Solar thermal polygeneration system for cooling, fresh water and domestic hot water supply: Experimental analysis

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Abstract

The demands for space air conditioning and clean drinking water are relatively high in Middle East countries. A sustainable and innovative approach to meet these demands along with production of domestic hot water is discussed in this paper. A solar thermal poly-generation (STP) system is designed and developed for production of chilled water for air conditioning using absorption chiller, pure water with membrane distiller and domestic hot water by heat recovery. The STP system has four major components: (i) Evacuated tube collector field (ii) 10TR Absorption chiller (iii) Air-gap membrane distillation units (iv) Heat exchangers integrated together to operate in four different modes for complete solar cooling, co-generation of pure water and domestic hot water, tri-generation of cooling, pure water and domestic hot water and co-generation of cooling and pure water. Experiments on different modes and the analyzed results show the advantages of combined operation through effective utilization of heat lost in the process operation.

Key-words: Absorption chiller, air gap membrane distillation, poly-generation, domestic hot water

Introduction

Electricity demand in United Arab Emirates (UAE) has increased tremendously in past two decades due to rapid industrialization and population growth. Around 30% of electricity consumption is accounted for providing air conditioning in the buildings [1] and it is more in summer months. UAE and adjacent countries in Middle East and North Africa (MENA) region does not have adequate natural fresh water resources and hence most of the fresh water demand is met by fossil fuel driven sea water desalination technologies. On the other hand UAE gains abundant solar irradiation with an average global irradiation potential of 600 W/m^2, which could be effectively utilized through solar thermal poly-generation systems for providing air conditioning in the buildings and fresh water through desalination. Hussain [2] designed and developed a hybrid poly-generation system for utilization in Kuwait, which simultaneously produces power, fresh water and cooling. The combination of Power-Reverse osmosis-Absorption refrigeration configuration obtained higher fuel savings compared to all other combinations. Picinardi [3] analyzed the performance of cogeneration system for production of cooling and desalination by integrating a single stage absorption chiller and humidification desalination process. Calise et al. [4] dynamically simulated a solar tri-generation system and analyzed energetically and economically for production of cooling, fresh water and electricity. The system is modeled with PVTs (Photovoltaic/thermal collectors) integrated with absorption chiller and multi-effect desalination system for providing tri-generation.

Membrane distillation (MD) is a thermal driven desalination process which utilizes low grade heat energy. The temperature difference between two side of hydrophobic micro porous membrane acts as the driving force in the process. Kullab [5] experimentally and numerically analyzed the performance of air gap membrane desalination (AGMD) system produced by SCARAB development AB for utilization in cogeneration power plants. Burrieza et al. [6] experimentally investigated the performance of AGMD modules for different flow rates and temperatures on the hot and cold side. The potential of solar thermal driven MD technology as an alternative to the conventional desalinations systems has been researched by several authors. In this paper we experimentally analyzed the performance of a flexible solar thermal poly-generation system (STP) to produce simultaneous cooling, pure water and domestic hot water (DHW) for the weather conditions of UAE. The system is operated for providing cooling for the office cabins in CSEM-UAE during the summer season.

Description and Integration of Poly-generation system

The schematic sketch of solar thermal polygeneration system investigated in the paper is shown in figure.1. The STP system is developed by integrating evacuated tube collectors, single stage absorption chiller and membrane distillation unit. The system is designed and developed as a flexible poly-generation system in order to operate in different modes for analyzing individual and combined processes. The semi-commercial membrane distillation modules developed by SCARAB development AB is utilized in this research.

