Paper ID: KL-05

Utilization of Solar Energy and Waste Heat for Water Heating, Drying and Desalination of Seawater

M.N.A.Hawlader

Department of Mechanical Engineering, Faculty of Engineering,
International Islamic University Malaysia,Jalan Gombak,
53100 Kuala Lumpur, Malaysia
**e-mail:mehawlader@iium.edu.my*

Abstract

The population growth of the world has led to a greatly increased demand for energy. Due to this growing global energy demand and concern for environmental degradation, the potential of running thermal system usingsolar energy is receiving considerable attention in recent years. Solar energy is clean and most inexhaustible of all energy resources. The heat pump commonly used for space cooling, a low temperature application, makes it an excellent match for the use of solar energy. A solar assisted heat pump system has been fabricated and installed for space cooling, water heating, drying and desalination. Besides solar energy, the system makes use of waste heat available from heat pump, which is normally released to the atmosphere leading to global warming. An unglazed evaporator collector absorbs solar energy and ambient energy.On condenser side of the heat pump, desalination chamber, water heater and cloth dryer are connected to make use of waste heat available from the heat pump system.This system is particularly suitable for hotels and hospitals where cooling, water heating and drying are always needed and enormous amount of waste heat is available.

Keywords: Solar energy, heat pump, space cooling, water heating, drying and desalination

1. INTRODUCTION

It is impossible for life to survive without water and the severe crisis of fresh water in semi-arid and arid regions of the world has created significant importance to find alternative sources of potable water. Efficient management of ground water and surface water would be an option but these resources will not be able to meet entire requirements due to rapid growth of population. Also, pollution is deteriorating the conditions of the available sources and affecting the entire water scenario. Desalination of seawater is an option, as abundant supply of it exists in nature [1-3].

Energy is an essential component for most desalination processes. The unreliable prices of fossil fuels, tremendous growth in demand and global warming have created a new dimension to look for sustainable energy resources with reduced impact on environment. Solar energy, a clean, environment friendly and sustainable resources can play an important role [2]. There can be significant utilization solar energy particularly in areas where low temperatures, less than 100^{o}C, are involved [4-5].

A combination of solar energy, ambient energy and waste heat is considered for production of hot water, provide drying and perform desalination [6]. Evaporator collectors are used for the collection of solar energy and ambient energy [7]. Several experiments were conducted by Abou- Ziyan [8] to identify appropriate refrigerant.Hawlader et al. [9]and Chyng [10] conducted experiments using solar assisted heat pump (SAHP) to produce hot water. The evaporator collector absorbed both solar energy and ambient energy due to low operating temperature. For refrigerant R134a, the coefficient of performance (COP) of the heat pump system reached as high as 9.Huang and Lee [11] studied the long term performance of solar assisted heat pump water heater. Grossman [12] carried out experiments with a solar heat pump system to provide cooling, dehumidification and air-conditioning. In 2003, Hawlader et al. [13] conducted series of experiments on a solar assisted heat pump system (SAHPS) to provide water heating and drying.

More than half of the building energy consumption is attributed to air conditioning urban households, especially for those buildings running air-conditioner all the day, such as hotels and hospitals. Conventional vapor compression air conditioning system throws the heat from a heat source (air-con room) to the ambient air without making an effort to recover it. A solar assisted heat pump(SAHP) system for air-conditioning, water heating and drying was proposed by Hawladeret al. [14]. Based on the principle, a SAHP systemhas beendeveloped where solar energy, ambient energy, and air con waste heat are used to provide hot water, drying and desalination. This paper includes a brief description of the system and the results obtained from it.

2. THE SYSTEM AND EXPERIMENTS

A heat pump system has been built, as shown in Figure 1, and located on the roof top of a buildingto evaluate performance under outdoor meteorological conditions. The system consists of four major sections: a solar assisted heat pump, a desalination unit, a dryer and a hot-water storage tank. For the collection of solar energy, a solar collector and an evaporator collector are used. A solar assisted air conditioning (heat pump) system provides energy required for desalination, drying and water heating.

