focused on membrane based dehumidification system for recovery of water from humid ambient air using a chilled cooling water. The modelling is done based on parameters which are depicted on Table. 1. The following conclusions can be drawn from this study.

- The increase in effectiveness of the cooling heat exchanger increases the recovery rate
- The increase in feed temperature increases the recovery rate.
- The increase in relative humidity of the feed increases the recovery rate.

The increase in inlet temperature of the cooling water decreases the recovery rate

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