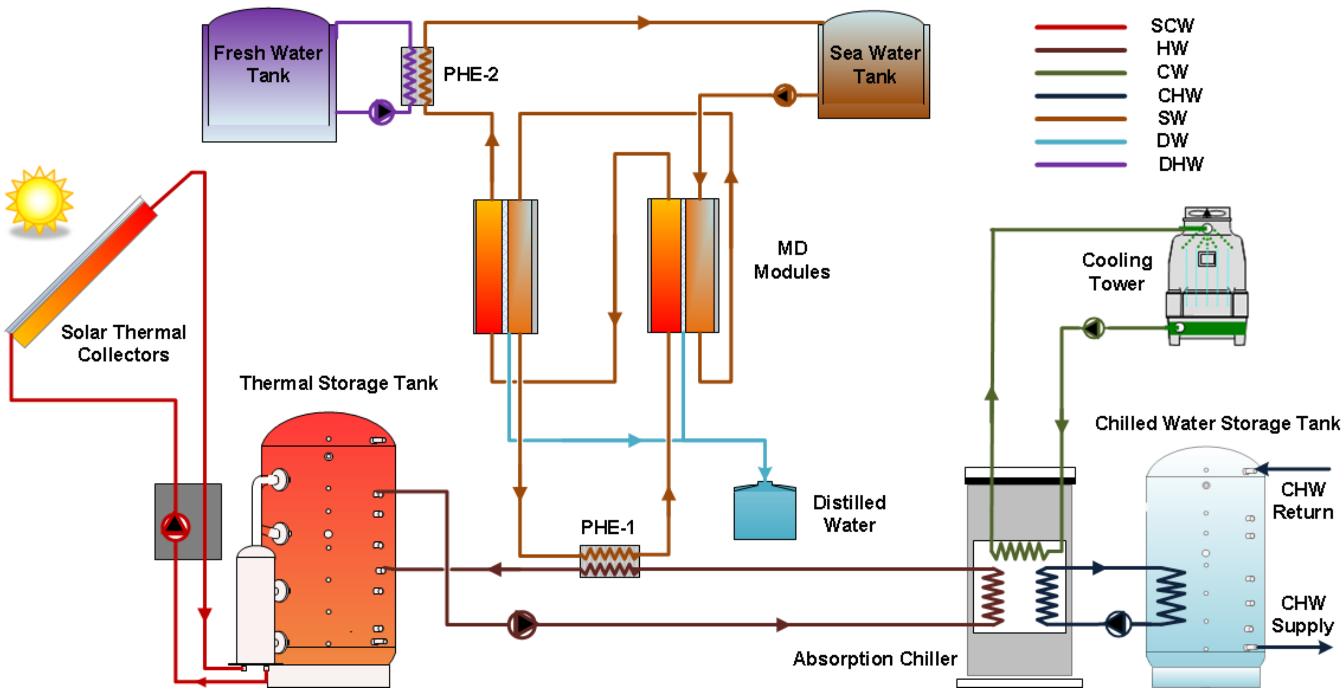

Figure 1. Schematic layout of solar poly-generation system

Figure 2. Solar thermal poly-generation unit

The evacuated tube collector field collects the thermal energy from solar radiation. The collected thermal energy heats up the fresh water stored in thermal stratified tank, which is then used to drive the poly-generation unit. The hot water from the thermal storage tank is supplied to the absorption chiller for initiating the chilling process. The chilled water produced by the chiller is stored in cold thermal storage tank, which is distributed to the office cabins of CSEM-uae. The hot water return from absorption chiller is utilized as the heat source for heating the saline water supplied to the membrane distiller using heat exchanger PHE1. The sea water is pre-filtered by two micro-filtration cartridges before filling into sea water storage tank. The sea water at ambient temperature is supplied to cold side of MD module, where it gets pre-heated through internal heat recovery by conduction and latent heat of condensation from hot side of MD and distillate channels respectively. The pre-heated sea water exits the MD modules and further gets heated with the heat absorbed from the heat exchanger (PHE1). The hot saline feed water enters the hot side of the MD module where it gets evaporated, passes through a hydrophobic membrane and condenses on cold side to produce pure distilled water. The hot brine leaving the MD system is passed to a second heat exchanger (PHE2), which extracts the thermal energy for simultaneous production of domestic hot water (DHW). Photographs of the solar thermal poly-generation system installed at CSEM-uae are shown in figure 2. The technical data of absorption chiller and membrane distillation systems are shown in table 1 and 2.

