NUMERICAL SIMULATION OF A HEAT PUMP ASSISTED REGENERATIVE SOLAR STILL WITH PCM HEAT STORAGE FOR COLD CLIMATES OF KAZAKHSTAN

by

Yessen SHAKIR[a], Balzhan SAPAROVA[a], Yerzhan BELYAYEV[a,d*], Aidarkhan KALTAYEV[a,d], Mohanraj MURUGESAN[b], and Jayaraj SIMON[c]

[a] Department of Mechanics, Al-Farabi Kazakh National University, Almaty, Kazakhstan
[b] Department of Mechanical Engineering, Hindusthan College of Engineering and Technology, Coimbatore, Tamil Nadu, India
[c] Department of Mechanical Engineering, National Institute of Technology, Calicut, India
[d] Department of Applied Mechanics and Engineering Graphics, Satbayev University, Almaty, Kazakhstan

Original scientific paper
https://doi.org/10.2298/TSCI17S2411S

A numerical model has been proposed in this work for predicting the energy performances of the heat pump assisted regenerative solar still with phase changing material heat storage under Kazakhstan climates. The numerical model is based on energy and mass balance. A new regenerative heat pump configuration with phase changing material heat storage is proposed to improve the performance. A comparison of results has been made between the conventional solar still and heat pump assisted regenerative solar still with phase changing material. The numerical simulation was performed for wide range of ambient temperatures between –30 and 30 °C with wide range of solar intensities between 100 and 900 W/m^2. The numerical simulation results showed that heat pump assisted regenerative solar still is more energy efficient and produce better yield when compared to the conventional simple solar still. The influences of solar intensity, ambient temperature, different phase changing materials, heat pump operating temperatures are discussed. The predicted values were found to be in good agreement with experimental results reported in literature.

Key words: *solar stills, phase changing material heat storage, heat pumps, cold climates, Kazakhstan*

Introduction

Kazakhstan is experiencing an acute shortage of water resources for the needs of industry, agriculture, and domestic drinking water. However, in Kazakhstan there are huge reserves of groundwater, including brackish water. There are the Caspian Sea and Balkhash Lake also. The production of clean water using various desalination technologies is a very important task for the socioeconomic development of Kazakhstan. In previous work [1], the performance of a heat pump assisted regenerative solar still was numerically simulated for the cold climates of Kazakhstan without heat storage. It was reported that the integration of a heat pump with a solar still has increased the productivity by 2-3 times when compared to conven-

* Corresponding author, e-mail: yerzhan.belyayev@gmail.com

tional solar still. In another work [2], an experimental investigation of a solar still equipped with an external latent heat storage system and evacuated tube collectors was presented. A maximum yield and daily efficiency of about 6.5 kg/m^2 day and 50% were obtained for a solar still with an external condenser filled with phase changing material (PCM). In a similar work [3], experiments have been conducted with sand and servo thermo medium oil as sensible heat storage medium in a single slope single basin solar still. The sand and servo therm medium oil showed higher productivity when compared to conventional still. Similarly, exergy analysis of a solar still combined with latent heat storage system was reported for the meteorological conditions of Morocco [4]. It was reported that the instantaneous exergy efficiency of the solar still is less than 5% during the daytime but there are some cases where it exceeds 80% at night-time due to the presence of latent heat storage medium. A double passes solar air collector, coupled with modified solar still packed with PCM, have been experimentally investigated [5]. The results showed that, the productivity approximately improved to 9.36 (L/m^2 day) for the double passes solar air collector-coupled modified solar still when compared to the conventional solar still, which has 4.5 (L/m^2 day). The research and developments of solar assisted heat pumps reported during last two decades were consolidated in a comprehensively review reported [6, 7]. The heat pump integration with solar still has significantly improved the yield when compared to the conventional solar stills [8, 9]. All the mentioned theoretical and experimental work was presented for warm climatic conditions where additional heating elements, such as a heat pump, were not used. Hence, the present research focus on numerical simulation of a heat pump assisted regenerative solar still integrated with PCM has been carried out under the climatic conditions of Almaty city in Kazakhstan. A numerical algorithm to study performance of heat pump assisted regenerative solar still with PCM heat storage system has been developed.

