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Analysis of solar desalination system using heat pump

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ABSTRACT

This paper investigates a pilot desalination system which consists of a direct expansion solar assisted heat pump (DXSAHP) coupled to a single-effect evaporator unit. The working fluid used is R134a and distillate is obtained via falling film evaporation and flashing in the unit. Experiments have been conducted in both day and night meteorological conditions in Singapore and the effects of solar irradiation and compressor speed have been studied against the system performance. From the experiments, the Performance Ratio (PR) obtained ranges from 0.43 to 0.88, the average Coefficient of Performance (COP) was 8 and the highest distillate production recorded was 1.38 kg/h.

1. Introduction

Desalination has enabled conversion seawater and brackish water into portable water and alleviated water shortages in some parts of the world, especially in the Middle East and island nations. As global population increases while more water sources get polluted, desalination will play an increasing prominent role. Desalination processes are energy intensive and costs [1]. Kalogirou [2] and Miller [3] pointed out that reducing energy consumption can have a major impact on overall water costs. Tzen and Morris [4] proposed the use of RES coupled with existing technologies as one method whereby reliance on fossil fuels can be reduced, desalination costs can be lowered in the long run and does not result in environmental degradation. In their study, Rodriguez and Camacho [5] considered the use of solar energy as one of the most promising applications of renewable energy for desalination. Furthermore, K. Thu et al. [6–8] and KC Ng et al. [9] had researched on renewable adsorption desalination technology and concluded that the introduction of solar significantly reduce energy consumption in water production.

Solar energy is the cleanest and most inexhaustible of all known energy resources. The low temperature thermal requirement of a heat pump makes it an excellent match for the use of solar and ambient energy [10]. Furthermore, in the conventional air con system in one end cools the room on the other end dumped energy into the environment leading to global warming. This dumped heat is termed as ‘waste heat’ [11] and can be utilized for useful purposes. A combination of solar energy and heat pump can improve the quality of the energy available and shows potential for different applications. The evaporator–collector used in such system can absorb both solar and ambient energy [12]. Hawlader et al. [13], Lu et al. [14] and Chyng [15] used solar assisted heat pump (SAHP) to produce hot water. Due to low operating temperature, the evaporator–collector absorbed both solar energy and ambient energy. Hawlader et al. [16] conducted series of experiments on an integrated solar assisted heat pump system (SAHPS) for the application of water heating, drying and air-conditioning. At the National University of Singapore, Solar Assisted Heat Pump (SAHP) systems for application for desalination were built for the evaluation of performance under the metrological condition of Singapore for various thermal applications. In this paper, a SAHP in conjunction with the single-effect desalination has been used to evaluate performance of the system to capitalize on the abundant sunshine in Singapore.

2. Heat pump desalination

The heat pump is a useful device in transforming low-grade heat from the air, ground and solar radiation into a usable source. Furthermore heat pumps also help to recycle waste heat to drive the system, thereby reducing energy consumption and make the system economically viable [17]. Experimental work had been done on the use of heat pumps for desalination in Mexico since 1981, and Siqueiros and Holland [18] found that the cost to produce potable water for cities was competitive to that of RO (Reverse Osmosis) and ED (Electro-Dialysis). Slesarenko [19] also calculated that

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connecting a heat pump to a thermal desalination plant could increase the economical and thermodynamic factors by 2–3 times.

Abou-Ziyan [20] showed that the performance of SAHP was better than conventional heat pump systems and also that the use of refrigerant R134a gave higher coefficient of performances over R22 and R404a.

3. Analytical model

The desalination system is assessed on Performance Ratio (PR), Coefficient of Performance (COP) and distillate production rate. To derive these performance indicators, a model of the SAHP system is developed.

3.1. Solar assisted heat pump

In an ideal Rankine cycle, the refrigerant enters the compressor as a saturated vapor (stage 1). It is superheated to a higher pressure and temperature (stage 2) before going into the condenser. After heat rejection Q_H, the refrigerant leaves as a saturated liquid (stage 3) and is throttled back to the evaporator pressure by passing through the expansion valve (stage 4). Refrigerant enters the evaporator as a low quality mixture and completely evaporates by absorbing heat, Q_L, from the surroundings. The modified system in this project (Fig. 1) consists of a compressor, two condenser coils, an expansion valve, a solar collector–evaporator and a cooling coil.