Item	Parameter	Unit	Value
Cooling capacity		kW	35.2
Chiller water	Inlet temperature	^oC	12.5
	Outlet temperature	^oC	7.0
	Rated flow rate	m^3/h	5.47
	Max operating pressure	kPa	588
Cooling water	Rated inlet temperature	^oC	31.0
	Rated outlet temperature	^oC	35.0
	Max operating pressure	kPa	588
	Rated flow rate	m^3/hr	18.4
Hot water	Rated inlet temperature	^oC	88
	Rated outlet temperature	^oC	83
	Inlet limit	^oC	70-95

Table 1. Technical data of Yazaki 10TR absorption chiller

Specification	**Value**
Membrane area	$2.8m^2$
Porosity (ϕ)	0.8
Membrane thickness (b)	0.2mm
Air gap length (L)	1mm
Height of the module	730mm
Width of the module	630mm
Thickness of the module	175mm

Table 2. Technical data of Membrane distillation units

Results and discussions

The STP system was operated in four different modes to analyze the merits and de-merits of integrating different processes together rather than operating individually. The experiments were conducted from 10:00 AM to 05:00 PM without any auxiliary back up heaters in the sunny weather conditions of United Arab Emirates. The experiments are conducted on during peak summer days with peak global radiation varies between 800 and 850 W/m^2 as shown figure 3 (a). The cooling energy produced by the STP is utilized for providing air conditioning to the office cabins of CSEM-UAE. A total of eight fan coils units are installed among three office cabins with a total floor area of 91.75 m^2. The sectional view of an office cabin is shown in figure 3(b). The building is constructed with plywood and insulated with thick layer of foam.

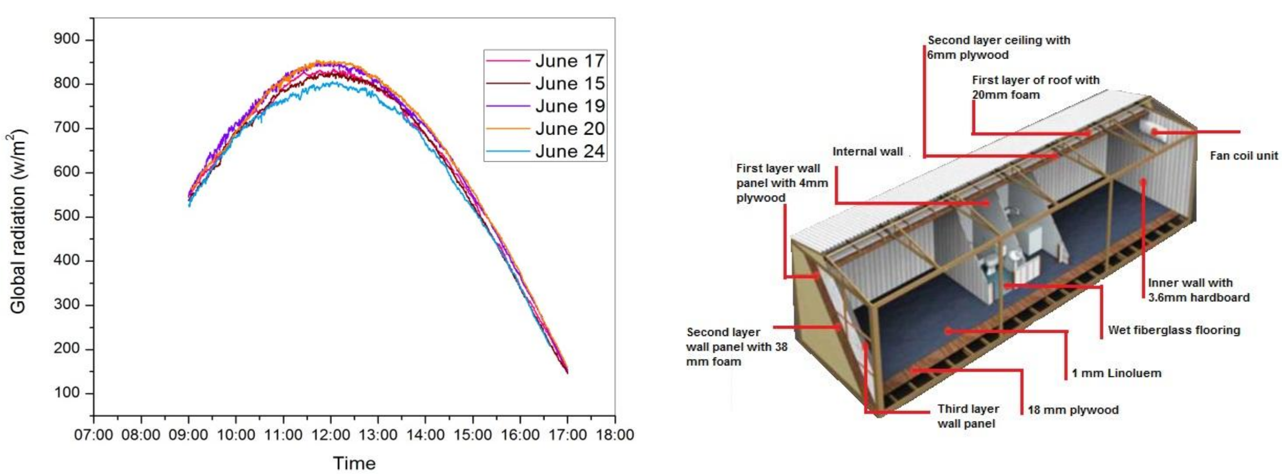

Figure 3. (a) Global Irradiation (b) Section view of office cabin

(i). Solar Cooling

The first mode of operation of the STP system is complete cooling and it is operated on typical summer day. In which both the desalination and domestic hot water supply processes are not operated. The temperature and energy profiles of this mode are shown figure 4 and figure 5. As shown in figure 4, the collector outlet temperature gradually increases from 8:30 AM during the charging process of stratified tank. The operation of absorption chiller starts at 10:00 AM as the tank top temperature reaches more than 88°C. Due to steep decrease hot water supply temperatures, fluctuations in production chilled energy and COP is obtained during the first hour of operation. Throughout the day, the COP of system varies between 0.55 and 0.62 as shown in figure 5. The refrigeration capacity stabilizes at 25 kW for most parts of the day.