System description

The schematic diagram of the heat pump assisted regenerative solar still, which will be used to conduct experiments is depicted in fig. 1. The heat pump assisted regenerative solar still consists of a R134a heat pump (using 500 W power input hermetically sealed reciprocating compressor, a shell and coil type condenser with paraffin wax thermal storage, a liquid re-

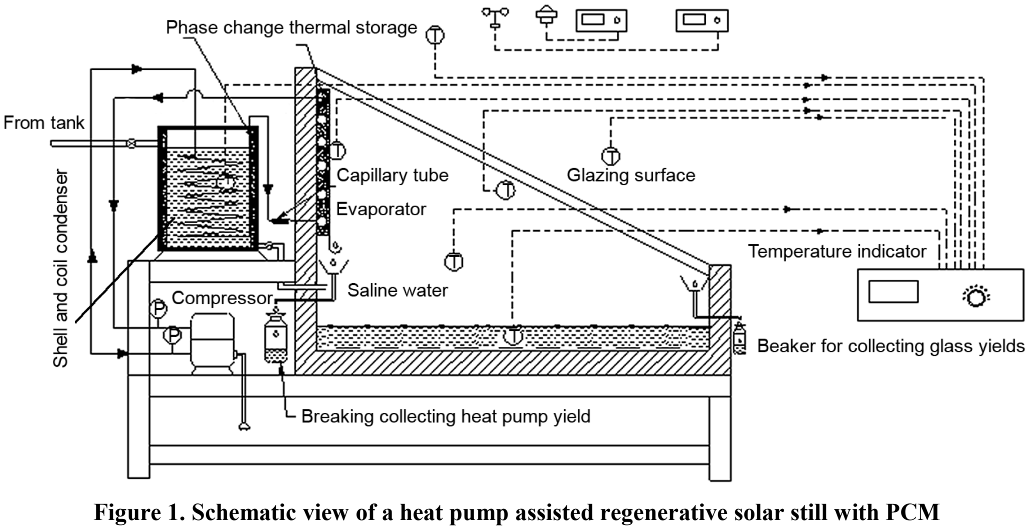

Figure 1. Schematic view of a heat pump assisted regenerative solar still with PCM

ceiver, a sealed-type refrigerant drier, a capillary tube expansion device and plate type evaporator dipped in brine solution (heat storage medium) integrated with a basin area of 1 m^2 to store brackish water. Two separate provisions have been made for collecting the condensate produced through the glass and also through the evaporator. The heat rejected in the condenser is used for preheating the water before entering into the basin. The preheating of water has enhanced the rate of evaporation in the basin. The evaporator inside the solar still is maintained below the dew point temperature, which influences the rate of condensation. During, the latent heat of the vapor is released, which is absorbed by the evaporator and pumps to the condenser. The water in the basin is heated by direct incident solar radiation transmitted through the glazing surface and also due to the effect of water preheating before entering the basin.

Mathematical model

The following assumptions are made for simulation of a regenerative solar still [1, 8, 9].

- All the proceses are steady-state.
- Pressure drop, potential, kinetic, and chemical effects are assumed to be negligible in heat pump circuit.
- Compression of the refrigerant vapor is assumed to follow a polytrophic process.
- Expansion of refrigerant liquid is considered to be isenthalpic.
- Uniform water temperature was maintained inside the still.
- Vapor losses from the still are negligible.
- Conduction losses inside the still are negligible.

Energy balance equations for different part of heat pump assisted regenerative solar still are as follows:

- Energy balance for glass cover

$$m_{\mathrm{g}} C_{\mathrm{g}} \frac{\mathrm{d}T_{\mathrm{g}}}{\mathrm{d}t} = (1-\rho_{\mathrm{g}})\alpha_{\mathrm{g}} G_{\mathrm{H}} + (q_{\mathrm{ev,w\text{-}g}} + q_{\mathrm{r,w\text{-}g}} + q_{\mathrm{c,w\text{-}g}}) - q_{\mathrm{r,g\text{-}a}} + q_{\mathrm{c,g\text{-}a}} \tag{1}$$

