Bulgarian Chemical Communications, Volume 48, Special Issue E (pp. 126 - 132) 2016

Numerical simulation of a heat pump assisted regenerative solar still for cold climates of Kazakhstan

Ye. Shakir[1], M. Mohanraj[2], Ye. Belyayev[1*], S. Jayaraj[3], A. Kaltayev[1]

[1]*Department of Mechanics, Al-Farabi Kazakh National University, Almaty, Kazakhstan*
[2]*Department of Mechanical Engineering, Hindusthan College of Engineering and Technology, Coimbatore, India*
3Department of Mechanical Engineering, National Institute of Technology, Calicut, India

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

Keywords: solar stills, heat pumps, cold climates, Kazakhstan

INTRODUCTION

Water is the main element and it is essential for all forms of life; for the existence of natural ecosystems, social and economic development of any country. Fresh water on Earth is just 3%. In addition, water resources are distributed according to the land surface is extremely uneven. By 2025, according to UN forecasts, the acute shortage of water will be experienced by more than 2.8 billion people. Increasing water scarcity is caused by the growing world population and the development of the global economy and climate change.

To date, as a result of combination of anthropogenic and natural factors the desertification processes in varying degrees subject to more than 70% of the territory of Kazakhstan. For example, the Aral Sea dried up almost 90%. Kazakhstan is experiencing an acute shortage of water resources for the needs of industry and agriculture and for drinking water.

This problem can be partially solved by the introduction of desalination systems, particularly solar desalination. The solar still integrated with external condenser increases the productivity of distillate by 2-3 times. In this paper the common use of heat pump with a solar distiller is proposed. In addition to cold climates use the heat pump for pre-heating of water is justified. Comprehensive discussion of using heat pump as the source of heat energy for desalination of seawater is presented in paper [1]. In paper [2] the technology of desalination based on freezing using a heat pump is discussed. According to ref. [2] COP of the heat pump is in the range of 8 to 12, which results in specific energy consumption in the range of 9 to 11 kWh/m^3 of produced water. In the following works [3-9] combination of desalination system with absorption heat pump is considered, whereas in other studies [10-13] integration with a compression heat pump is performed. LiBr–H_2O absorption heat pump desalination system thermal performance is studied in [3-4, 7]. For example, in [3] thermal and economic performance comparison between absorption heat pump and ejector heat pump water desalination system has been conducted. The results show that the absorption heat pump has a more favorable thermal performance than the ejector heat pump only in certain parameters ranges. In [7] it is shown that thermal performance ratios of the absorption heat pump desalination system of 2.4–2.8, which are higher by 50–70% than those for the single-effect thermal vapor compression system. The superior performance of high temperature operation for the absorption heat pump single-effect system makes it extremely suitable for adoption by remote and small communities [7]. Solar assisted heat pump desalination system performance character-ristics under meteorological conditions of Singapore have been investigated in [11]. The performance

* To whom all correspondence should be sent:
yerzhan.belyayev@gmail.com

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 [11]. The simulation results of the paper [12] showed that the efficiency of the solar still with compression heat pump is 75% higher than that of the conventional solar still. In this paper we investigate numerically the thermal performance of the solar desalination in coupled with a heat pump under meteorological conditions of Kazakhstan.

SYSTEM DESCRIPTION

The schematic diagram of the proposed heat pump assisted regenerative solar still is depicted in Fig.1. The system used consists of a 500 W hermetically sealed reciprocating compressor, a shell and coil type condenser, plate type evaporator with basin area 1 m^2 that accommodates brackish water. The heat release from condenser during the condensation of R134a preheat the water before entering to the basin, moreover, the solar intensity transmitted through the glazing surface is also used to heat the water and makes the brackish water to evaporate. The evaporated water will start condensate on the back side of glazing surface, which will be collected separately as glass yield. The evaporator placed inside the still will also dehumidify vapor mixture and collected separately as an evaporator yield. The heat rejection in the condenser has maintained constant water temperature inside the basin even there is fluctuating in solar intensity and daily off sunshine hours.