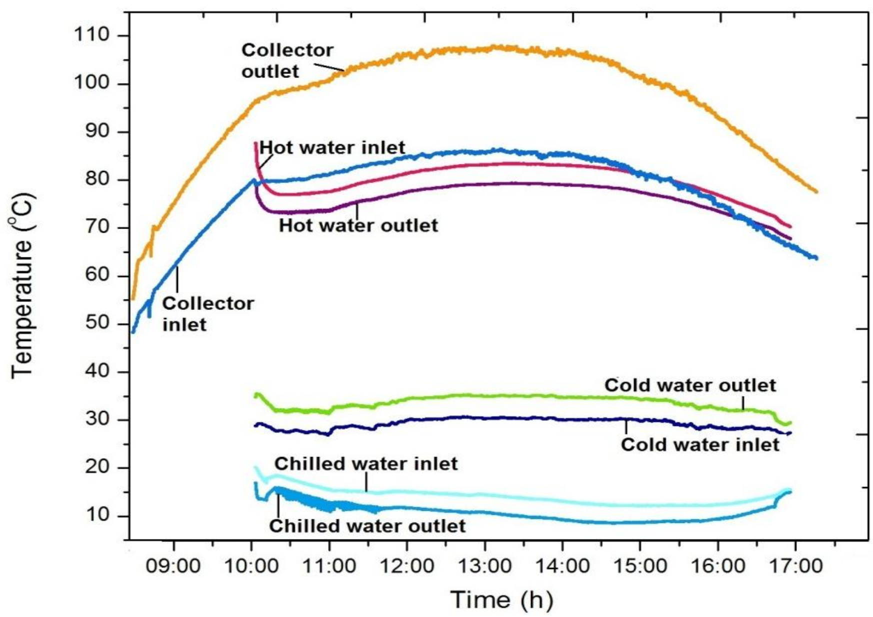

Figure 4. Temperature profile of solar cooling mode

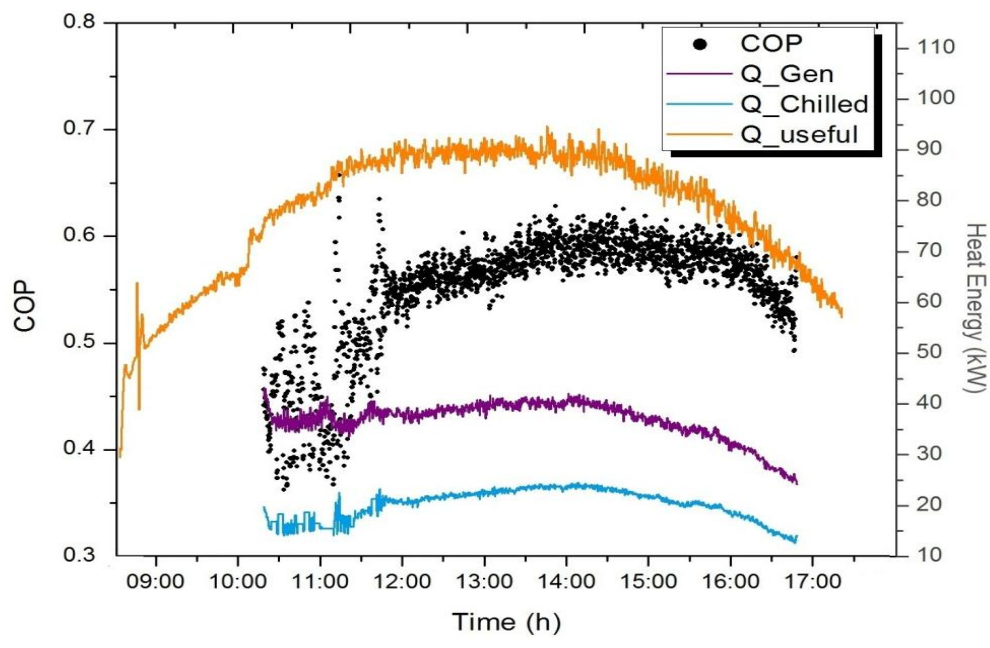

Figure 5. Energy flows of solar cooling mode

(ii). Co-generation of distilled water and domestic hot water

In this mode of operation, thermal energy from solar collectors is utilized completely for the MD unit to produce distilled water and the waste heat from MD is recovered for producing hot water for domestic applications. Figure 6 shows the temperature profiles and productivity of two-stage MD operation. Saline feed water at conductivities greater than 65,000µS/cm was distilled using two AGMD modules to produce distilled water at conductivities less than 50µS/cm and the heat recovered from MD hot side is used to produce DHW at an average of 55°C. With a feed flow of 1140 l/h, the productivity reached a maximum