- Energy balance for the evaporator

$$m_{\mathrm{e}} C_{\mathrm{e}} \frac{\mathrm{d}T_{\mathrm{e}}}{\mathrm{d}t} = q_{\mathrm{c,w\text{-}e}} + q_{\mathrm{ev,w\text{-}e}} - q_{\mathrm{ev,f}} \tag{2}$$

- Energy balance for the water

$$m_{\mathrm{w}} C_{\mathrm{w}} \frac{\mathrm{d}T_{\mathrm{w}}}{\mathrm{d}t} = (1-\rho_{\mathrm{g}})(1-\alpha_{\mathrm{g}})\alpha_{\mathrm{w}} G_{\mathrm{H}} - (q_{\mathrm{ev,w\text{-}g}} + q_{\mathrm{r,w\text{-}g}} + q_{\mathrm{c,w\text{-}g}}) \frac{A_{\mathrm{g}}}{A_{\mathrm{w}}} + q_{\mathrm{c,b\text{-}w}} + \frac{W}{A_{\mathrm{w}}} \tag{3}$$

- Energy balance for the absorber

$$m_{\mathrm{b}} C_{\mathrm{b}} \frac{\mathrm{dT}_{b}}{\mathrm{d}t} = (1-\rho_{\mathrm{g}})(1-\alpha_{\mathrm{g}})(1-\alpha_{\mathrm{w}})\alpha_{\mathrm{b}} G_{\mathrm{H}} - q_{\mathrm{c,b\text{-}w}} - q_{\mathrm{c,b\text{-}pcm}} \tag{4}$$

- Energy balance for the PCM

$$M_{\mathrm{eq}} \frac{\mathrm{d}T_{\mathrm{pcm}}}{\mathrm{d}t} = q_{\mathrm{c,b\text{-}pcm}} - q_{\mathrm{loss}} \tag{5}$$

where M_{eq} is the equivalent heat capacity of PCM [10], and it is indicated in different phases of the PCM during the process of state change from solid to liquid as follows:

$$M_{\mathrm{eq}} = m_{\mathrm{pcm}} C_{\mathrm{s,pcm}} \qquad \text{for} \qquad T_{\mathrm{pcm}} < T_{\mathrm{m}}$$
$$M_{\mathrm{eq}} = m_{\mathrm{pcm}} L_{\mathrm{pcm}} \qquad \text{for} \qquad T_{\mathrm{m}} \le T_{\mathrm{pcm}} < T_{\mathrm{m}} + \delta'$$
$$M_{\mathrm{eq}} = m_{\mathrm{pcm}} C_{\mathrm{l,pcm}} \qquad \text{for} \qquad T_{\mathrm{pcm}} > T_{\mathrm{m}} + \delta'$$

The rate of condensation is estimated:

$$\frac{\mathrm{d}m_{\mathrm{c}}}{\mathrm{d}t} = \frac{q_{\mathrm{ev,w}}}{H_{\mathrm{w}}} = \frac{A_{\mathrm{w}} q_{\mathrm{ev,w\text{-}g}} + A_{\mathrm{e}} q_{\mathrm{ev,w\text{-}e}}}{A_{\mathrm{w}} H_{\mathrm{w}}} \tag{6}$$

Method of solution

Numerical algorithm for solution of eqs. (1)-(6) based on the fourth order Runge--Kutta method [1]. Computer program for implementation of numerical algorithm developed by means of C++ programming language. As the initial conditions for temperature at the different part of the heat pump assisted solar still ambient temperature were assumed. At the first time step this temperature value was used to calculate convective and radiative heat transfer coefficients. Based on this values and physical properties temperatures at the different positions of the system were calculated. The basic system parameters assumed in numerical simulation are listed in tab. 1 [9].

