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Analysis of Humidification Dehumidification Desalination System

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--***ABSTRACT***--

A unique and simple solar desalination system has been developed using humidification and dehumidification process. The system consists of humidification and dehumidification chamber. The key point is the psychrometric energy re-use, most of the energy required for the desalination process is recovered from the dehumidification chamber. A psychrometric analysis of the system is presented. Further analysis was conducted using experimental data to optimise the performance of the system. The system produced 18kg/h of fresh water using 3kW energy input. The effect of operating conditions which include flow rates and temperatures of feed water, air and cooling water are also presented.

KEYWORDS;- *psychrometric, humidification, dehumidification, desalination*

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I. INTRODUCTION

A novel water desalination system was designed. The system employs the concept of humidification dehumidification based on psychrometric energy process using a special membrane. It consist of the humidification chamber which contains an evaporation core (E-core) where evaporation takes place and dehumidification chamber which contain an evaporation-condensation core (E/C-Core) where both evaporation and condensation takes place for energy recycling and water production respectively.

The key point is the psychrometric energy "re-use", a little thermal energy is put into the humidification and dehumidification process. Most of the energy is from the psychrometric energy from the condensing of the moisture in the carrier gas. The HDD system could be one stage, or multiple stages such as two stages. The schematic of one stage solar HDD process is shown in Fig.1. The system is featured with high efficiency and low cost Evaporation/Condensation core (E/C core) and Evaporation Core (E-Core). The E/C core contains a special membrane with two channels, the evaporation channels with hydrophilic surface and condensation with hydrophobic surface. This makes the condensation and evaporation process in the E/C core very efficient.

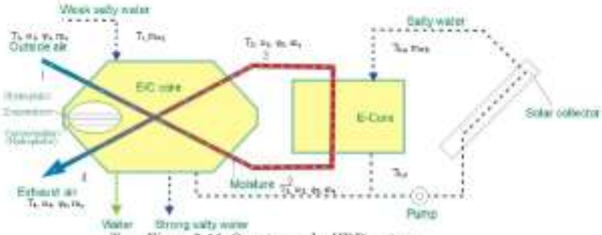

Figure 1. One stage solar HDD system

As shown in Fig. 1, the outside air at point 1 gets humidified in evaporation channel of E/C core to become point 2, and the energy required is from the condensation channel of the water condensation, so most of the energy for desalination is reused. Air at point 2 then pass E-core to get humidified further from solar energy input to become point 3, then air at point 3 pass the condensing channel of the E/C core to get dehumidified and at last discharged as exhaust air.

II. DESIGN OF THE DESALINATION SYSTEM

The Dehumidification Chamber

The dehumidification chamber is an important part of the desalination unit. It is designed to utilise all energy that can be re-used thus increasing efficiency and enhancing the amount of fresh water that can be produced. The dehumidification chamber consists of E/C-core which is made of special membrane for both evaporation and condensation processes. It consists of two channels as shown in Figure 2; the evaporation (hydrophilic) and condensation (hydrophobic) channels.

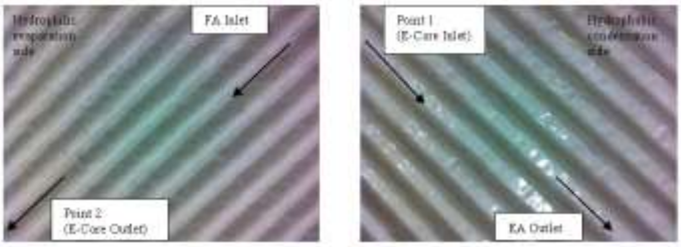

Figure 2. Polymer membrane with condensation channel laminated with plastic

The special membrane serves as heat exchanger where heat of condensation is transferred and utilised in the evaporation channel. Cooling seawater or brackish water and fresh air are mix in the evaporation channel in order to aid evaporation. At the same time they aid in condensation process by extracting the heat from the vapour in the condensation channel. The principle of the psychrometric energy process desalination (PEPD) is illustrated in Figure 4.

Figure 4. Principle of the PEPD membrane E/C-Core

The following equations where used to illustrate the possibility of reduction in both energy and cooling requirement of E/C-Core. A comparison was made for when condensation only occurs at the Core without evaporation.

$$q_{cond} = m_a(h_3 - h_4) = q_{latent} \qquad 1)$$

$$q_{evp} = m_a(h_2 - h_1) \qquad 2)$$

$$q_{E/C} = (q_{cond} - q_{evp}) \qquad 3)$$

$$m_{w,c} = \frac{q_{E/C}}{c_p(T_{c,o} - T_{c,i})} \qquad 4)$$

Having known or assumed the initial operating conditions, all other system parameters such as energy requirement, cooling water requirement and fresh water production rate can be obtained using equations 1 to 4. The analysis was carried out for individual processes namely, the condensing process, the evaporation process and the combined simultaneous evaporation/condensation process.