Under steady state condition, the useful energy output of a flat-plate solar collector, Q_u, is given by Hottel–Whillier [21] equation as the difference between absorbed solar radiation and the thermal loss, where A_C is area of the collector and F_R the collector heat removal factor.

$$Q_u = A_c F_R[S - U_L(T_i - T_a)] \tag{1}$$

This is also equivalent to the enthalpy change of refrigerant passing through the collector multiplied by the relevant mass flow rate, $m_{r,1}$, through the collector.

$$Q_{u,1} = m_{r,1}(h_{12} - h_{11}) = Q_u \tag{2}$$

The collector efficiency is defined as the ratio of the useful gain in a time period over the corresponding incident solar energy.

$$\eta = \frac{\int Q_u \mathrm{d}t}{A_c \int G_T \mathrm{d}t} \tag{3}$$

The energy balance equation of the cooling coil under steady state is [22]

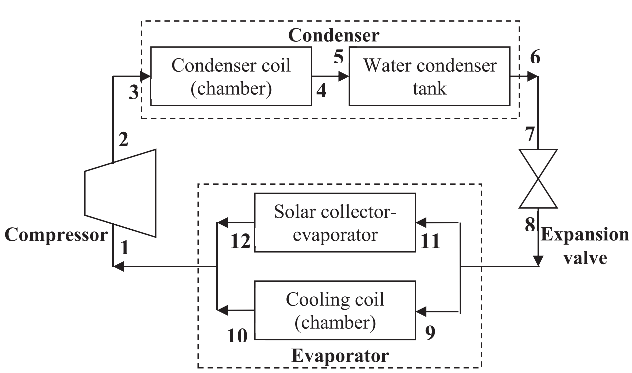

Fig. 1. Schematic diagram of SAHP (refer for numbered subscripts in equations).

$$Q_{u,2} = m_{r,2}(h_{10} - h_9) = m_{cond} \times h_{fg,sat} \tag{4}$$

The work input of the compressor can be found using

$$W_{comp} = m_{r,t}(h_2 - h_1) \tag{5}$$

where

$$m_{r,t} = m_{r,1} + m_{r,2} \tag{6}$$

For the first condenser coil which is in the chamber, the energy change is

$$Q_{c,1} = m_{r,t}(h_4 - h_3) \tag{7}$$

and the second condenser coil in the water tank which heats up incoming feedwater,

$$Q_{c,2} = m_{r,t}(h_6 - h_5) \tag{8}$$

Hence a simple overall energy balance of the system, assuming negligible heat loss to the ambient and working components, is given by

$$Q_{c,1} + Q_{c,2} = Q_{u,1} + Q_{u,2} + W_{comp} \tag{9}$$

3.2. Distillate production

In the process of thermodynamic flashing, the liquid is exposed to a sudden pressure drop below the saturation vapor pressure corresponding to the feedwater temperature. Part of this liquid vaporizes to regain equilibrium under adiabatic conditions, and the latent heat of vaporization is drawn from the remaining liquid whose temperature drops towards the saturation temperature of the chamber. The distillate obtained is

$$m_f = \frac{m_{feedwater} C_p \left(T_{feedwater} - T_{sat}\right)}{h_{fg,sat}} \tag{10}$$

After flashing, the remaining feedwater fall onto the condenser coil at the bottom of the chamber. Assuming that the condenser coil tubing is wetted uniformly by a thin continuous film of water, heat transfer occurs between the superheated refrigerant in the coil and the film which is near or at the saturation temperature. Hence

$$m_{evap} = \frac{m_{r,t}(h_4 - h_3)}{h_{fg,sat}} \tag{11}$$

3.3. Performance indicators

3.3.1. PR (Performance Ratio)

It is defined as the amount of distillate produce per 2326 kJ of heat input or number of pounds of distillate produce per 1000 Btu of heat.

$$PR = \frac{2326 m_{d,actual}}{Q_{in}} \tag{12}$$

where

$$Q_{in} = Q_{preheater} + W_{comp} \tag{13}$$

and

$$Q_{preheater} = m_{feedwater} C_p \left(T_{feedwater} - T_{feedtank}\right) \tag{14}$$