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Solar assisted heat pump desalination system

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Abstract

This paper describes a novel system of solar assisted heat pump desalination. A single effect desalination unit has been designed and fabricated, and it is connected to an existing solar assisted heat pump. The system consists of a compressor, condenser, evaporator, solar evaporator-collector, desalination chamber, feed tank, vacuum pump and distillate collection unit. A vacuum pump is connected to the desalination chamber. A spray nozzle has been used to generate droplets of feed water in the desalination unit. The feed water has been preheated before being sprayed by the nozzle. The desalination unit incorporates both falling film evaporation and flash distillation concepts. A series of experiment has been conducted on the system under different operating and meteorological conditions of Singapore. The effects of feed temperature and flashing have been investigated. The performance ratio and the coefficient of performance (COP) have been evaluated. The performance ratio (PR) obtained from the experiments ranges from 0.77 to 1.15 and COP of the system was found to vary between 5.0 and 7.0.

Keywords: Solar desalination; Heat pump; Performance ratio; Coefficient of performance

1. Introduction

The technology of desalination for sustainable water is well established. As desalination is energy incentive, high investment of capital and cost of fuel are major considerations. The fluctuating prices of crude oil will cause the operating costs of desalination to vary significantly. The depletion of fossil fuels leads to increased applications of the renewable energy resources. The use of solar energy in thermal desalination processes is one of the most promising applications of renewable energy for the conversion of seawater to fresh water [1]. As solar energy is a clean energy source, it is receiving greater attention for various applications using different techniques in view of global energy needs and concern for environmental

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degradation. The potential of seawater desalination using solar energy finds importance in many regions of the world lacking in conventional energy resources, where there are good insolation levels and abundant seawater resources. Solar still has been used for a long time to produce fresh water from seawater and brackish water.

The application of heat pump in water desalination has been receiving attention in terms of its potential for cost reduction. Experimental work on heat pump assisted water purification has been carried out in Mexico since 1981 [2]. It has been found from the analysis that heat pump assisted desalination unit can either be designed as small scale mobile unit to be used in disaster area or scaled up in size to produce potable water for cities at a cost competitive with reverse osmosis and electrodialysis technologies. The potential of heat pump in desalination technologies lies with its capability of reducing consumption of expensive electric power and recovering waste heat.

This paper introduces a single-effect solar assisted heat pump desalination system. Basically, a desalination system has been coupled with an existing heat pump assisted solar hot water supply system. Some preliminary experimental investigations have been made to find the effect of flashing and feed water temperature on the performance of the system.

2. Performance parameters

The important performance parameters of the solar assisted heat pump desalination system are solar evaporator collector efficiency, co-efficient of performance (COP) and performance ratio.

2.1. Solar assisted heat pump

The direct expansion solar assisted heat pump (DX-SAHP) is adopted for this experiment. The working fluid used is a refrigerant and it undergoes a phase change (expands) in the evaporator-collector panel where it is evaporated due to incident solar radiation (Fig. 1).

At the exit of the evaporator-collector, the refrigerant is in a superheated state. Another evaporator coil acts as a condenser for water vapor and the refrigerant leaves in a superheated vapor state due to absorption of latent heat of condensation of water vapor generated in the desalination chamber. Under steady state conditions, the energy balance equation for the evaporator collector is given by Hottel and Whillier equation [3]

$$Q_{evap1} = F_R A_c \left[I_T (\tau\alpha) - U_L (T_f - T_a) \right] \quad (1)$$

Also

$$Q_{evap1} = \dot{m}_{ref1} (h_{10} - h_8) \quad (2)$$

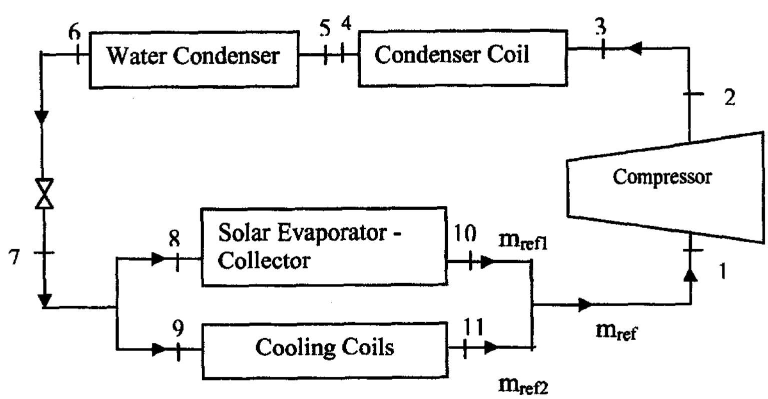

Fig. 1. Schematic diagram of the modified heat pump system.