As seen in all cases in Figure 5, energy is directly proportional to amount of fresh water production. The higher the water produced, the higher the energy required. The calculated energy given up during condensation is approximately equal to the latent heat based on amount of fresh water production. The difference between the two values is substantially due to the approximations used in the calculation, given that the heating of air is in fact due to the condensation of water. Around 70% of the heat of condensation which is the amount required for evaporation can be re-used. And thus only 30% energy input is required for further evaporation at the humidification chamber. It can be seen that the energy requirement of the E/C-core is significantly reduced when compared to if the dehumidification chamber where to contain condensation process only.

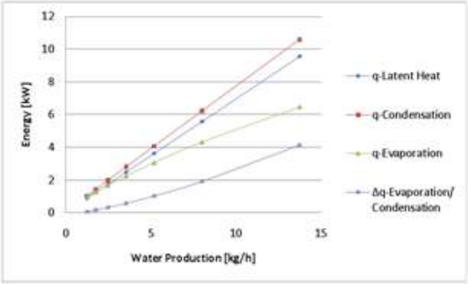

Figure 5. Reduction of energy consumption for the E/C-Core

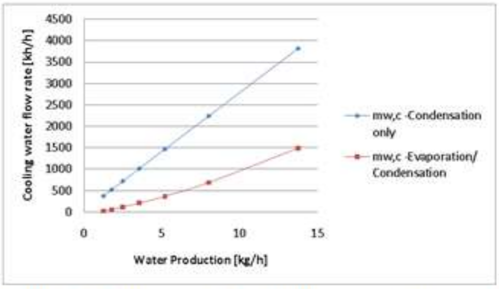

Figure 6. Comparison of cooling water requirement for condensation and E/C-Core

Another important parameter is the amount of cooling water requirement in the dehumidification chamber. This was calculated using equation 4. And the amount of cooling water is dependent on the energy at the E/C-core. The variation of cooling water with fresh water production is shown in Figure 6. The amount of cooling water increases with increase in fresh water production. It was found out that the amount of cooling water requirement could be reduced by up to 80% if the E/C-Core is used in the dehumidification chamber.

The Humidification Chamber

It is intended to use honeycomb arrangement of cellulose papers as the contact surface in the E-Core. The commercial honeycomb celluloses as evaporative pads are widely available (Figure 7). The cellulose material is impregnated with decay-resisting chemicals to give good durability, self-supporting and also to provide efficient wetting.

Figure 7. Honeycomb cellulose paper

The humidification chamber was designed based on minimum amount of water that can be evaporated using the specified initial conditions. This is highly dependent on the outside temperature and relative humidity, air flow rate and hot water temperature difference between the inlet and outlet of the humidification chamber ΔT. Figure 8 and 9 shows variation of energy water evaporation rate with air flow. It can be seen that air flow rate is directly proportional to both the energy and water evaporation rate.

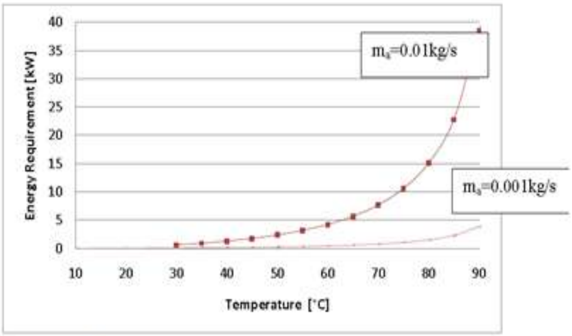

Figure 8. Variation of energy requirement with temperature over different air flow

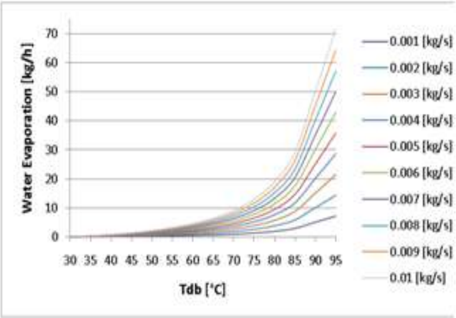

Figure 9. Variation of water evaporation with temperature over different air flow

III. PSYCHROMETRIC ANALYSIS

The following mathematical model can be used to evaluate the basic properties required for the analysis of the desalination unit.

