Desalination and Water Treatment
www.deswater.com
21 (2010) 66–72
September

doi: 10.5004/dwt.2010.1218

Performance analysis of an integrative unit for air conditioning and desalination

S. Kalaiselvam[a], M. Udayakumar[b], S. Jeyasheela[c]

[a]*Centre for Nanoscience and Technology, Anna University, Chennai 600 025, India*
[b]*Department of Mechanical Engineering Anna University, Chennai 600 025, India*
[c]*Department of Chemistry, Anna University, Chennai 600 025, India*
Tel. +91 44 2220 3262; Fax. +91 44 2230 1656; email: kalai@annauniv.edu (Kalaiselvam. S), udayathegreat@yahoo.co.in (Udayakumar.M), jeyasheelasiva@gmail.com (Jeyasheela. S)

Received 27 May 2009; accepted 2 March 2010

ABSTRACT

This paper presents a new innovative system for air-conditioning and desalination driven by a mechanical vapor compression cycle. The distillation process efficiently utilized the latent heat of ambient air by using the surface temperature of the evaporator coil. The production of fresh water depends on the specific humidity of the atmospheric air. The humidifier unit is the key component that separates the salt from the saline water; hence, it is specially designed and fabricated to obtain high heat and mass transfer. This experimental study highlights the production of fresh water of 95 kg/day with the circulation of 69.4×10^{-3} kg/s of sea water combined with the refrigeration effect of 3500 W with a compressor power of 614 W. The water obtained has a concentration of 105 ppm of total dissolved solids (TDS) with the P_H of 6.8, which can be considered as the attributes of drinking water. The performance of the desalination unit is found to be 4.2. This system also has unique features such as moderate installation and operating costs, with simplicity in the production of fresh water.

Keywords: Desalination; Vapor compression; Evaporative cooling; Humidification

1. Introduction

An adequate and consistent supply of fresh water is an essential requirement for human and other living beings. The total amount of global water reserves is about 1.4 million cubic kilometers. Oceans constitute about 97.5% of the total amount and the remaining 2.5% fresh water is present in the atmosphere [1]. It was estimated that the production of 1 million m^3/day requires 10 million tons of oil per year, due to the high cost of conventional energy sources [2] which are also environmentally harmful. Desalination is the process of removing soluble salts from saline water to render it suitable for drinking, irrigation, or industrial applications. Droughts, population increase and changes in the infrastructure for the production of pure water increased the demand for pure water. To meet the ever-increasing demand of the consumers various water desalination industries were set up. Competition among the water desalination plants provides the consumer with a quality product at an affordable rate. Humidification and dehumidification is a promising technique for the production of fresh water in remote and sunny regions. The efficiency of the system depends on the efficiency of each component such as air heaters, evaporator and condenser [3,4].

*Corresponding author

Table 1
Soluble gas concentration in seawater

Gaseous	Concentration (ppm)	Some probable dissolved species
Carbon	28	HCO_3^-, CO_3^{-2}, CO_2
Nitrogen	11.5	N_2 gas, NO_3^- NH_4^-
Oxygen	6	O_2 gas
Argon	0.43	Ar gas

Table 2
Total dissolved solids

Water sample	Total dissolved solids, mg/l
Well water	250–500
Typical river water	200–750
Typical brackish water	1500–6000
Typical sea water	36,000
Water for irrigation	1000

Desalination in small capacity plants is highly vulnerable due to the rapid evolution of the reverse osmosis process, and has been used for large scale multi-stage flashing (MSF) desalination plants. The mechanical vapor compression (MVC) system of desalination has many advantages over conventional MSF and reverse osmosis (RO). The pretreatment must be designed to face the worst water quality, providing a stable and good RO feed water [5]. This research focuses on a conceptual design for water desalination by the MVC system. In order to utilize the latent heat of the condensation of water efficiently, the condenser area must be made large. Hence the overall heat transfer coefficient of the condenser is expected to be small. Besides, the large reductions in the condensation heat transfer co-efficient were due to the mass transfer resistance occurring in the progression of the condensation of water vapor with non-condensable air [6,7]. However, a small diameter tube was used to overcome this problem [8]. In the present work, a new integrated system for air-conditioning and desalination was experimentally investigated for various operating conditions. The combined effect produced by the air-conditioning and desalination system exhibited a good performance and a simplicity in the production of fresh water.