of 12.5 l/h during noon time and a total of 80 liters of pure water is produced for 7 hours of daily operation as shown in figure 7(b). Gain to output ratio (GOR) is the performance evaluation parameter commonly used in membrane distillation systems. Overall GOR of two stage systems is 0.7 which is much higher compared to single stage system. Compared to single stage operation, 45% more productivity is obtained for two stage process and also heat could be recovered effectively from MD hot side for DHW production. As shown in figure 7(b), from the total useful energy, 50% energy has been utilized for this mode of operation from which 75% is recovered for DHW production and the remaining is used for distillate production.

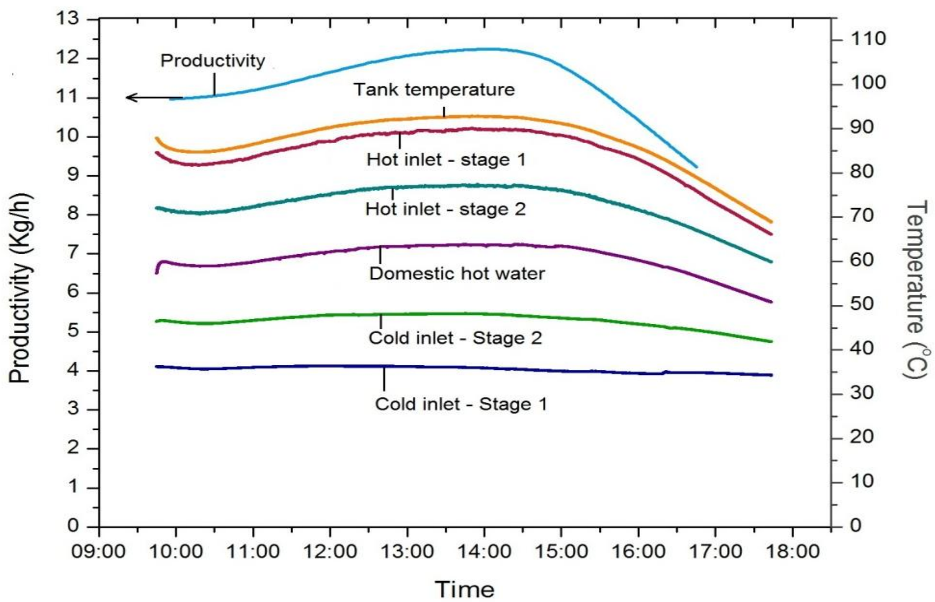

Figure 6. Productivity and temperature profiles distilled water and DHW co-generation mode