Table 1. Basic parameters of the heat pump assisted solar still

Parameter	Symbol	Value	Unit
Mass of the glass cover	m_{g}	10.12	kgm^{-2}
Specific heat of glass	C_{g}	800	Jkg^{-1}°C^{-1}
Absorptivity of glass	σ_{g}	0.0475	–
Reflectivity of glass	ρ_{g}	0.0735	–
Mass of water	m_{w}	20.60	kgm^{-2}
Specific heat of water	C_{w}	4178	Jkg^{-1}°C^{-1}
Absorptivity of water	σ_{w}	0.05	–
Mass of plate absorber	m_{b}	15.60	kgm^{-2}
Specific heat of plate absorber	C_{b}	480	Jkg^{-1}°C^{-1}
Absorptivity of plate absorber	σ_{b}	0.95	–
Thermal conductivity of plate absorber	k_{b}	16.30	Wm^{-1}K^{-1}
Thermal conductivity of insulation	k_{i}	0.039	Wm^{-1}K^{-1}
Mass of evaporator	m_{e}	7.35	kgm^{-2}
Specific heat of evaporator	C_{e}	385	Jkg^{-1}°C^{-1}

Results and discussion

A numerical modeling for predicting the energy performances of a heat pump assisted regenerative solar still with PCM heat storage was developed and simulated for Fort-Shevchenko town of Kazakhstan on the eastern shore of Caspian Sea. Kazakhstan is one of the leading countries in the Central Asian region with the average annual solar radiation potential. Kazakhstan has four climatic conditions such as, winter, summer, autumn, and spring. Annual duration of sunshine is 2200-3000 hours, and the estimated capacity of 1300-1700 kW per 1 m^2 per year, which exceeds that of Northern and Central Europe. The average solar irradiation observed during the year 2016 is illustrated in fig. 2 for Fort-Shevchenko town. From fig. 2, it is confirmed that the monthly average solar irradiation of about 600 W/m^2 was observed during the month of June 2016. The length of potential sunshine was about 5 hours during winter climates and about 12 hours during summer climates. During winter climates, the average solar irradiation was observed to be about 100 W/m^2 for the period of four months. The average solar irradiation will be above 400 W/m^2 for the period of six months. Remaining two months have solar irradiation potential in the range between 200 and 300 W/m^2. Similarly, the yearly ambient temperature variations are illustrated in fig. 3. From fig. 3, it is confirmed that, the average ambient temperature was varied between 262 and 296 K. Due to low ambient temperature, the glazing surface was maintained at low temperatures, which ensures good moisture condensation. The wind velocity variations are depicted in fig. 4. It is observed that the wind velocity was varied between 2 and 3 m/s. Monthly average relative humidity is presented in fig. 5.