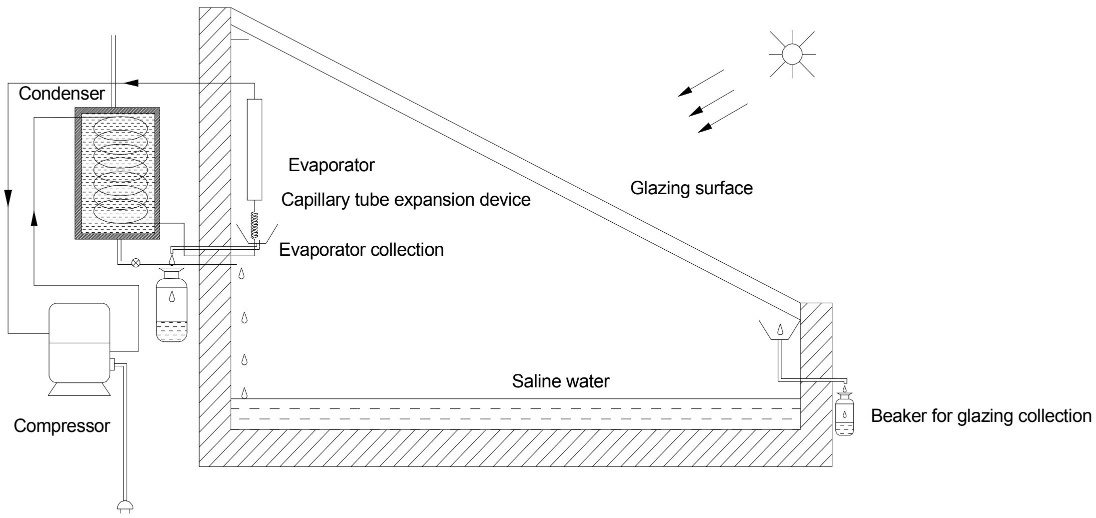


Fig.1. Schematic view of the heat pump assisted regenerative solar still

MATHEMATICAL MODEL

To simulate the performance of heat pump assisted regenerative solar still the following mathematical model according to [12] was formulated. Basic assumptions of mathematical model:

1) all the process are steady state;
2) pressure drop, potential, kinetic and chemical effects are assumed to be negligible in heat pump circuit;
3) compression of the refrigerant vapor is assumed to follow a polytrophic process;
4) expansion of refrigerant liquid is considered to be isenthalpic;
5) the water temperature gradient is negligible;
6) vapor losses through the side, as well as other losses are negligible;
7) the heat conduction within the still is negligible.

According to [12] energy balance equations for different part of heat pump assisted regenerative solar still are as follow:

Energy balance for glass cover:

$$m_g \cdot C_g \cdot \frac{dT_g}{dt} = (1-\rho_g)\cdot \alpha_g \cdot G_H + (q_{ev,w-g} + q_{r,w-g} + q_{c,w-g}) - \\ - q_{r,g-a} + q_{c,g-a} \quad (1)$$

Energy balance for the evaporator

$$m_e \cdot C_e \cdot \frac{dT_e}{dt} = q_{c,w-e} + q_{ev,w-e} - q_{ev,f} \quad (2)$$

Energy balance for the water

$$m_w \cdot C_w \cdot \frac{dT_w}{dt} = (1-\rho_g)\cdot(1-\alpha_g)\cdot \alpha_w \cdot G_H - \\ -(q_{ev,w-g} + q_{r,w-g} + q_{c,w-g})\cdot \frac{A_g}{A_w} + q_{c,b-w} + \frac{W}{A_w} \quad (3)$$

Energy balance for the absorber

$$m_b \cdot C_b \cdot \frac{dT_b}{dt} = (1-\rho_g)\cdot(1-\alpha_g)\cdot(1-\alpha_w)\cdot \alpha_b \cdot G_H - \qquad (4)$$
$$- q_{c,b-w} - q_{loss}$$

The rate of condensation is estimated:

$$\frac{dm_c}{dt} = \frac{q_{ev,w}}{H_w} = \frac{A_w \cdot q_{ev,w-g} + A_e \cdot q_{ev,w-e}}{A_w \cdot H_w} \qquad (5)$$

In the right hand side of expressions (1)-(5) unknown terms mainly describe convective and radiative heat transfer between different parts of the heat pump assisted solar still according to [12].

METHOD OF SOLUTION

Numerical algorithm for solution of (1)-(5) based on the fourth order Runge-Kutta method [12]. 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. In Table 1 the basic system parameters are performed.