(iii) Trigeneration

This mode is a combination of complete cooling and cogeneration modes. Figure 8 and figure 9 summarize the performance of absorption chiller and MD+DHW processes respectively. As shown in figure 8, the chilled water is produced at an average of 14^{o}C when the hot water inlet temperature varies between 70^{o}C and 75^{o}C during the day. Mean chilled energy production of 14 kW is achieved in this mode, which is sufficient to fulfill cooling demand of two office cabins with COP varying between 0.45 and 0.50. By integration of MD+DHW process with the cooling process, whole system turns into tri-generation mode. This mode has an advantage of utilizing the total available energy effectively to produce DHW along with cooling and pure water production. In this mode, single stage membrane distillation unit is integrated with the system leading to a mean hourly production of 4 l/h with an average delta T of 30^{o}C between hot and cold side of MD. As shown in figure 9, an average energy of 30 kW is consumed by MD process out of which 25 kW is recovered for domestic hot water production at a mean temperature of 55^{o}C. In this case, 170W of thermal energy is used for kg of pure water production which is five times less than the reported values in literature [6] without heat recovery option.

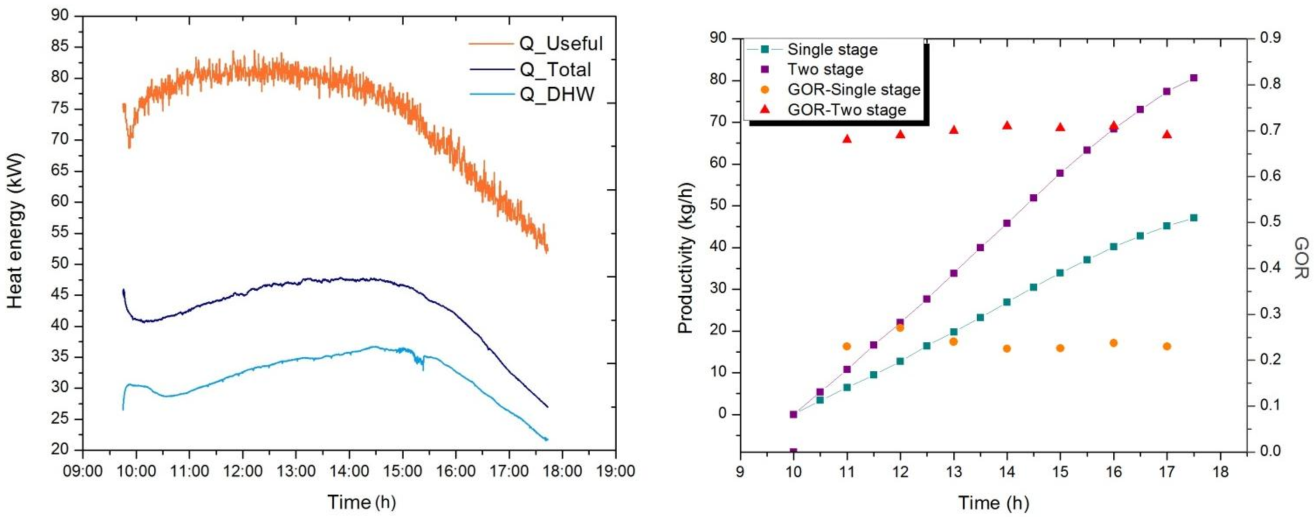

Figure 7. (a) Energy flows in membrane distiller (b) Cumulative productivity and GOR