The hermetic reciprocating compressor is coupled with a three phase induction motor, whereby the speed of the motor is controlled by a frequency inverter. The evaporator-collector is made of copper absorber plate and coated with black paint. Serpentine copper tubes, with external diameter of 9.5mm, are brazed onto the bottom of the collector plate. The bottom part of the collector evaporator is insulated with polyurethane foam to reduce heat lost from the plate's bottom. The room evaporator is located in a space to be cooled to provide comfort condition. The evaporator collector and room evaporator are connected in parallel with individual expansion valve. The condensing coils for heating saline water and fresh water run in parallel using control valves, while the dryer is connected in series.

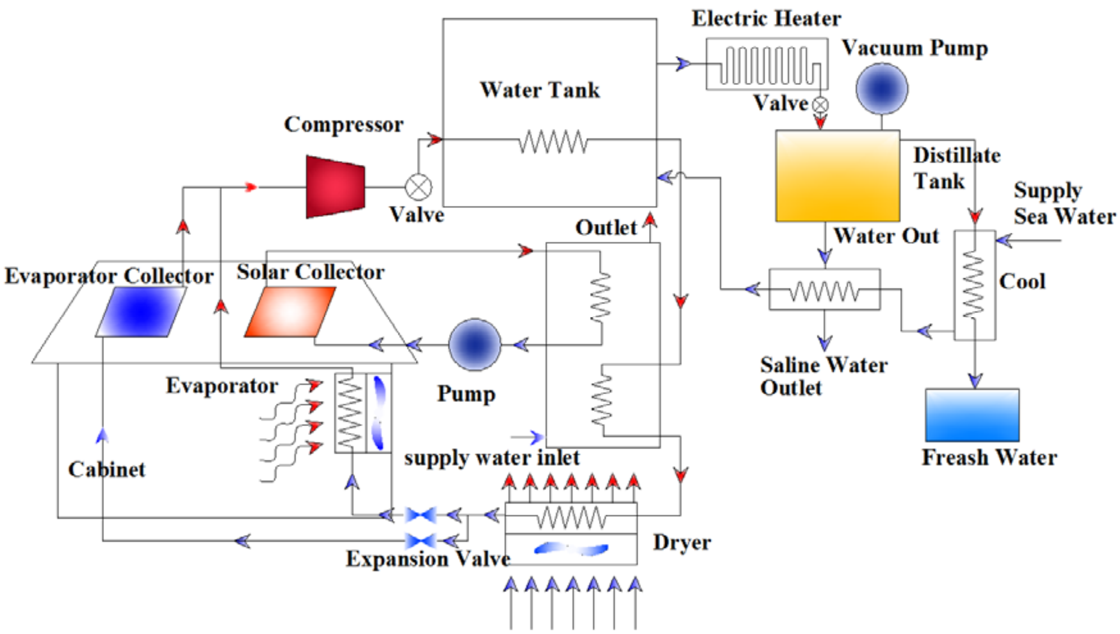

Figure 1. An integrated solar heat pump system for water heating, drying and desalination

Solar Assisted Heat Pump (SAHP)

The SAHP consists of a hermetic type reciprocating compressor, evaporators(evaporator-collector and room evaporator), condensers(condensing coil in lower portion of desalination chamber, water-cooled condenser, air-cooled condenser), and lastly expansion valves. The evaporator components are connected in parallel to each other, while the condensers are connected in parallel / series, with by-pass system.

In the compressor, saturated /slightly superheated refrigerant vapor at a lower pressure enters the inlet and is compressed to a high pressure and temperature. The superheated vapor first enter the condenser coil in the chamber filled with saline seawater, where it releases sensible and latent heat and raise the temperature to the desired level. The condenser coil in seawater chamber and hot water tank are arranged in parallel with appropriate control to maintain the desired temperature level. Subsequently, to ensure total condensation of refrigerant before it reaches the expansion valve, the refrigerant will flow through the air-cooled condenser. Latent heat released from the condensation of refrigerant vapor is recovered by water and air in the water-cooled condenser and air-cooled condenser, respectively. In this system, the recovered heat in the water-cooled condenser and air-cooled condenser are used for water heating and drying purposes.