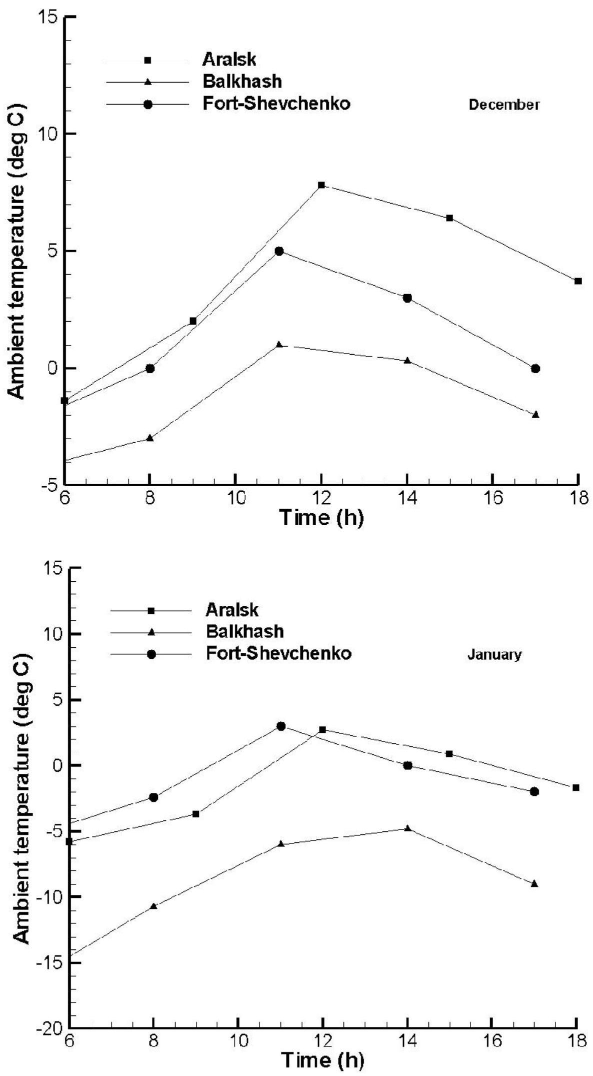
Table 1. Basic parameters of the heat pump assisted solar still

Parameter	Symbol	Value	Unit
Mass of the glass cover	m_g	10.12	$kg\ m^{-2}$
Specific heat of glass	C_g	800	$J \cdot kg^{-1} \cdot °C^{-1}$
Absorptivity of glass	σ_g	0.0475	-
Reflectivity of glass	ρ_g	0.0735	-
Mass of water	w_g	20.60	$kg\ m^{-2}$
Specific heat of water	C_w	4178	$J \cdot kg^{-1} \cdot °C^{-1}$
Absorptivity of water	σ_w	0.05	-
Mass of plate absorber	m_b	15.60	$kg\ m^{-2}$
Specific heat of plate absorber	C_b	480	$J \cdot kg^{-1} \cdot °C^{-1}$
Absorptivity of plate absorber	σ_b	0.95	-
Thermal conductivity of plate absorber	k_b	16.30	$W \cdot m^{-1} \cdot K^{-1}$
Thermal conductivity of insulation	k_i	0.039	$W \cdot m^{-1} \cdot K^{-1}$
Mass of evaporator	m_e	7.35	$kg\ m^{-2}$
Specific heat of evaporator	C_e	385	$J \cdot kg^{-1} \cdot °C^{-1}$

RESULTS AND DISCUSSION

Temperature variation of different parts of the distiller was numerically estimated for cold climate conditions of Kazakhstan. In the present paper three small cities of Kazakhstan were considered: Aralsk, Balkhash and Fort-Shevchenko, which are corresponding to Aral sea, Balkhash lake and Caspian sea. As the ambient temperature the coldest day of the winter months of 2014-2015 was taken. Fig.2 shows the temperature variation of the coldest day of December (2014), January (2015) and February (2015).

Fig.3 shows the average daily direct and diffuse solar radiation on a horizontal surface with actual conditions of cloudiness, W/m^2. Kazakhstan is one of the leading countries in the Central Asian region with the average annual solar radiation potential. 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. According to Fig.3 the average daily intensity of solar radiation in the summer season is about 600 W/m^2. Similarly, for the winter season in the above cities is about 180-200 W/m^2.