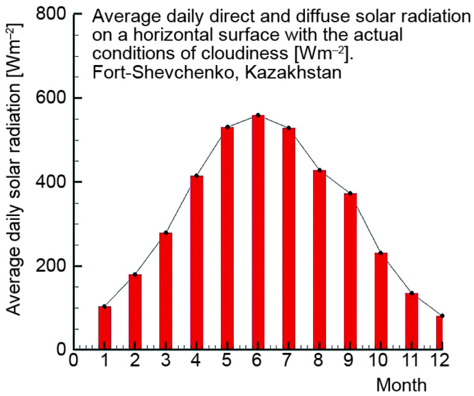

Figure 2. Monthly average solar irradiation

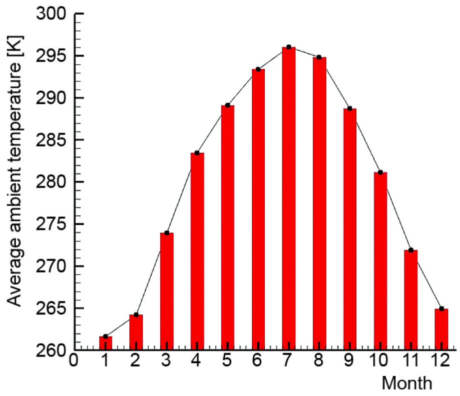

Figure 3. Monthly average ambient temperature

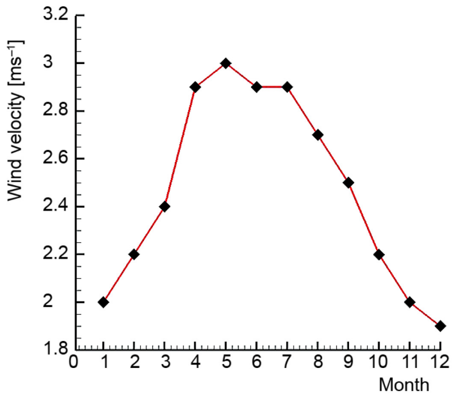

Figure 4. Monthly average wind velocity

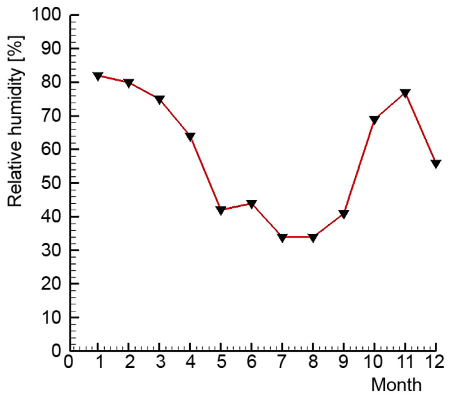

Figure 5. Monthly average relative humidity

In fig. 6 (Fort-Shevchenko town for July), the simulated temperature variations at typical locations inside the solar still were depicted. Temperatures at typical locations inside the solar still were numerically simulated under the influence of phase change materials and compared with the heat pump assisted solar still without phase change materials. From fig. 6, it is observed that, at the beginning of the day the temperatures gradually increase, reaching maximum at 12 and 14 hours, then gradually decreased. Due to the high absorption coefficient of the absorption plate with black paint, its temperature reaches a maximum value of 86.6 and 99.7 °C in July with and without PCM, respectively. The temperature of the glass is

74.2 and 83 °C with and without PCM. Almost 20 °C differences between absorber and glass temperatures are due to convective heat exchange with ambient air and water vapor condensation at the evaporator. Water temperature is 92 °C without PCM. In the case of PCM packed configuration, the water temperature was raised to 84 °C. The PCM temperature is 66.5 °C. In fig. 7, the productivity of heat pump assisted regenerative solar still with and without PCM are shown. More than 75% of condensed water is produced by evaporator comparing to glass cover. More quantity of water gets condensed over the cold surfaces of the evaporator plates. The yield obtained by glass and evaporator without using PCM are high when compared to configuration using PCM due to the absorption of heat by the PCM.

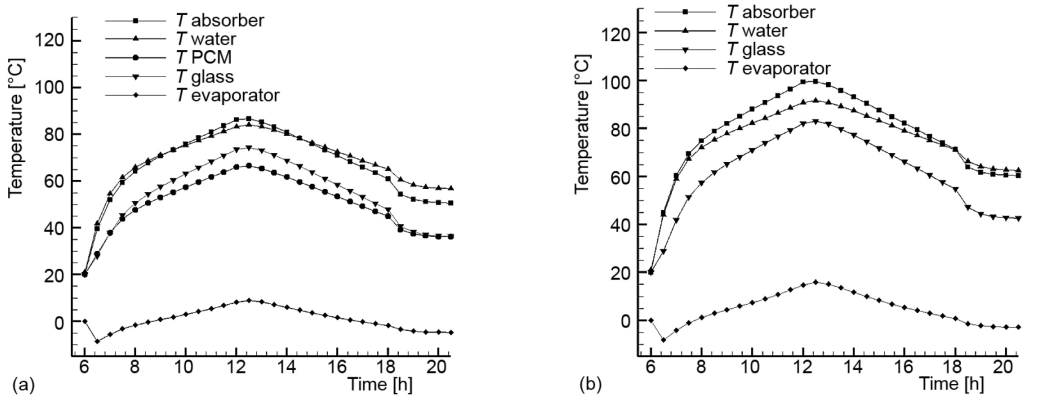

Figure 6. The temperature variation of the different solar still parts; (a) with PCM, (b) without PCM

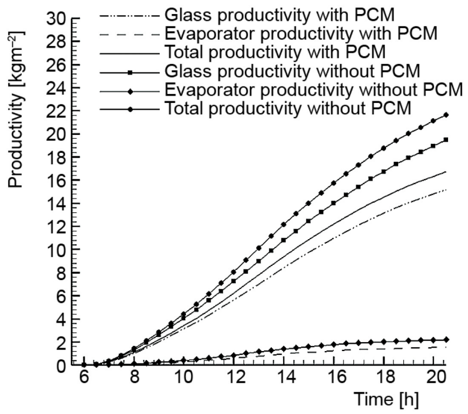

Figure 7. Productivity of still under different modes of operation

The water temperature variations with and without heat pump are depicted in fig. 8. It is observed that, the water temperature without a heat pump is much lower than with its inclusion. Also after 6 p. m., the water temperature drops to the level of the environment. Whereas the heat pump integration with the solar still has maintain the water temperature in the range of 60 °C during night hours. In fig. 9, the temperature variations without heat pump under the influence of PCM are illustrated. The paraffin 62 was selected as a PCM in this work. The melting temperature of paraffin 62 is in the range between 52 and 60 °C. It was assumed as 54 °C in this simulation work.