2. Saline water

The various gases in seawater are nitrogen, oxygen, argon, and carbon dioxide. The solubility of CO_2 in seawater is larger than that of the other gases. This is due to the reactivity of CO_2 in seawater leading to the carbonate and bicarbonate equilibrium. The gas concentration in seawater [9] is presented in Table 1. The blend of water vapor and non-condensable gases can be treated as optimum water resources. This is classified according to the total solids dissolved in it [10], and it is represented in Table 2.

Saline water is a combination of both sea and brackish water, and holds huge quantities of dissolved salts, which makes it incompatible for direct use in industries, homes or irrigation. The total salt concentration in saline water is expressed in terms of either salinity, which is defined as the total amount of solids (grams) held in 1 kg of saline water, after all the carbonate has been transformed into oxides all the bromide and iodide have been replaced by chloride and all organic matter has been completely oxidized.

2.1. System configuration and principle

A schematic representation of the integrated desalination and air-conditioned system is shown in Fig 1. The desalination unit is configured by a traditional heat pump including an evaporator, condenser, expansion valve, compressor, and other components such as a blower, humidifying tower, water storage tanks and dehumidifying heat exchanger. Ambient air is heated by means of an electric heater having a capacity of 1 kW (auxiliary heater is provided if excessive heat is necessary). Air is blown over the humidifier, where sea water from the storage tank sprays over heated air and concentrated saline water is dropped and separated. This results in an increase in the moisture content of the air. It is then driven off to the air cooled condenser where a little amount of fresh water is collected. The capacity of the condenser selected for the system is 1.5 Refrigeration tons (RT). The remaining quantity of the humid air is sent to the evaporator in which the moisture in the humid air is completely condensed. The fresh water thus obtained is collected in the storage tank.

The collected fresh water was too chill. Hence, the cold from the fresh water could be utilized by the pre-condenser unit to decrease the temperature of the humid air as well as to increase the dehumidification efficiency. Concentrated saline water can be re-circulated until all the salt is removed from the saline water. A significant drop in the surface temperature of the evaporator coil may not be achieved, which would result in decreasing the rate of the condensation of the water vapor on the evaporator coil surface, and thus the system gives a lower yield [11]. These systems function at temperatures less than the atmospheric boiling point and use a variety of methods to vaporize

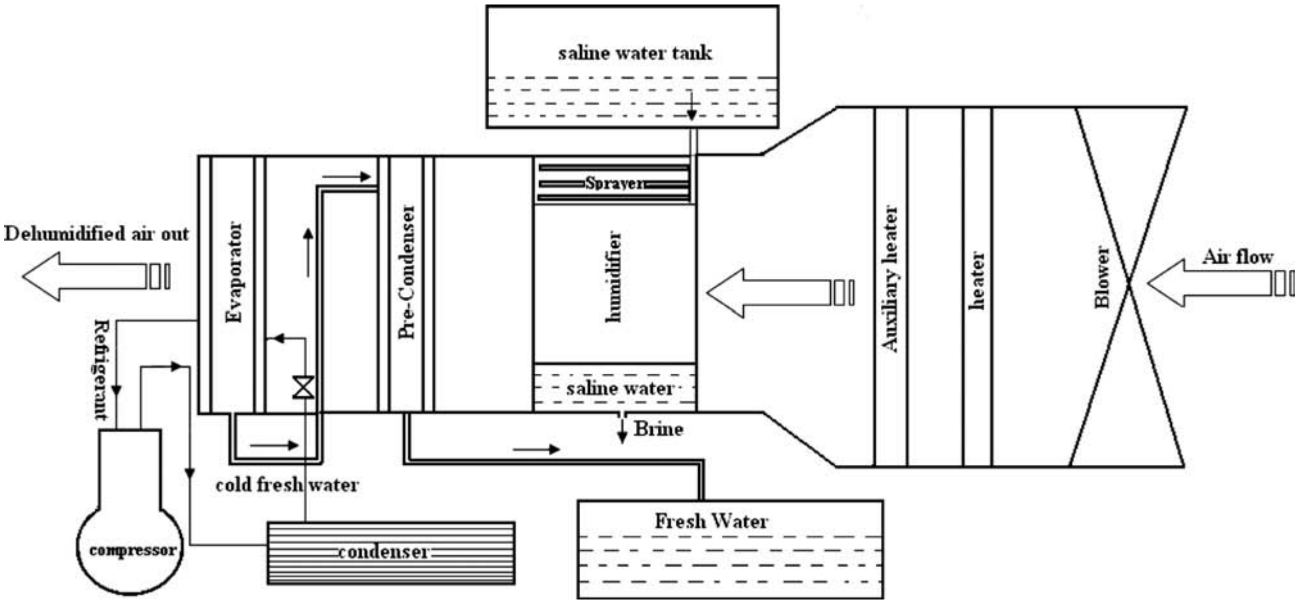

Fig. 1. Schematic representation of the integrated system.