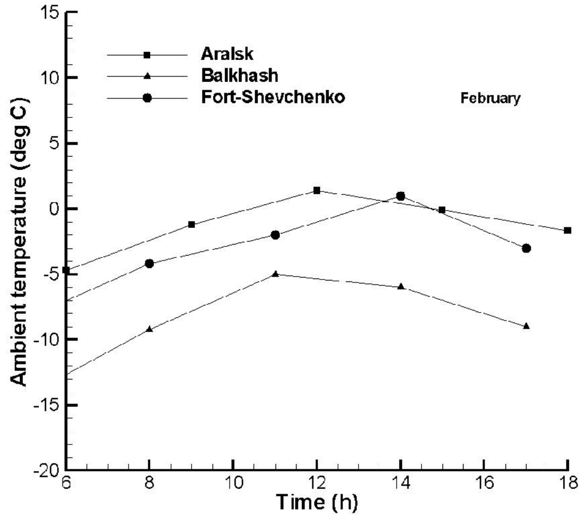


Fig.2. The temperature variation of the winter coldest day of 2014-2015

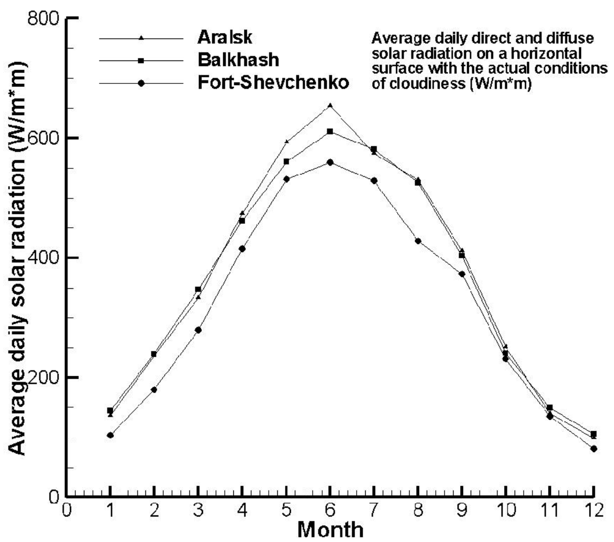
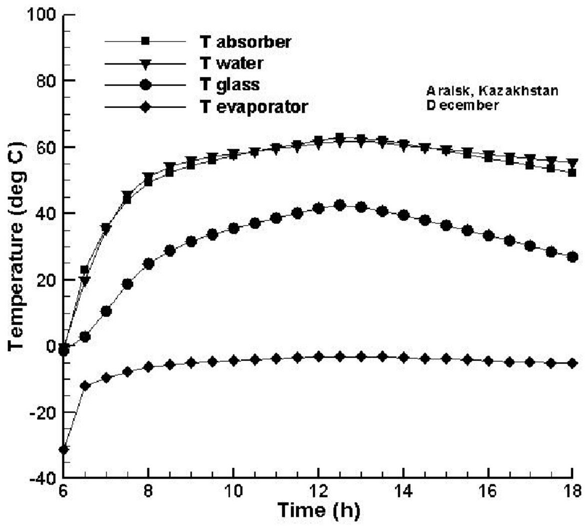
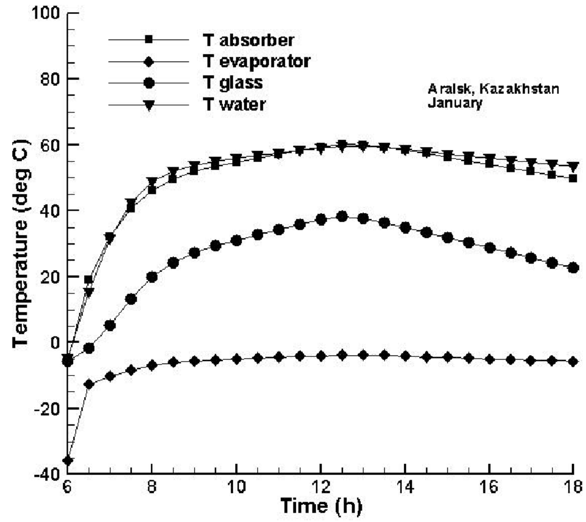