The saturated or sub-cooled liquid refrigerant from the condensers will then be split into two separate branches. Each branch will lead the refrigerant to separate evaporator components. Refrigerant mass flow rate in each branch is regulated by the thermostatic expansion valve before entering the evaporator components. In the evaporator-collector, collector plate gained solar energy from solar radiation, ambient energy from ambient air and latent heat due to condensation of water vapor present in the air. Energy gained by the collector plates is then transferred to vaporize the refrigerant in the serpentine tubes. In the room evaporator, refrigerant vaporizes by receiving thermal energy from room air, while the room air is cooled by releasing heat to the cold refrigerant flowing through finned tube. The mass flow rate of refrigerant in each evaporator is regulated to ensure refrigerant exit in each evaporator either in saturated or slightly superheated vapor state. The two streams of refrigerant vapor are then mixed together before entering the compressor inlet and the cycle continues.

The process of desalination

Although there are a number of ways to convert seawater to fresh water, a common overall processapplies to all schemes. Actual nature of each step would depend on the desalination method used. Figure 2 shows the steps involved in the process.

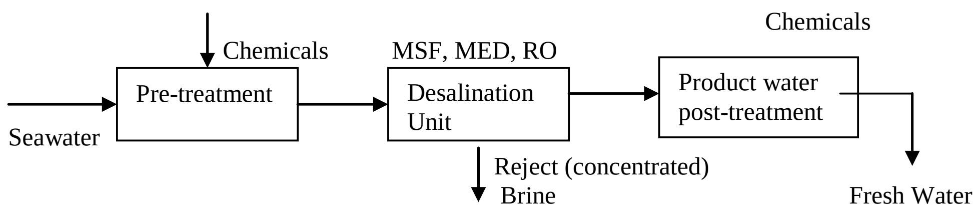

Figure 2. Schematic diagram of a desalination process

The nature of the pre-treatment depends to a great extent on the type of intake system and the nature of pollution in the surrounding sea. The supply of water directly from shallow bays near the shore may provide seawater with high contents of bacteria, algae and suspended solid. Normally, seawater drawn from the open ocean is cleaner and requires less pre-treatment steps. Pre-treatment of raw feed water is necessary to preserve the life and reliability of the desalination equipment. As stated earlier, there are a number of methods available for the conversion of seawater to fresh water. Irrespective of the method of conversion process, the product water should have a total dissolved solid (TDS) content of less than 500 ppm [15]. Table 1 shows the typical constituents of seawater and potable water. This product water is not suitable for direct human consumption and some form of post-treatment is necessary to control sodium and chloride ions and its pH. A treatment with acid, H_2SO_4, controls carbonate scale formation and convert any sulphides to H_2S. The acidified water is then sent to a stripping tower to remove excess CO_2 and H_2S gases. Chlorine is then added as a disinfectant. Finally lime, $Ca(OH)_2$, is added to increase water hardness and decrease corrosion risks, while fluoride is added to reduce dental cares.

In the desalination section, the system consists of a seawater tank, desalination chamber fitted with a vacuum pump, a condenser coil to cool vapor generated in desalination chamber, and a distillate tank. The saline feed-water is preheated by the condensing vapor and, subsequently, by the reject brine. In practice, the temperature of feed water before entering the desalination tank should not be below 70˚C. After passing through the electrical heater, the water will enter the desalination chamber. The desalination chamber will be evacuated to a pressure of about 0.12 bar, hence, the corresponding temperature of water will drop from 100^{o}C at standard atmospheric pressure to 50^{o}C at the pressure of 0.12 bar. Upon entering the desalination chamber, the water will undergo thermodynamic flashing and evaporation. The remaining part of the saline water passes through a coil and releases additional heat to feed water. Vapors produced from flashing and evaporation will rise to top of the chamber, pass through a cooling coil and the water is collected in a fresh water tank, as shown in the Figure 1.

Table 1. Typical constituents of seawater and potable water [15,16]

Constituents	Seawater[1] (mg/L)	Potable Water[2] (mg/L)
Barium	0.02	1.0
Calcium	412	75
Carbonates	28	150
Chloride	19500	250
Copper	$1x10^{-4}$	1.0
Fluoride	1.3	1.5
Iron	0.002	0.3
Lead	$5x10^{-7}$	0.05
Magnesium	1290	50
Manganese	$2x10^{-4}$	0.05
Mercury	$3x10^{-5}$	0.001
Nitrates/Nitrogen	11.5	10
Phosphates	0.06	0.4
Potassium	380	10
Silica	2	7.1
Sodium	10770	200
Sulphates	905	400
Total dissolved solid	33387 (ppm)	500 (ppm)
pH	8.0	6.5 - 8.5
Turbidity	3 - 15 NTU	5 NTU

Solar water heater

The hot water tank acts as a condenser for the heat pump and receives heat from the refrigerant as well as solar collector. Water condenser absorbs most of the heat from the superheated refrigerant. There is a phase change for refrigerant from superheated vapor to saturated two-phase mixture of vapor and liquid. Water absorbs bulk of latent heat of condensation of the refrigerant. Also, water from the storage tank is circulated through a conventional solar collector using a pump. This pump operates only when useful energy is collected from the sun.