The efficiency of evaporator-collector η_{evap1} is defined as the ratio of the useful gain over some specified time period to the incident solar energy over the same time period.

$$\eta_{evap1} = \frac{\text{useful energy absorbed}}{\text{energy incident in the plane of collector}} = \frac{\dot{m}_{ref1}(h_{10}-h_8)}{A_c S} \quad (3)$$

Under steady state conditions, the energy balance equation for the condensing coils is given by

$$Q_{evap2} = \dot{m}_{ref2}(h_{11}-h_9) \quad (4)$$

The overall energy balance equation between the evaporator, compressor and condenser is

$$Q_{cond} = Q_{evap1} + Q_{evap2} + W_{comp} \quad (5)$$

Mass flow rate of refrigerant, $\dot{m}_{ref}$ is given by

$$\dot{m}_{ref} = \frac{W_c}{(h_2-h_1)} \quad (6)$$

Refrigerant mass flow rate balance

$$\dot{m}_{ref} = \dot{m}_{ref1} + \dot{m}_{ref2} \quad (7)$$

The coefficient of performance (COP) of the modified heat pump is given by

$$COP_H = \frac{\text{Thermal energy rejected by condensers}}{\text{Energy input to compressor}} = \frac{(h_3-h_4)+(h_5-h_6)}{(h_2-h_1)} \quad (8)$$

2.2. Performance ratio

The performance ratio (PR) is an important parameter describing relative advantages of different desalination systems. The PR of desalination process is commonly defined as kg distillate per 2326 kJ of heat input.

$$PR = \frac{2326 M_v}{\dot{Q}_{in}} \quad (9)$$

where $\dot{Q}_{in}$ is the energy input.

2.3. Thermodynamic flashing

Flashing effect can be utilized when feed water temperature is more than the saturation temperature at that pressure.

If $\Delta T_{superheat}$ is the temperature difference between the feed water and saturation temperature inside the desalination chamber corresponding to its pressure

$$\Delta T_{superheat} = T_F - T_C$$

Applying energy balance,
Latent heat of vapourisation = heat loss due to flashing

$$\dot{m}_f = \frac{\dot{m}_F C_{p,F}(\Delta T_{superheat})}{h_{fg,F}} \quad (10)$$

Here, the feed water is assumed to attain the saturation temperature after flashing.

3. Experiments

The single-effect solar assisted heat pump desalination system was built by combining a desalination chamber with an existing direct expansion solar assisted heat pump (DX-SAHP) system for supplying hot water. The whole experimental set-up consists of a desalination chamber, cooling coil evaporator DX-SAHP, condenser coil acting for falling film evaporation and an additional condenser coil immersed in water to obtain hot water simultaneously and also to ensure complete condensation of refrigerant. The experimental set-up is shown in Fig. 2. Tap water was used for preliminary experimental