Fig.3. Average daily direct and diffuse solar radiation, W/m^2

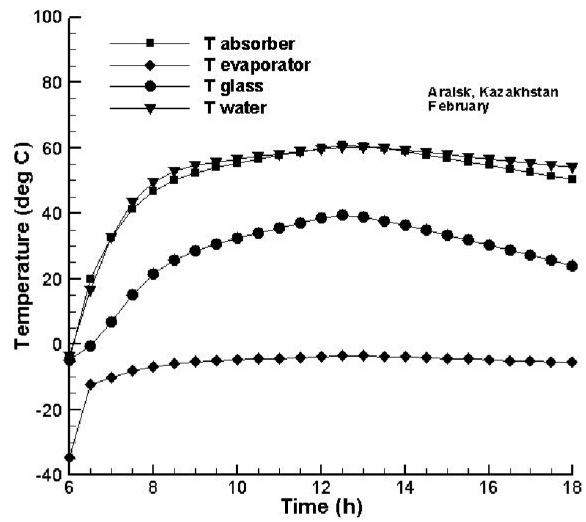
The temperature variation of different parts of the distiller in function of time for the coldest winter days is presented in Fig.4 for Aralsk near Aral sea. It is known that the Aral Sea dries up and is now divided into two parts Large and Small Aral. Today, the Small Aral restored by constructing Kokaral dam by Kazakhstan. On the part of the Small Aral Sea the Aralsk city is located, where there is the prospect of using solar desalination for domestic purpose.



a)



b)



c)

Fig.4. The temperature variation of the different solar still parts (Aralsk)

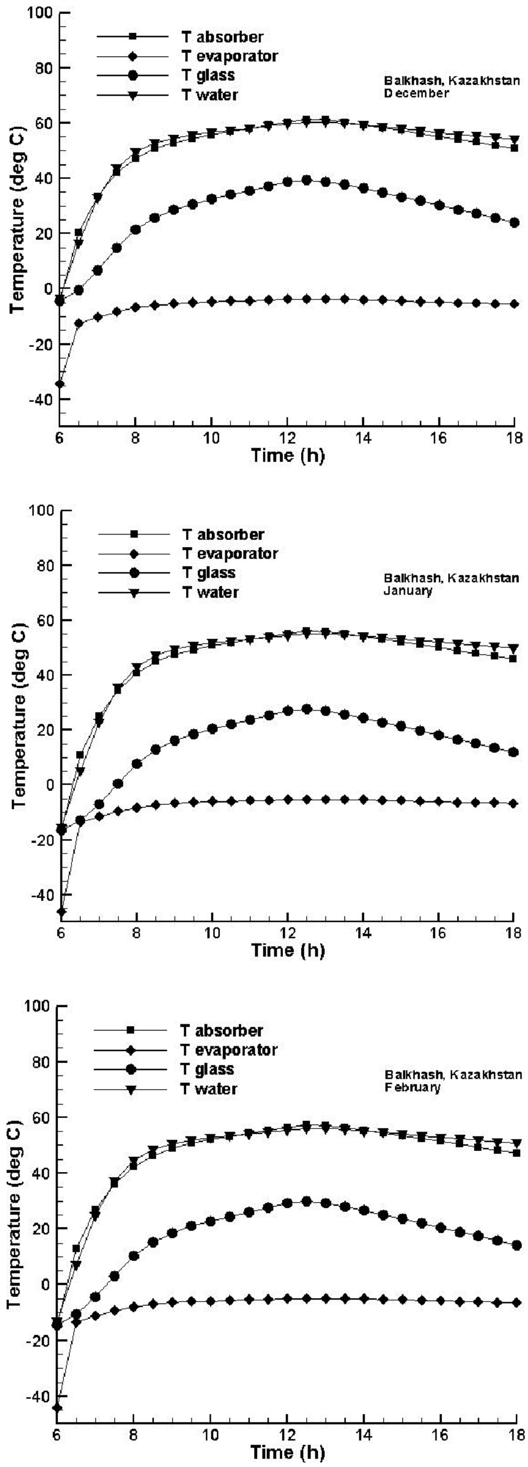


Fig.5. The temperature variation of the different solar still parts (Balkhash)

According to the Fig.4 at the beginning of the day the curves gradually increase, reaching maximum at 12 h and 14 h, then gradually decreased. Due to the high absorption coefficient of the absorption plate with black paint it's temperature reaches a maximum value of 63 ^{o}C in December, 61 ^{o}C in January and February. Accordingly the temperature of the glass is 43 ^{o}C, 39 ^{o}C and 40 ^{o}C, respectively. Almost 20 ^{o}C difference between absorber and glass temperatures is due to convective heat exchange with ambient air and water vapor condensation at the evaporator. Water temperature is practically same as absorber temperature for all three winter months.