Specific humidity,

This is also referred to humidity ratio. It is the moisture content of water vapour in dry air. The specific humidity can also be expressed in terms of partial pressure p_{vs}

$$\omega = 0.622 \frac{p_{vs}}{p - p_{vs}}$$

$$p_{vs} = \exp(23.5771 - \frac{4042.9}{T - 37.58})$$

Relative humidity is given by;

$$\phi = \frac{p_{vs}}{p}$$

Enthalpy of moist air, *h*

This is the specific enthalpy of dry air summed with specific enthalpy of water vapour multiplied by the corresponding moisture content.

$$h = h_a + \omega h_v$$

$$h = c_{pa}T + \omega(2501 + 1.9T)$$

The properties of moist air and liquid water are obtained from Engineering Equation Solver (EES). Dry air properties are evaluated using the ideal gas formulations presented by Lemmon [1]. Moist air properties are evaluated using the formulations presented by Hyland and Wexler [2] which are in close agreement with the data presented in ASHRAE Fundamentals [3]. EES calculates water properties using the IAPWS (International Association for Properties of Water and Steam) 1995 Formulation [4]. The EES was used to calculate psychrometric properties (water content as humidity ratio and enthalpy) of moist air for temperature up to 90°C and 10-100% relative humidity. Figure 10 and 11 shows variation of moisture content in one kilogram of dry with temperature for different relative humidity. The maximum achievable moisture content is 1.4 kg/kg at 90°C and 100% relative humidity. There is general increase of amount of water content with temperature and relative humidity. The enthalpy also increases with increase in temperature and relative humidity.

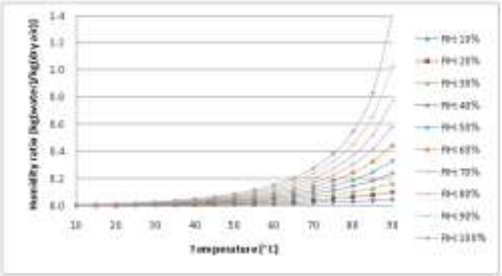

Figure 10. Variation of moisture content with temperature for different relative humidity

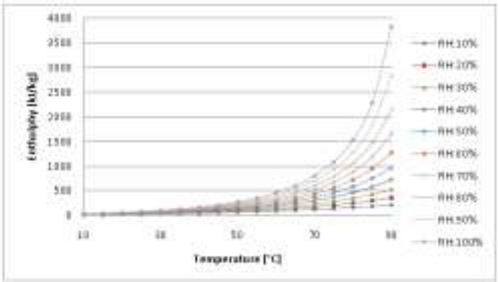

Figure 11. Variation of enthalpy with temperature for different relative humidity

IV. PERFORMANCE ANALYSIS

In order to investigate the theoretical performance of the HDD system, a mathematical model was used. The mathematical model includes energy and mass balances for the humidification chamber and dehumidification chamber. Figure 12 shows a schematic of the humidification and dehumidification process. Water evaporates from the water stream into the air during humidification process. The removal of the latent heat for evaporation from the water stream as well as the transfer of sensible heat from the water to the air stream occurs. During the dehumidification process, the heat and mass transfer processes are reversed, where water condenses from the air stream. Also, latent and sensible heats are transferred from the air stream to the cooling water stream.

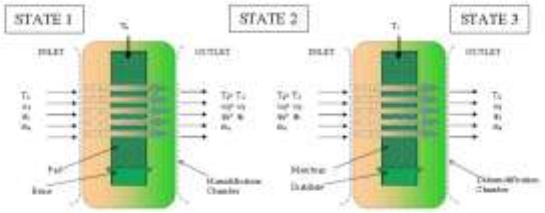

Figure 12. Schematic of HD process showing the basic parameters

The total energy Q_{input} consumed by the system is the combination of heat input (from solar collector and/or electric heater) and energy consumed by auxiliary components (pumps and fan). This is given by;

$$Q_{input} = Q_{aux} + Q_{hum} \qquad (6)$$

Where Q_{input} is the energy input at the humidification chamber. This is calculated as follows:

$$Q_{hum} = m_{w,h} c_p (T_{h,i} - T_{h,o}) = Q_{sol} + Q_{heater} \qquad (7)$$

Where Q_{hum} is mass flow rate of hot water in the humidification chamber, is specific heat capacity of water, and are temperatures at the inlet and outlet of the humidification chamber.