Drying with hot air

After the water condenser, the refrigerant may be in a state of two-phase or saturated condition. The air condenser ensures complete condensation of refrigerant vapor and may be slightly sub-cooled before it reaches he expansion valve. The energy recovered from the air condenser is used for low temperature application, such as drying – it may be grain drying or cloth drying depending on the nature of applications.

3. RESULTS AND DISCUSSION

Meteorological conditions

Singapore and Johor Baru, Malaysia are located at about latitude $1^o22'$N and longitude $103^o55'$. There is hardly any seasonal variation of the meteorological conditions in Singapore or Johor Bahru. Figures 3 and 4, show the values of solar radiation, wind speed, ambient temperature, and relative humidity in 2008. It can be seen that the temperature generally reaches around 30 °C, with the maximum value of about 35 °C. Wind speed varies from around 1 to 4 m/s, with relative humidity between 65% and 85%, and solar radiation varies from 400 to more than 1000 W/m^2 for the condition considered.

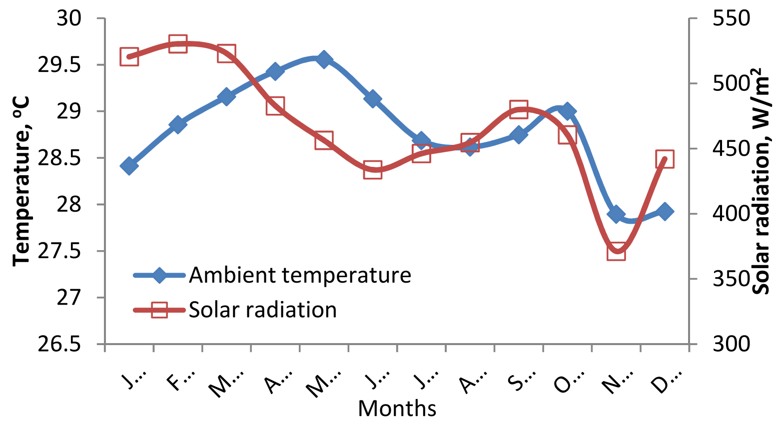

Figure 3.Variation of monthly ambient temperature and solar radiation

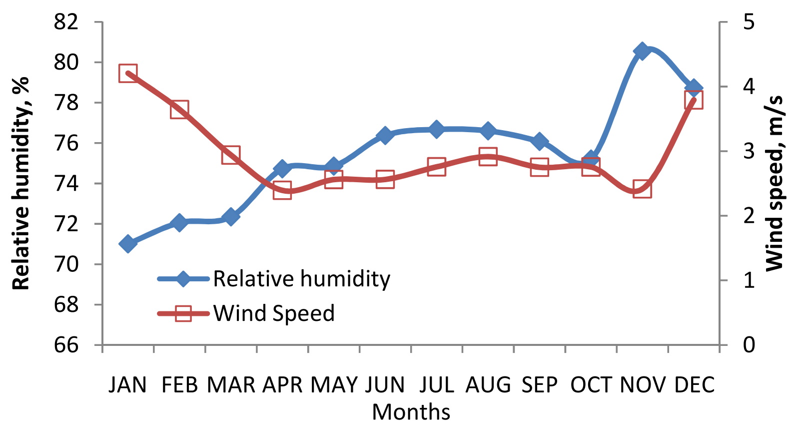

Figure 4.Variation of monthly relative humidity and wind speed

Performance of Water and Evaporator collectors

The evaporator collector uses refrigerant after the expansion valve. The operating temperature of the collector is much lower than the atmospheric air temperature. The collector is unglazed and coated with matt black paint. It absorbs allthe radiation incident upon it. As the operating temperature of the collector is lower than the atmospheric temperature, it also gains energy from the environment by convection. Due to low temperature of the collector surface, lower than the dew point, there is condensation of the water vapor in the air and the collector absorbs latent heat of condensation. Hence, the evaporator collector absorbs both solar energy and ambient energy.