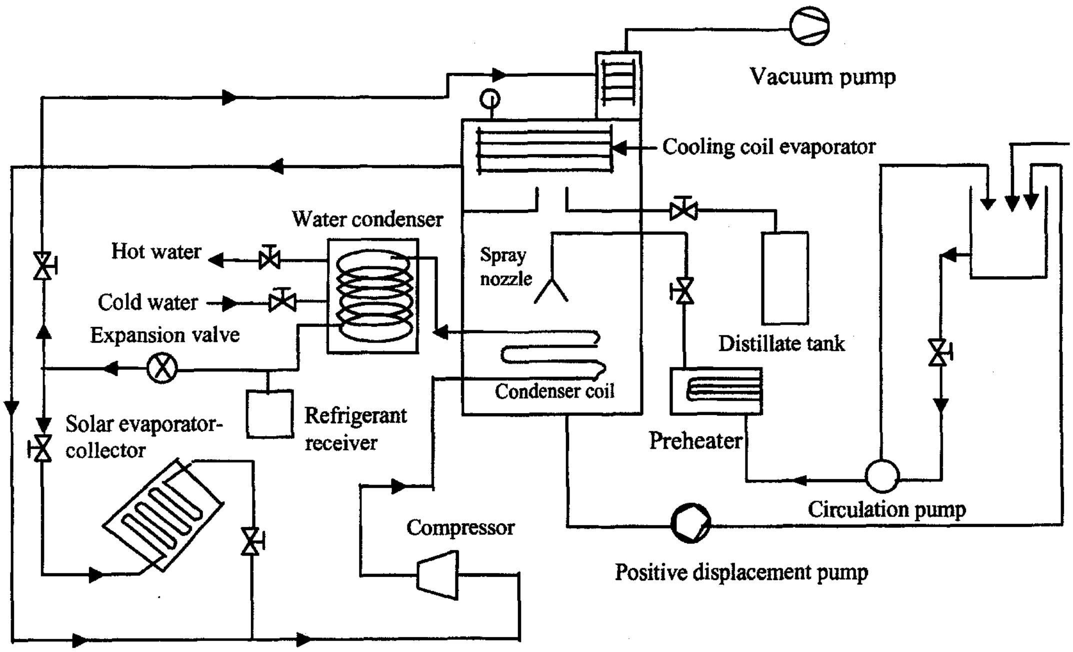

Fig. 2. Schematic diagram of the experimental set-up.

investigations instead of seawater. The desalination chamber consists of condenser coil on the bottom and evaporating coil on the top. A spray nozzle was used to spray the feed water on the condensing coil inside which the refrigerant (R134a) condenses and providing latent heat for the evaporation of the falling film. The resultant water vapor condenses on the evaporator coil located at the top of the chamber. The condensed water is then collected in a distillate tank. Both the chamber and the tank can be maintained at low pressure by vacuum pump.

The solar evaporator-collector is of flat plate type with an area of 1.5 m^2. Refrigerant from the expansion valve enters the evaporator-collector as a two-phase mixture and leaves the evaporator as superheated vapor due to solar heating. A water condenser tank was connected in series to the outlet of the condenser coil in the desalination chamber to remove further heat from the refrigerant so that the refrigerant can enter the expansion valve at subcooled state. The experimental set up was controlled by a variable frequency inverter, which can be adjusted to control the motor speed. The inverter can be preset to the desired frequency (20, 25 and 30 Hz). In this way, the operating condition of the DX-SAHP can be varied. Another variable for the setup is the feed inlet temperature that is maintained by a thermoset.

4. Results and discussion

Experimental studies were conducted for DX-SAHP desalination system under different operating conditions. The operating variables are compressor speed (1200, 1450 and 1800 rpm) and feed water inlet temperature. The effect of flashing was also investigated.

4.1. Effect of flashing

In order to achieve flashing effect, feed water temperature was set to a temperature higher than the saturation temperature corresponding to the pressure inside the chamber. Feed water flow rate has been fixed at 9.54 kg/h and chamber pressure is 0.136 bar. Data have been obtained at different compressor speed. From Fig. 3 it is evident that with the increase of degree of superheat of the feed water, the distillate production increases.

4.2. Performance ratio

The variation of PR with time was computed at an interval of one hour. Using the preheater heat input as the only source of heat, the highest value of PR is 1.15 at 1800 rpm. It is evident from Fig. 4 that a higher value of PR was obtained at higher compressor speed.

4.3. Coefficient of performance

Coefficient of performance of the heat pump had been evaluated at different time of the experiments with different compressor speed. Fig. 5 shows the result at three different speeds of the compressor. It can be seen that the COP, generally, decreases with time during the experiment.

This trend is due to the fact that the condensing temperature increases during the experiment. The water in the tank gets heated up and, hence, the condenser releases less heat. In addition, the higher the compressor speed, the lower the heat pump COP. It is due to the fact that a higher compressor speed lowers the evaporating temperature.

4.4. Solar collector efficiency

The efficiency of the collector at various compressor speeds was evaluated. A maximum experimental efficiency of 88.4% was obtained at 1800 rpm. From Figs. 6 and 7 it is seen that the efficiencies of the collectors increase with an increase in compressor output. A higher compressor speed results in higher mass flow rate. Thus, the refrigerant absorbs more energy with a higher flow rate for the same amount of solar input.

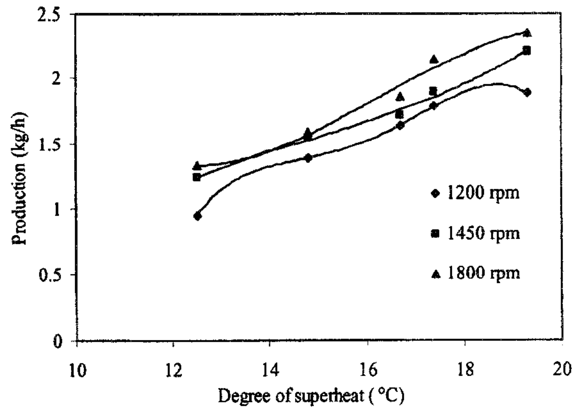

Fig. 3. Effect of flashing on quantity of distillate collected at different compressor speed.