saline water. The main limitation of these systems is the need to compress a huge amount of air in addition to vapor [12]. The humidifier unit of the system was specially fabricated to increase the effect of the heat and mass transfer. It is a key element in sorting out the salt from the saline water. Hence, it needs a larger humidifier. The volume of humidifier selected for the present system is 490 × 480 × 390 mm. The impact of the water temperature on the system productivity has been examined at various values of water temperatures. The only limitation found in the system is that it exhibits a larger specific power consumption of 15.7 kWh/m^3. A huge condenser area is required due to the low value of the overall heat transfer coefficient. Also, the larger humidifier length is obtained because of the difference in the range of temperature [13]. Moreover, using compression heat pumps in this case is not convenient, as the unit capacity is limited [14].

The uncertainties of the experimental results were calculated based on the uncertainties in the measurements of the various independent variables [15]. The estimated uncertainties in the performance of the air conditioner and the performance energy ratio of the system are determined by equations (2) and (3).

$$\frac{\delta Q_{\mathrm{evp}}}{Q_{\mathrm{evp}}} = \sqrt{\left(\frac{\delta m_{\mathrm{a}}}{m_{\mathrm{a}}}\right) + \frac{\delta t_{\mathrm{ra}}^2 + \delta t_{\mathrm{sa}}^2}{(t_{\mathrm{ra}} - t_{\mathrm{sa}})^2} + \frac{\delta T_{\mathrm{ra}}^2 + \delta T_{\mathrm{sa}}^2}{(T_{\mathrm{ra}} - T_{\mathrm{sa}})^2}} \tag{1}$$

$$\frac{\delta \mathrm{COP}}{\mathrm{COP}} = \sqrt{\left(\frac{\delta Q_{\mathrm{evp}}}{Q_{\mathrm{evp}}}\right)^2 + \left(\frac{\delta W}{W}\right)^2} \tag{2}$$

$$\frac{\delta \mathrm{PER}}{\mathrm{PER}} = \sqrt{\left(\frac{\delta m_W}{m_W}\right)^2 + \left(\frac{\delta W}{W}\right)^2} \tag{3}$$

In this experiment the COP depends on the mass flow rate of the air supply to the evaporator, the dry-bulb and wet-bulb temperature of the air, and the power input. The accuracy of a hot wire anemometer with a range of 0–10 m/s, having an uncertainty larger than ±0.015 m/s, and an RTD with the range of 0–100°C, is to be ± 0.1°C, and the estimated uncertainty of the electric watt hour meter of 10 KW is ± 0.15%. Hence the calculated accuracy of the COP is 0.069 (6.9 %), and the PER is 0.052 (5.2 %). For the experimental integrated unit for air conditioning and desalination, the controlled parameters during the experimentation are listed in Table 3.

The thermodynamic process of air stream is shown in Fig. 2. The ambient air is sensibly heated to the state 2, heat and mass transfer takes place between the

Table 3
Controlled condition during the experimentation

Conditions	Wide range
Supply air	40–70°C
DBT	25–32°C
WBT	
Air flow	0.01–0.08 kg/s
Cooling water	0.01–0.08 kg/s

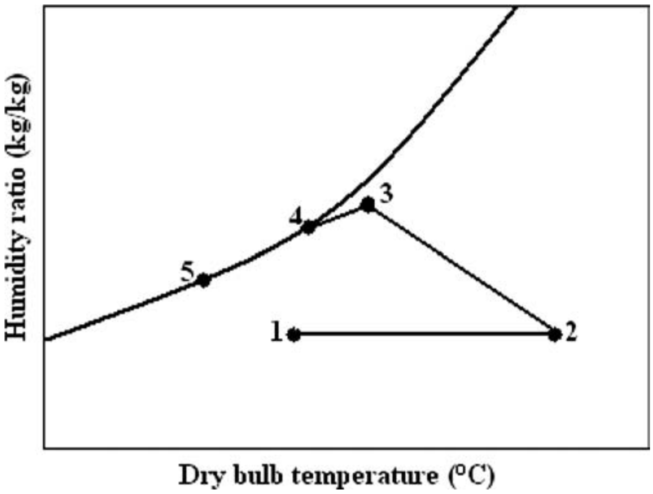

Fig. 2. Psychrometric representation of the unit.