The solar water collector is normally glazed to reduce heat losses. A part of the solar radiation is transmitted through the glass cover and absorbed by the absorber panel. As a result the panel will be heated and, normally, the operating temperature is much higher than the ambient temperature and there will be heat losses to the atmosphere. Figure 5 shows the efficiency of the water and evaporator collectors. Evaporator collector operates at a much higher efficiency than the water collector.

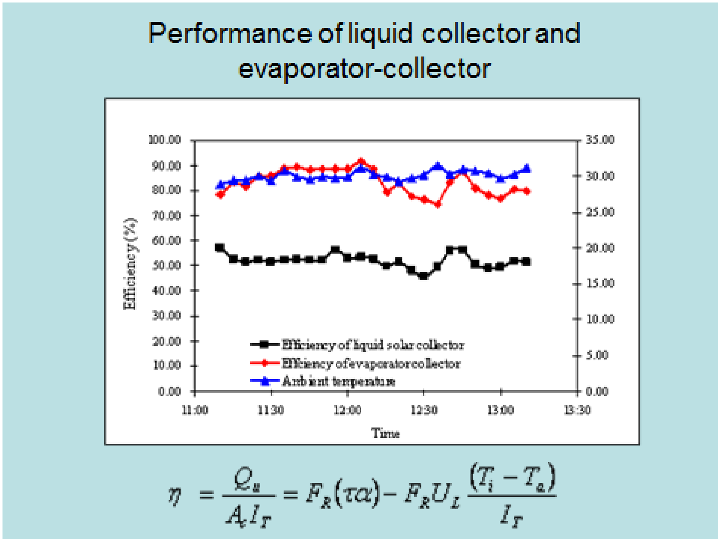

Figure 5: Efficiency of evaporator and water collectors.

Space cooling (Air-con)

As seen from Figure 6, room temperature was cooled from 27°C to 20°C in one hour and became stable. In the room evaporator, refrigerant after expansion valve absorbed heat from room air and became super-heated at the evaporator outlet. As seen from the Figure 7, evaporating heat of room evaporator dropped from 7.8kW to 6.6kW when then room temperature reduced from 27°C to 20°C. It is due to the fact that the temperature difference between air and refrigerant declined as a result of drop of room temperature.

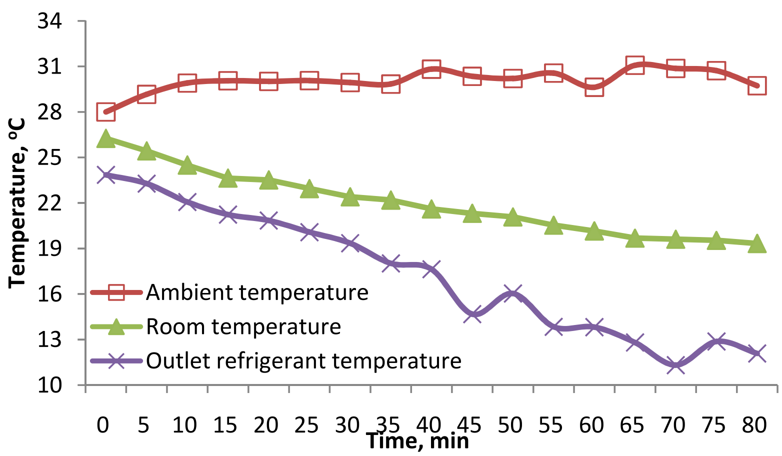

Figure 6 Variation of temperature of ambient, room and outlet refrigerant.

Water heating

Figure 8 shows the variation of temperatures of water and refrigerant. The temperature of the 400 liters of water in the tank increases in a steady manner and rises from 34°C to 60°C in about 65 minutes. With the rise of water temperature, the condensing heat released in water condenser declined due to the fact that the temperature deference between refrigerant and water decreases.