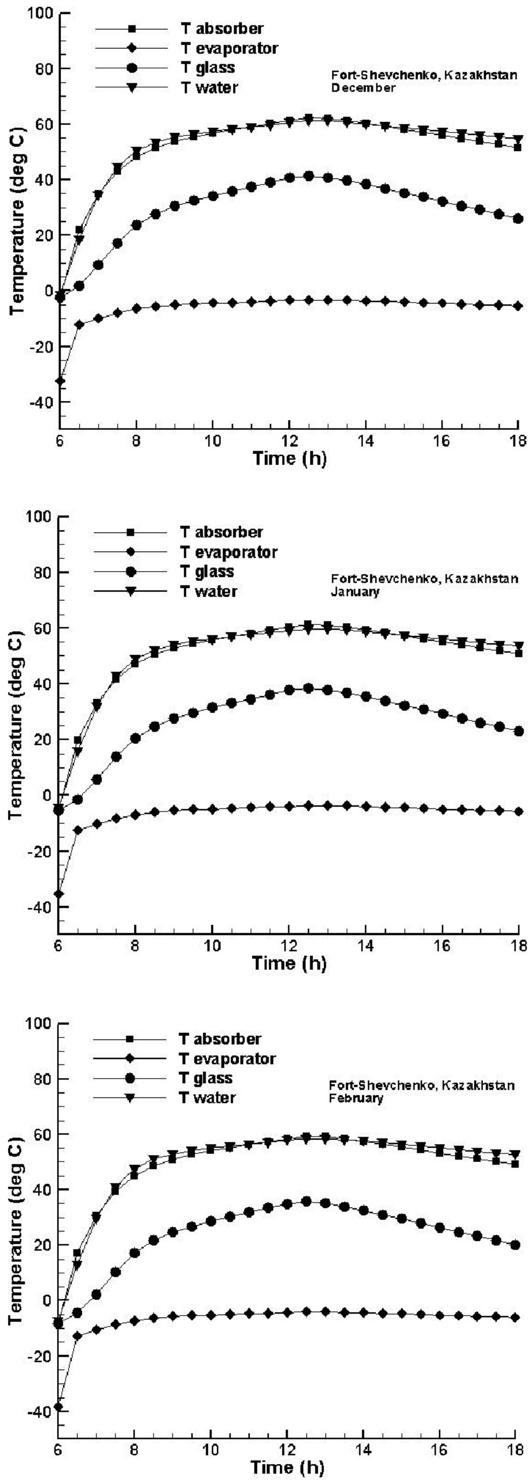


Fig.6. The temperature variation of the different solar still parts (Fort-Shevchenko)

Analogically, temperature variation for Balkhash and Fort-Shevchenko cities are illustrated in Fig.5 and Fig.6.

From Fig.5 it is obvious, that for Balkhash maximum absorber temperature is 62 ^{o}C in December, 56 ^{o}C in January and 58 ^{o}C in February. While in Fort-Shevchenko, these figures are 63 ^{o}C, 62 ^{o}C and 60 ^{o}C, respectively.

Fig.7 shows the temperature variation for the month July in Fort-Shevchenko.

Comparing to the winter conditions maximum absorber temperature reaches a value 91 ^{o}C for July (Fig.7).

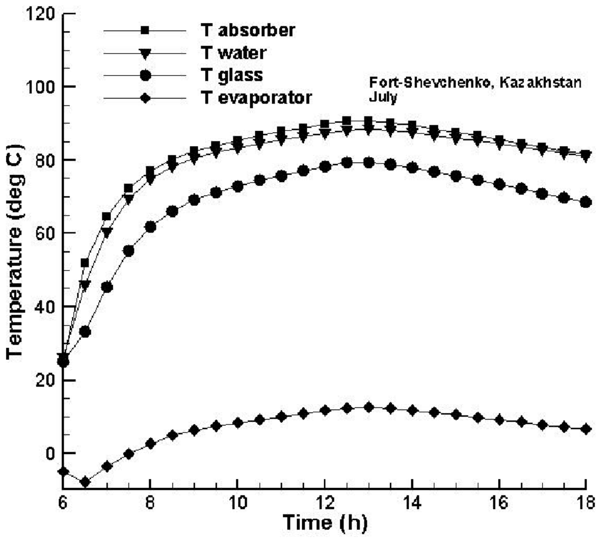


Fig.7. The temperature variation of the different solar still parts (Fort-Shevchenko)

Comparison of productivity at the evaporator and the glass cover is presented in Fig.8.