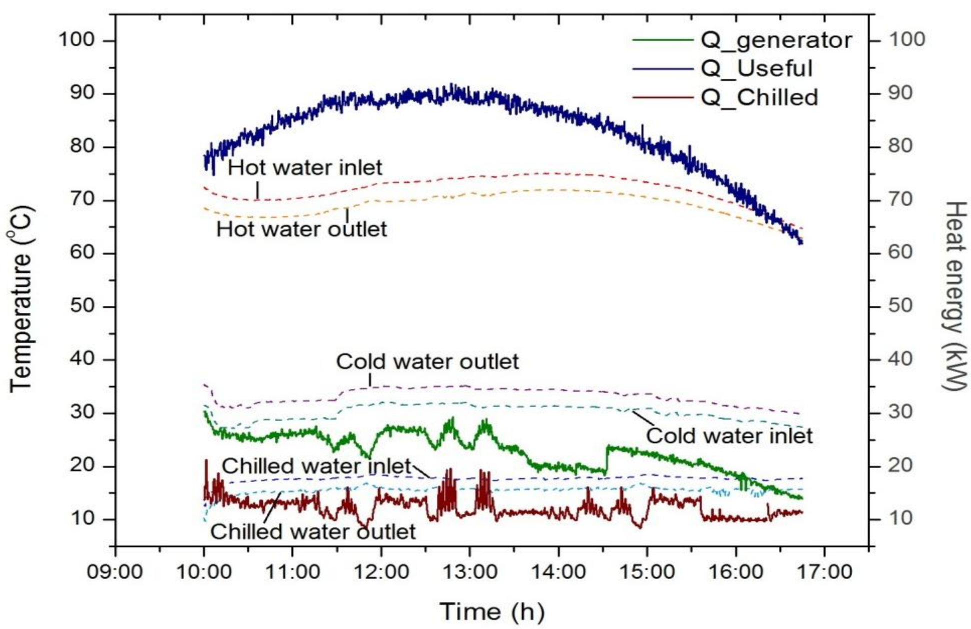

Figure 8. Temperature and energy profile of the absorption chiller in trigeneration mode

(iv) Co-generation of cooling and desalination

The fourth mode of operation includes a two-stage MD module to increase the pure water production rather than obtaining sufficient temperatures for DHW during heat recovery through single stage. Figure 10 shows the performance of two stage MD and DHW system in tri-generation mode. The performance of solar cooling remains similar to the earlier mode of operation. However, compared to the earlier mode of operation, an average of 2kg/h of distilled water is produced from the two MD modules. Since the DHW could not be obtained at sufficient temperatures (average of 50^{o}C), this mode could be termed as co-generation of cooling and desalination instead of tri-generation. This mode is particularly useful in summers during which DHW is not required at high temperatures and also pure water requirement is higher.

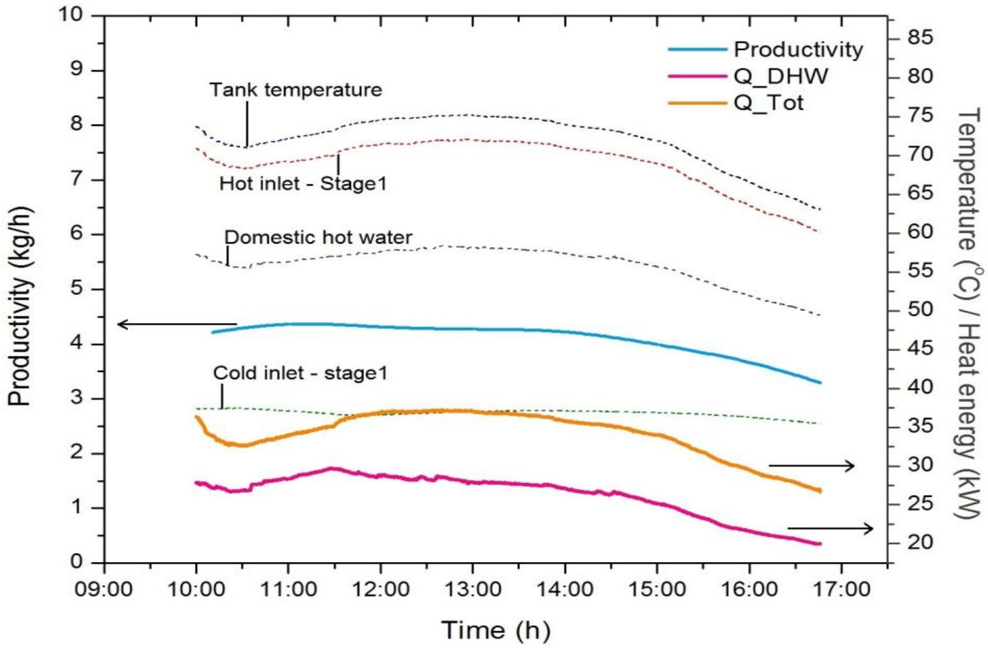

Figure 9. Temperature, energy flows and productivity of MD system in trigeneration mode