About 6 °C temperature was observed by integrating the PCM in the still. The solar still absorbs more heat during its phase change. The maximum temperature of paraffin reaches 57 °C. This temperature is not sufficient for melting PCM. The energy efficiency and the average daily fresh water production for each month are plotted in fig. 10. According to fig. 10, the minimum efficiency is observed in January – 43%, the maximum in August – 54%. The energy efficiency of a heat pump assisted regenerative solar still is the ratio of evaporative heat transfer to the solar radiation intensity on the absorber plate and power input to the heat pump [10].

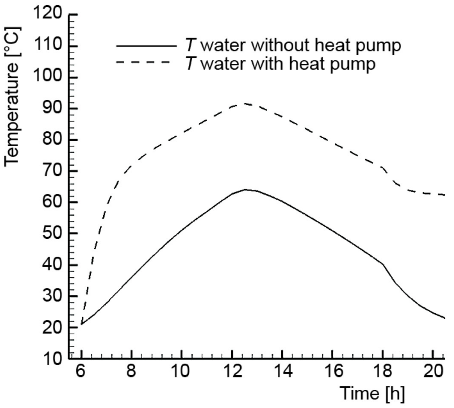

Figure 8. Basin water temperature variation with and without heat pump

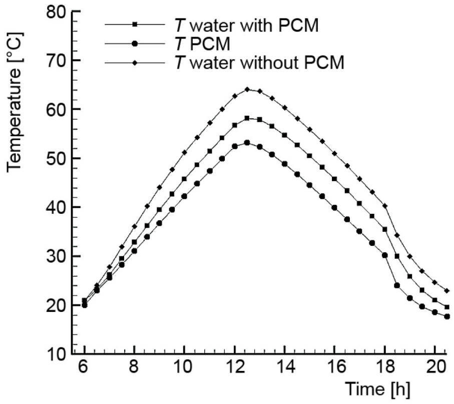

Figure 9. Temperature of water and PCM inside the still

Conclusions

Numerical results showed that integration of heat pump with solar still has improved the productivity of solar still when compared to conventional solar still. The following major conclusions are drawn from this research.

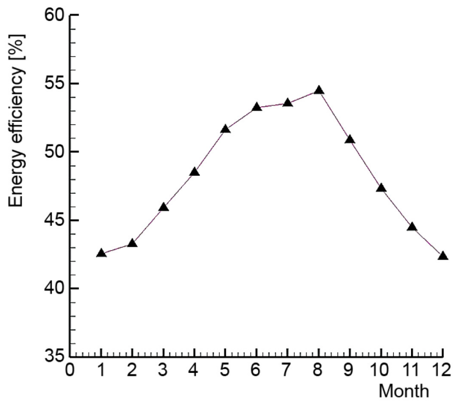

Figure 10. Variations of energy efficiency with months

- The integration of heat pump with the conventional solar still has significantly increases the productivity to 16 liters per day per m^2.
- The heat pump system integrated with solar still preheats the water before entering into the basin and also recovers the heat inside the solar still during condensation of vapor.
- Numerical results are compared with preliminary experimental results. It was observed that the temperature difference was observed within ±3 °C.
- The integration of heat storage with the heat pump has retained the heat for longer duration, which improves the performance rate of evaporation.
- The phase change material packed in the evaporator maintains consistent cooling effect and maintain below the dew point temperature of air-vapor mixture.
- The results confirmed that, the heat pump assisted regenerative solar still is a good option for producing good quality drinking water

Further, the economical and environment feasibility of the proposed configuration are progressing in authors research laboratory.

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Paper submitted: March 22, 2017
Paper revised: May 26, 2017
Paper accepted: August 30, 2017