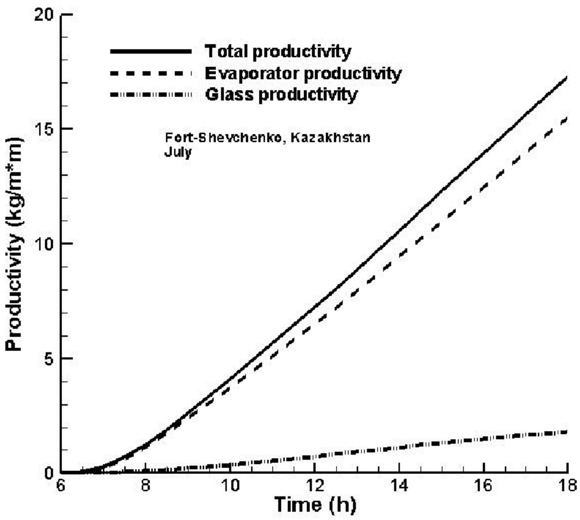


Fig.8. Productivity of the distiller for July in Fort-Shevchenko

More than 75% of condensed water is produced by evaporator comparing to glass cover (Fig.8). A large amount of water vapor is condensate very quickly due to the low temperature of the refrigerant.

The average daily fresh water production for each month is plotted in Fig.9 for each city.

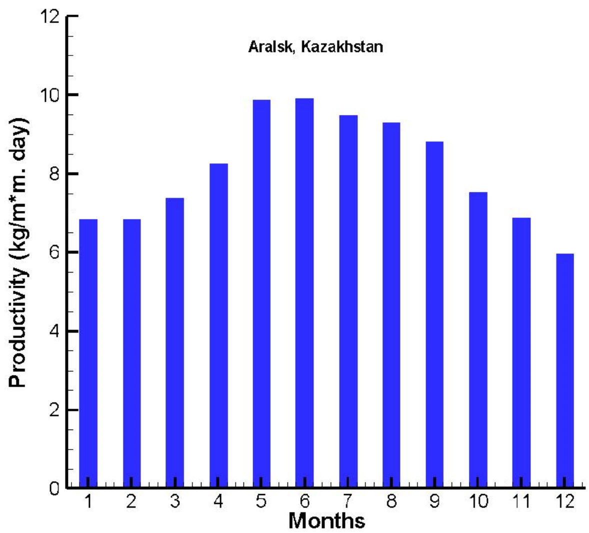
According to the Fig.9 the maximum daily production of fresh water reaches in summer, when the solar radiation reaches the maximum value. The average daily solar distiller production for Aralsk is 9.91 kg/m^2/day in July, for Balkhash is 10.16 kg/m^2/day in July and for Fort-Shevchenko is 9.72 kg/m^2/day in July.

CONCLUSION

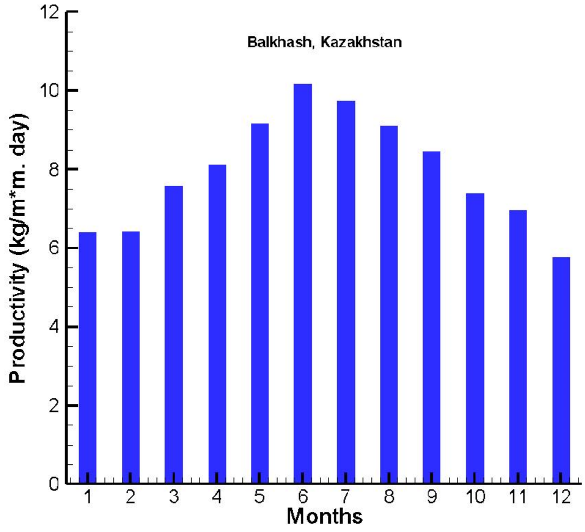
Numerical simulation of a heat pump assisted regenerative solar still under meteorological conditions of Kazakhstan has been carried out and following conclusions are drawn:

- Numerical results are found to be closed to the experimental results found in literature;
- The heat pump assisted regenerative solar still produced 75% improved productivity when compared to simple solar still;
- Numerical simulation results for three different locations: Aralsk, Balkhash and Fort-Shevchenko confirm that heat pump assisted regenerative solar still is suitable for producing good drinking water in remote locations of Kazakhstan.