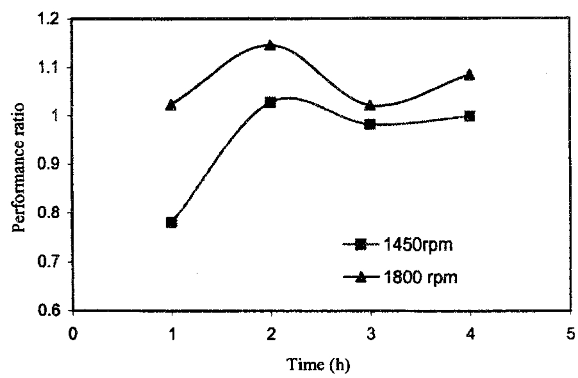

Fig. 4. Performance ratio at different time of the experiment.

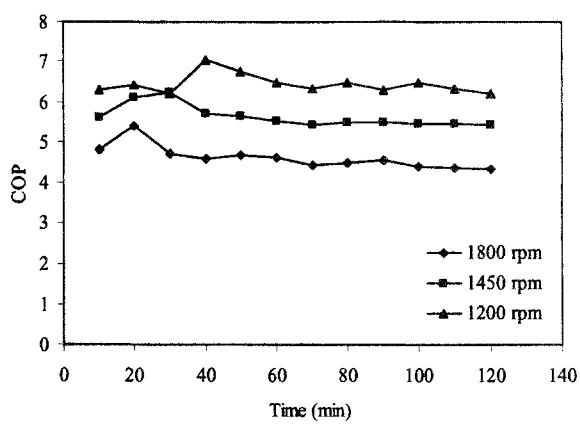

Fig. 5. Variation of coefficient of performance with time at different compressor speed.

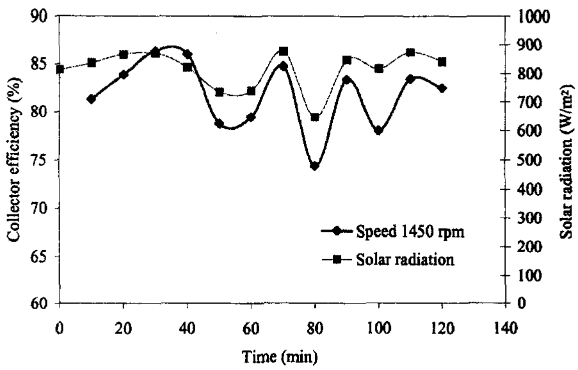

Fig. 6. Variation of collector efficiency with time at 1450 rpm.

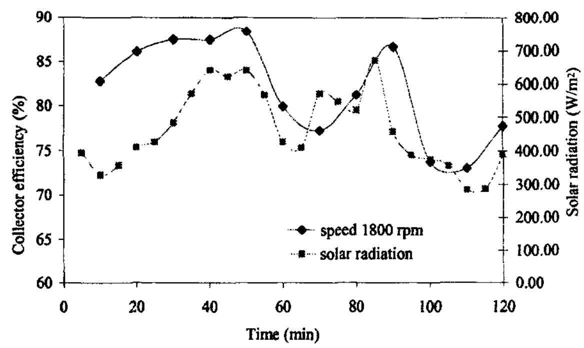

Fig. 7. Variation of collector efficiency with time at 1800 rpm.

5. Conclusions

Some preliminary experimental results of the single-effect solar assisted heat pump desalination system have been presented in this paper. Based on the experimental findings, the performance ratio obtained ranges from 0.77 to 1.15 when heat input is based on preheater only. The co-efficient of the performance (COP) ranges from 5.0 to 7.0. The system can be effectively used for a small scale desalination system whereby hot water can be obtained.

6. Symbols

A_c — Area of collector, m^2
A_e — Area of evaporator, m^2
C_P — Specific heat, kJ/kg
F_R — Collector heat removal factor
h — Enthalpy, kJ/kg
h_{fg} — Enthalpy of vaporization, kJ/kg
I_T — Solar irradiation on the collector surface, W/m^2
m_{ref} — Mass flow rate of refrigerant, kg/s
M_v — Amount of distillate, kg
Q_{evap} — Heat in put in evaporator, W
Q_{in} — Heat input, W
S — Absorbed irradiation, W/m^2
T_a — Air temperature, K
T_c — Saturation temperature, K
T_f — Collector fluid temperature, K
U_L — Collector overall loss coefficient, W/m^{2}K
W_c — Compressor work input, W
$\tau\alpha$ — Transmittance absorptance product

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