ambient air and the saline water at state point 3. This results in increase in the specific humidity of the atmospheric air. That humid air is driven through state point 4, where it is slightly cooled and dehumidified by a pre condenser unit. That pre-cooled humid air consequently reaches state point 5, where the cooling and dehumidification process is completed. Thus, the fresh water is obtained in the fresh water tank. The performance energy ratio can be defined as the ratio between useful energy and energy inputs [16]. The outlet air was found too cold and dry state hence that dehumidified dry air can be trapped in the condenser unit, which results, in increasing refrigeration effect and decreasing the temperature of the cooler coil to obtain more fresh water.

2.2. Product water quality

The quality of the product is determined by the physical, chemical, and bacteriological properties of the collected water. Testing of the water to determine the level of treatment is necessary to supply quality water [17]. The physical characteristics of the raw water source that must be evaluated, are total dissolved solids (TDS), P_H, hardness turbidity, as shown in Table 4. The developed distillation process involves

Table 4
Product quality results

Serial no	Tests	Results
1	TDS	105 ppm
2	P_H	6.8
3	Hardness	450 mg/l
4	Turbidity	6 NTU

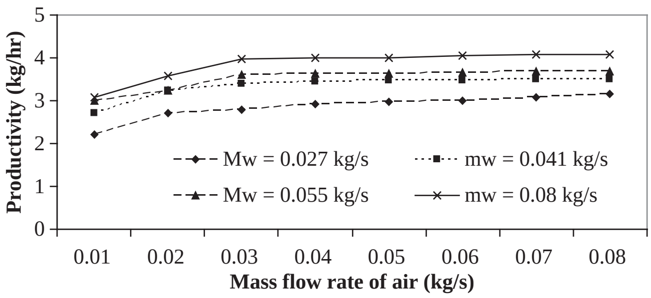

Fig. 3. Effect of air mass flow rate on system productivity.

evaporating the saline water and the vapor thus produced, which is usually salt free, and condenses to form the product. The water thus produced produced was analyzed for the TDS. The analysis showed that the quality of water produced is very high. Generally, saline water with a TDS of about 35,000 ppm was used for desalination [18]. This was reduced to about 105 ppm in the fresh water produced in this experiment.

3. Results and discussions

The effect of the inlet water mass flow rate on the system productivity at various inlet air mass flow rates is presented in Fig 3. It shows that the productivity of the system increases with an increase in the inlet mass flow rate of water and air till an optimum value is reached The maximum value of water production is 1.1×10^{-3} kg/s when the mass flow rate of water and air is 69.4×10^{-3} kg/s at air and water temperatures of 28 and 18°C, respectively.

The effect of the cooling water mass flow rates on fresh water production at various cooling water inlet temperatures is shown in Fig. 4. The maximum value of water production of 1.15×10^{-3} kg/s is achieved by the maximum flow rate of water at 80×10^{-3} kg/s and a temperature of cooling water at 15°C.

Increasing the cooling water mass flow rate and decreasing its temperature, leads to a significant drop in the surface temperature of the evaporator unit which

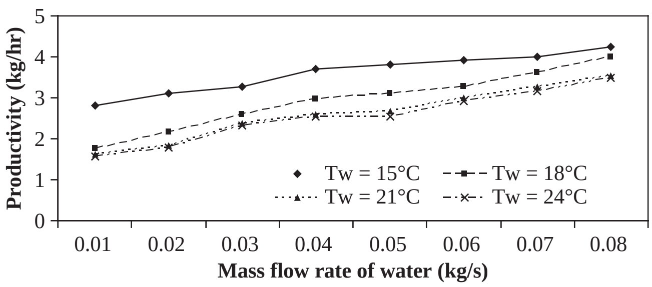

Fig. 4. Effect of various flow rates of water at different cooling water temperatures.