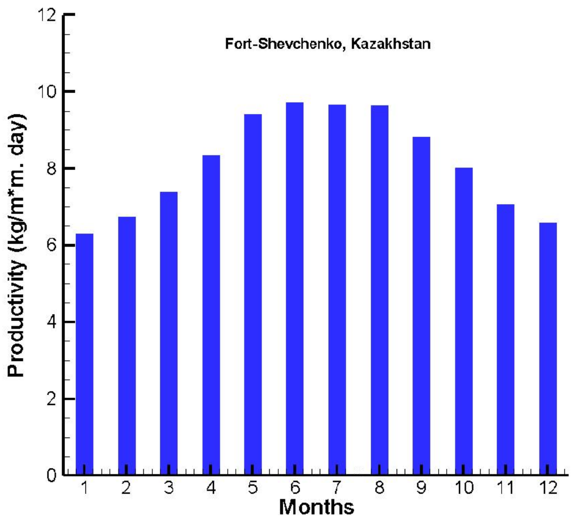
Further, the authors are developing a commercial regenerative solar still for producing good drinking water in water scarcity locations of Kazakhstan.



a)



b)



c)

Fig.9. The average daily production for different months

REFERENCES

1 Jinzeng Chen, Suyi Huang, A discussion of “Heat pumps as a source of heat energy for desalination of seawater”, Desalination, 169 (2004), 161–165.

2 M.V. Rane, Y.S. Padiya, Heat pump operated freeze concentration system with tubular heat exchanger for seawater desalination, Energy for Sustainable Development, 15 (2011), 184-191.

3 Yongqing Wang, Noam Lior, Thermoeconomic analysis of a low-temperature multi-effect thermal desalination system coupled with an absorption heat pump, Energy 36 (2011), 3878–3887.

4 Diego C. Alarcón-Padilla, Lourdes García-Rodríguez, Julián Blanco-Gálveza, Design recommendations for a multi-effect distillation plant connected to a double-effect absorption heat pump: A solar desalination case study, Desalination, 262 (2010), 11-14.

5 Diego-César Alarcón-Padilla, Lourdes García-Rodríguez, Application of absorption heat pumps to multi-effect distillation: a case study of solar desalination, Desalination , 212 (2007), 294-302.

6 V.V. Slesarenko, Desalination plant with absorption heat pump for power station, Desalination, 126 (1999), 281-285.

7 Faisal Mandani, Hisham Ettouney, Hisham El-Dessouky, LiB - H_2O absorption heat pump for single-effect evaporation desalination process, Desalination , 128 (200), 161-176.

8 Ahmad Al-Ansari, Hisham Ettouney , Hisham El-Dessouky, Water–zeolite adsorption heat pump combined with single effect evaporation desalination process, Renewable Energy 24 (2001), 91-111.

9 Iman Janghorban Esfahani, Seung Chul Lee, Chang Kyoo Yoo, Evaluation and optimization of a multi-effect evaporation–absorption heat pump desalination based conventional and advanced exergy and exergoeconomic analyses, Desalination, 359, (2015), 92-107.

10 Ahmed A.A. Attia, New proposed system for freeze water desalination using auto reversed R-22 vapor compression heat pump, Desalination, 254, (2010), 179-184.

11 M.N.A. Hawlader, Prasant K. Dey, Sufyan Dia, Chan Ying Chung, Solar assisted heat pump desalination system, Desalination, 168 (2004), 49-54.

12 Hanen Ben Halima , Nader Frikha, Romdhane Ben Slama, Numerical investigation of a simple solar still coupled to a compression heat pump, Desalination, 337, (2014), 60-66.

13 Zakaria Mohd Amin, M.N.A. Hawlader, Analysis of solar desalination system using heat pump, Renewable Energy, 74, (2015), 116-123.