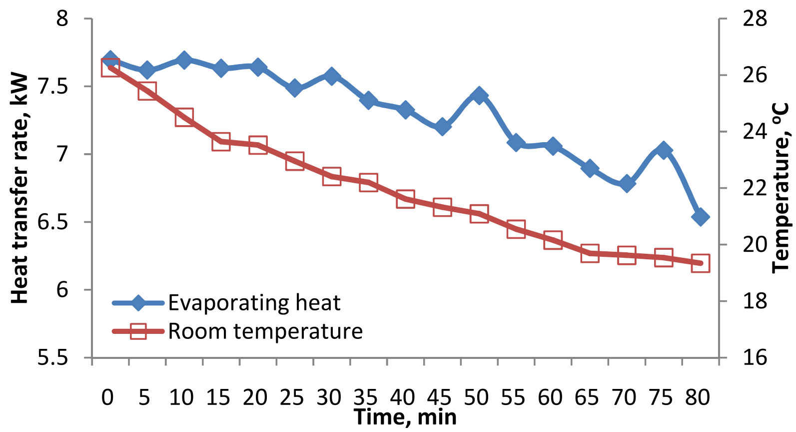

Figure 7 Variation of room temperature and evaporating heat with time.

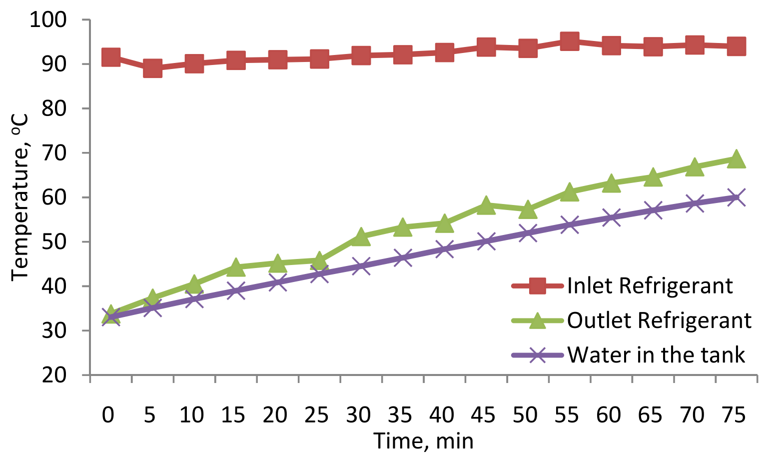

Figure 8. Variation of temperatures of water and refrigerant with time

Desalination

In the desalination chamber, thermodynamic flashing and evaporation occur almost simultaneously. Uniform flashing of water takes place when feed water enters the desalination chamber through the spray nozzle, at a temperature higher than water's saturation temperature. Condensing coil located at the bottom of the chamber, provides thermal energy to heat up and evaporates remaining feed water that does not vaporize during flashing. Vapor produced from flashing and evaporation will rise to the top of the chamber, where it will be condensed by the cooling coil, as shown in Figure 1.

The desalination is obtained by single stage MED technique. As shown in Figure 9, desalination rate increases with radiation and then as time passes it comes to a steady rate of 9.6 kg/hr.

Drying

Figure 10 shows the variation of air temperature and moisture content of material during the drying process. In this drying process, temperature of the water in the water condenser was maintained at 60℃ by controlling the water flow rate. It enabled the stabilization of the temperature of air for drying.

As seen fromFigure 10, the inlet air, with the temperature of around 30℃ and RH of 0.6, was heated to around 36℃ in air condenser. This warm airis allowed to flow through the drying chamber and discharged after releasing heat in the drying process. Textile with the bone dry weight of 1.5kg was wetted and hanged in the drying chamber. The moisture content of material was reduced from 0.9 to 0.09 in 60 minutes. The drying falls mostly in the falling rate region. With the declination of moisture content, the temperature difference between the inlet and outlet of the drying chamber declined gradually. In full mode operation, the heated air temperature is normally lower than 40℃ because the refrigerant from compressor condensed in water condenser and released most of condensing heat before it went through the air condenser to heat the ambient air. When the water is bypassed, the air temperature in the dryer can be as high as 55°C.