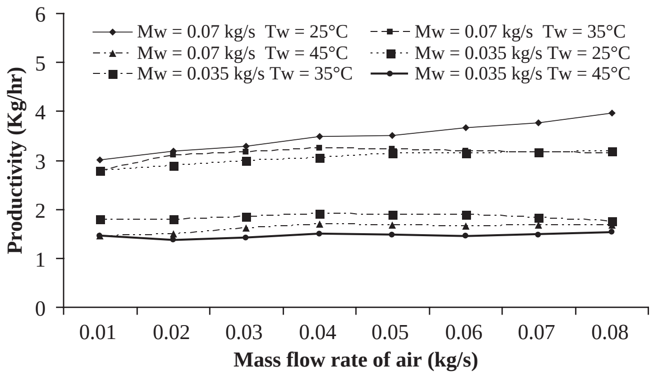

Fig. 5. Effect of air and water flow rates on system productivity at various temperatures of sea water.

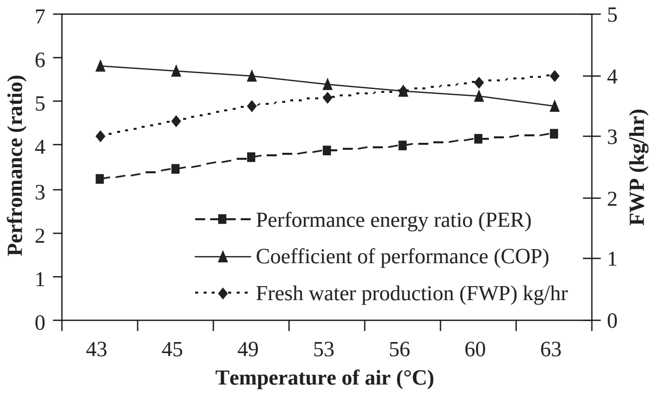

Fig. 7. Effect of air temperature on system performance.

results in increasing the rate of the condensation of water vapor on the cooler coil surface and, thus, the system gives a higher yield. The effect of the saline water temperature on system productivity at different air flow and water mass flow rates is illustrated in Fig. 5.

It can be inferred from the figure that the saline water temperature has a considerable influence on the system productivity. This is due to the fact that an increase in the saline water temperature increases the temperature of the inlet water to the humidifier which causes an increase in the moisture content of the air leaving the humidifier, thus increasing the quantity of fresh water production. A huge quantity of fresh water production was obtained at the rate of 1.1×10^{-3} kg/s by the maximal flow rate of both air and water at 80×10^{-3} kg/s with a minimal temperature of water at 25°C.

The impact of the inlet air temperatures at various water mass flow rates on system productivity are analyzed and shown in Fig. 6. It is concluded that the productivity of the system increases with increasing air temperature and inlet water mass flow rate to an optimum value. The maximum water production is 1.08×10^{-3} kg/s when the mass flow rate of water at 77.7×10^{-3} kg/s, and inlet temperature of air to the humidifier is 43°C.

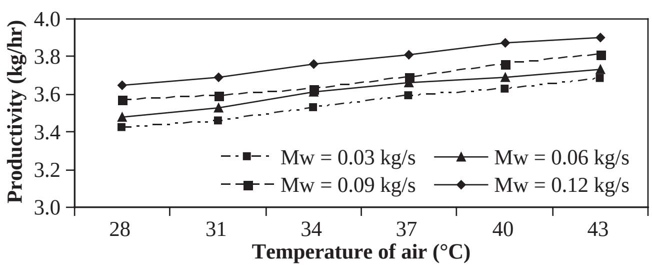

Fig. 6. Effect of various air flow rates at different water flow rates.

The performance efficiency ratio can be defined as the ratio between useful energy and primary energy input, in other words, the ratio between the fresh water produced by the system and the primary energy needed to produce fresh water.

A air temperature plays a major role on fresh water productivity, and energy performance as represented in figure 7. The performance of the desalination and air-conditioning systems is identified as 3.2 and 5.78, respectively, when the inlet temperature of air is 43°C. Also, the fresh water production of the system achieved is 1.1×10^{-3} kg/s in the same condition. It is found that the efficiency of the air conditioning system is 4.9 when the temperature of the inlet air to the humidifier is 63°C.

This shows that the atmospheric air temperature increases with an increase in the fresh water production rates, which obviously increases the efficiency of the desalination. Hence, there is a decrease in the performance of the air conditioning system. Thus for a better performance, the system needs to be optimized. The effect of the system performances can be analyzed by various air and water flow rates, and various inlet water temperatures to the humidifier as shown in Fig. 8.