The condensation energy is the energy given up in order to obtain fresh water.

$$Q_{output} = h_l \text{ x } W_p \qquad (8)$$

Where *l h* (=2400 kJ/kg) is the latent heat of condensation and *p W* is the amount of fresh water produced. This is given by;

$$W_p = m_a(\omega_2 + \omega_3) \qquad (9)$$

The coefficient of performance (COP) of the system indicates how efficient the system operates. This is the energy given up for condensation (latent heat of condensation) divided by the overall energy input in the system. If the energy input is greater than the latent heat of condensation, then the COP is less than one. Hence a very high COP means the system is highly efficient. The COP is calculated as follows;

$$COP = \frac{Q_{output}}{Q_{input}} \qquad (10)$$

Mathematical analysis based on equations 6-10 has been performed. In performing the analysis the following assumptions have been made;

- The processes involved operate at steady-state conditions.
- There is no heat loss from the humidifier or the dehumidifier to the ambient.
- Pumping and fan power is negligible compared to the energy input to the heater.
- It was assumed that the system is a control volume, thus air mass flow rate is constant.
- The conditions at state one is always less than conditions at state two and three.
- Conditions at state two reaches full saturation.
- Condition at state three is less than state two.
- Temperature difference at inlet and outlet of the humidifier is 5°C.

The spreadsheet software was used to carry the mathematical analysis using mathematical psychrometric models in section 3. The calculated psychrometric properties were compared with that of the EES and another commercial psychrometric software called CYTSoft. The model was in agreement for both enthalpy of moist air and specific humidity (humidity ratio) with that obtained using the software as shown in Figure 13. There was a 0.01% deviation compared to ESS and 0.84% compared to CYTSoft.

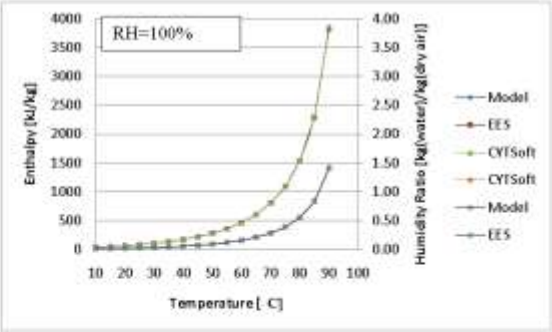

Figure 13. Calculated pyschrometric models using spreadsheet compared to ESS and CYTSoft

Thus the model was used to carry out the mathematical analysis using Microsoft Excel spreadsheet for the range of given temperatures (10-90°C) at 5°C interval and relative humidity (10-100%) at 10% interval. The selection of the temperature interval for the simulation is based on assumption that temperature variations in the humidifier are small. This assumption was validated through experimental measurements which indicate the temperature differences between the inlet and outlet of the humidification chamber averages 5°C.

The maximum COP obtained was 3.4 and it corresponds to only 0.14kg/kg water content (moisture content). This is ten times lower than the maximum achievable water content obtained per kg of dry air obtained in section 3. On the other hand the maximum achievable water content can be obtained at higher temperatures with COP at 0.9 which is just below one. Thus the higher the temperature, the higher the possible amount of fresh water that can be obtained and the lower the COP of the system. The optimum operating conditions was selected for when maximum water production occurs at COP is greater than one. Such condition exists at 80-90% relative humidity state one.

However, higher COP can be obtained at less than 5°C ΔT (temperature difference between state one and state two). Consider the following case calculations in Table 1. Here also the psychrometric properties at state two are greater than that at state one and three. And condition at state three was considered in worst case scenario at full saturation. It can be seen in case one that even though the ΔT is high at 10°C, a reasonable COP greater than one was obtained. And when ΔT was below 5°C there was general increase in COP for both case two and case three. It can be seen as the COP increase from 4 to 7, there was only a tiny fraction of increase in water content.

Table 1. Theoretical calculations of the performance of the HDD system

	STATE 1				STATE 2				STATE 3				CALCULATED				
Case	T1	Φ	Ω	h	T2	φ	Ω	h	T3	φ	ω	H	ΔT	Qi	Wp	Qo	COP
1	60	85	0.13	386	70	70	0.17	519	25	100	0.02	76	10	133	0.15	362	2.7
2	67	93	0.21	612	70	95	0.26	752	25	100	0.02	76	3	140	0.24	574	4.1
3	68	100	0.25	715	70	100	0.28	804	25	100	0.02	76	2	88	0.26	622	7.0
T = [°c], φ = [%], ω = [kg/kg], h = [kJ/kg], Q = [kJ], Wp = [kg]																	

V. CONCLUSION

While amount of water that can be condensed has limit, the COP of the system is theoretically infinite. And so a good optimisation technique is to achieve the maximum achievable fresh water production first and then recover the energy used to produce the water which can then be used for reheating, thus allowing energy re-use. Hence the COP of the system can be drastically improved. Base on the analysis carried out it is evident that there is potential for energy re-use in order to achieve high energy efficiency for fresh water production.

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