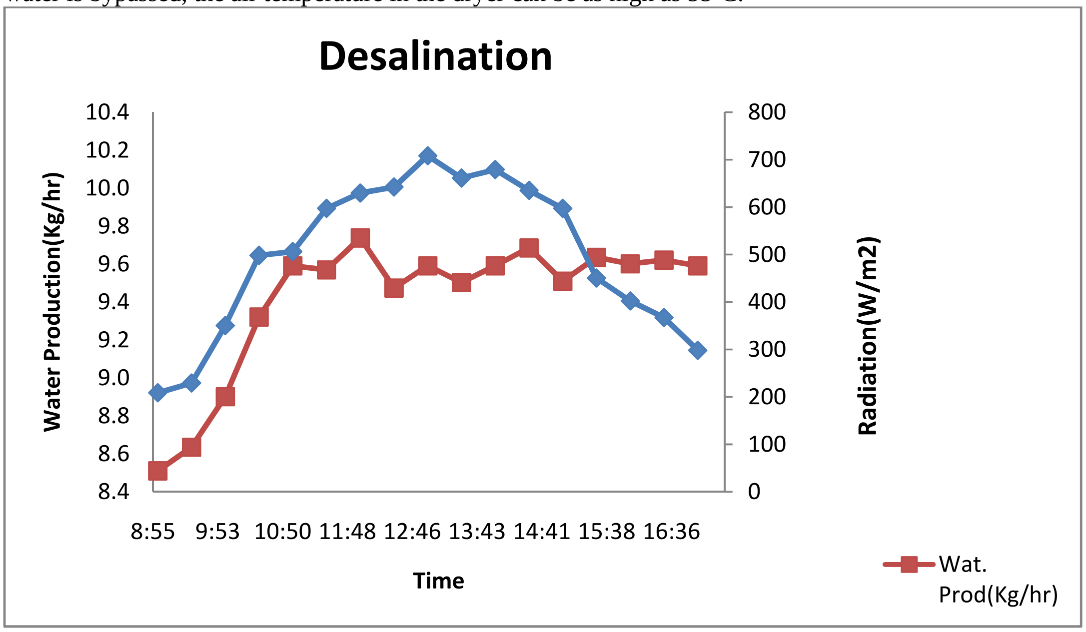

Figure9 Variation of Water desalination and solar radiation with time

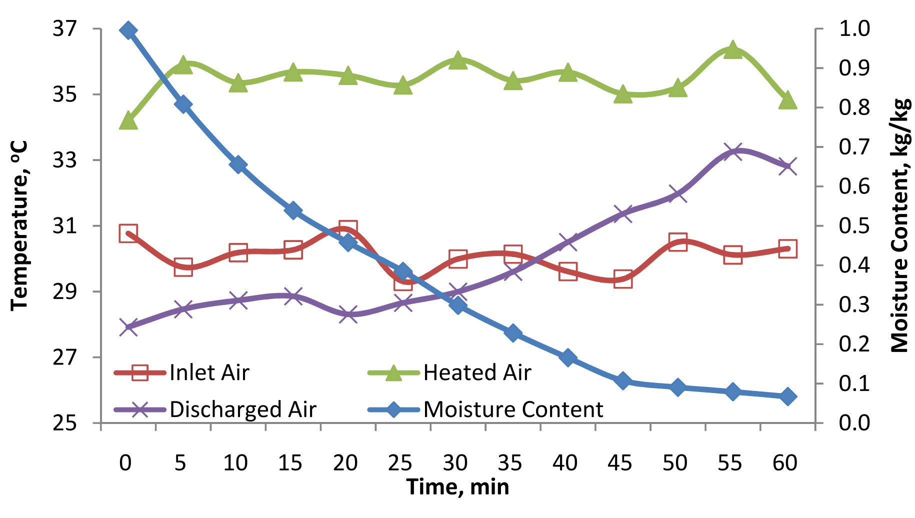

Figure 10 Variation of air temperature and moisture content with time [17]

4. CONCLUSIONS

The solar assisted heat pump system operates on Rankine cycle where one of the innovative featuresis the use of an inexpensive unglazed evaporator-collector, which enables collection of ambient energy.The energy absorption from evaporator collector and space cooling is 28% and 33%, respectively.This gives 14 kW (for a system where the compressor input is 3.5 kW) heat in the condenser side for desalination,water heating and drying. Due to the use of double condenser arrangement, the drying performance is limited and restricted by the water temperature in water condenser. It can be resolved by bypassing the water condenser leading to a constant drying air temperature as high as 55^{o}C.The system is considered environment friendly, encourage a reduction inglobal warming and offers a good potential for supporting basic human need, WATER.

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