Figure 8 shows that the performance of the air conditioning unit is decreased when the maximal flow rate and maximum saline water temperature are achieved. Moreover, the performance of the desalination unit is increased, either by increasing the flow rate or decreasing the cooling water temperature. The optimum design parameters of the system are investigated to obtain the maximum performance of the air condition unit of 5.7 when the minimal flow rate of air and water is 10×10^{-3} kg/s, respectively, at a cooling water temperature 15°C. Moreover, the performance of the air conditioning unit is found to be as low as 5.1 when the maximum flow rate of saline water and ambient air is

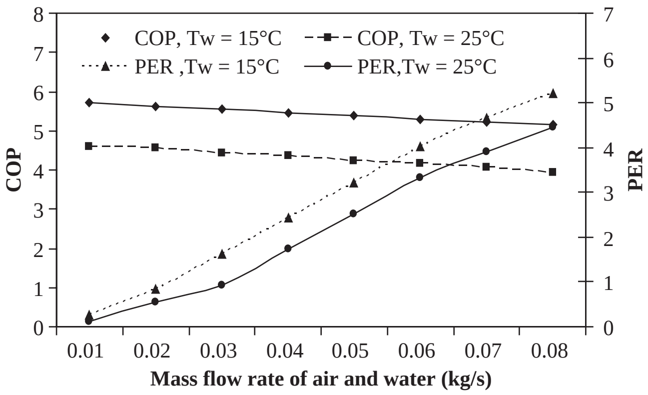

Fig. 8. Effect of system performances at various flow rates of air and water.

80×10^{-3} kg/s and the maximum cooling water temperature to the humidifier is 25°C.

An appreciable performance of 5.1 (of desalination) is achieved when the maximum flow rate of saline water and ambient air to the humidifier is 80×10^{-3} kg/s with a cooling water temperature of 15°C. Moreover, desalination is decreased too low as 0.1 when the minimum flow rate of saline water and ambient air is 10×10^{-3} kg/s and the inlet cooling water temperature is 25°C. The effect of absolute humidity on the system productivity is shown in Fig. 9. It shows that a significant development on the system productivity is observed with an increase in the specific humidity. The maximum fresh water production is 0.2×10^{-3} kg/s with the specific humidity of 0.022 kg of water vapor/kg of dry air.

4. Conclusion

This research work was performed to experimentally investigate the effect of the various parameters, such as operating conditions, and design parameters on the desalination system, using the humidification–dehumidification technique. The results indicated that the water and air mass flow rates have a significant influence on the system productivity. The fresh water production of the system is 1.1×10^{-3} kg/s for 0.07 kg/s of water and air flow rate at temperatures of 18 and 28°C, respectively. The performance efficiency ratio (PER) of the system is also found to be 4.2, which is relatively high compared with that of other desalination processes. In addition, this system requires a lesser compressor power of about 614 W per RT. The performance of the system is strongly affected by the initial water temperature and water flow rate. Moreover, increasing the cooling water mass flow rate and decreasing its temperature leads to a substantial progress in unit productivity. Finally, it is illustrated that the system performance is strongly affected by the air temperature. This system could be efficiently used where the temperature and humidity remain constant throughout the year. If there is a drastic change in these parameters it would lead to an increase in specific power consumption.

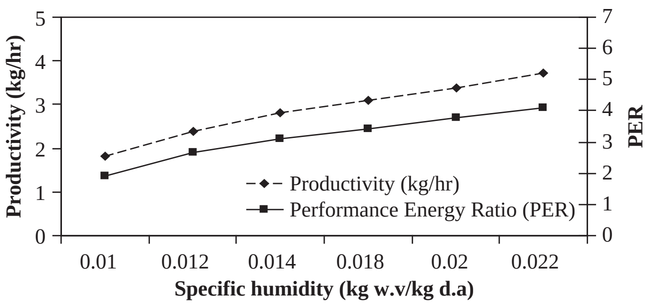

Fig. 9. Effect of absolute humidity on productivity and PER.

Nomenclature

COP	coefficient of performance
W	power input (kW)
ppm	parts per million
TDS	total dissolved solids
MSF	multi stage flashing
RO	reverse osmosis
MVC	mechanical vapor compression
RT	refrigeration tons
PER	Performance energy ratio
m	mass flow rate (kg/s)
T	dry-bulb temperature (°C)
FWP	Fresh water production (kg/ hr)
Q	heat transfer rate (kW)

Greek symbols

ω	humidity ratio (kg (water)/kg (dry air))

Subscripts

w	water
a	air
evp	evaporator
ra	return air
sa	supply air

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