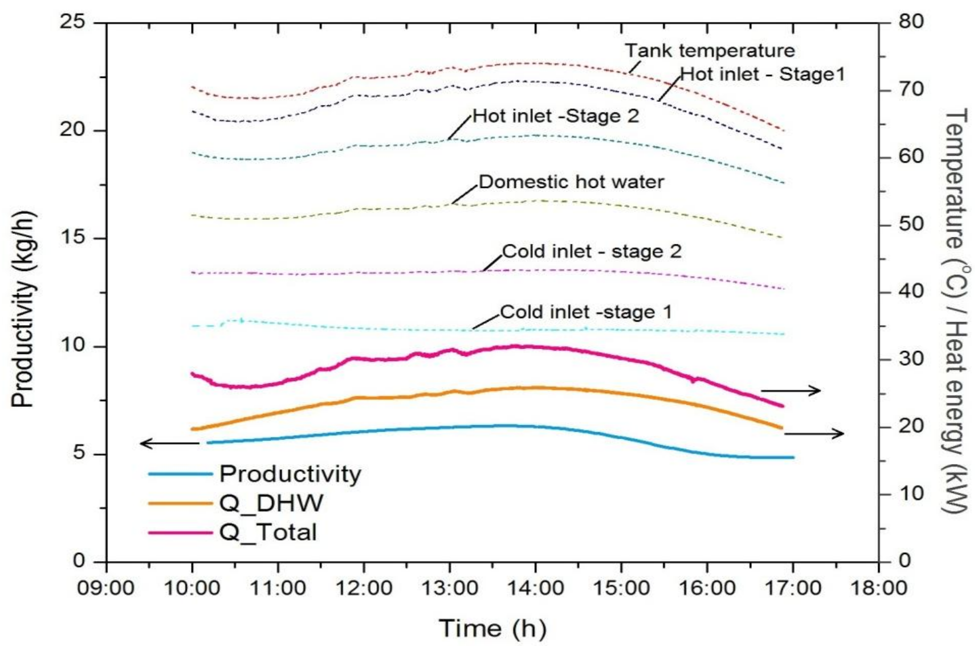

Figure 10. Temperature, energy flows and productivity of MD system in mode (iv)

Conclusions

A solar thermal driven poly-generation system has been developed with a flexibility of operating it in different configurations. Main focus of this paper is to analyze the advantages of combining different processes together rather than operating individually. Experiments have been carried on the system consisting of evacuated tube solar thermal collectors, absorption chiller, membrane distillation unit and heat exchangers for heat absorption and recovery. Operation in different modes shows that co-generation of pure water and DHW is useful in winter when cooling is not needed, tri-generation operations for the remaining time expect the summer in which co-generation of cooling and desalination is more beneficial. In tri-generation mode, heat could be recovered effectively from MD process for DHW production thus reducing overall energy consumption by MD for kg of water production. However, from application view point capacities of different processes are need to be optimized to fit into reasonable application.

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References

1. Kazim, A.M. Assessments of primary energy consumption and its environmental consequences in the United Arab Emirates. *Renew. Sustain. Energy Rev.* 2007, *11*, 426-446.
2. Hussain, H.J. Development of a hybrid powerplant for Kuwait: The simultaneous production of power, fresh water and cooling, Doctoral thesis, Cranfield University, United Kingdom, March 2010
3. Picinardi, A. Cogeneration of cooling energy and fresh water. Doctoral Thesis, University of Bergamo, Italy, 2011.
4. Calise, F.; d'Accadia, M.D.; Piacentino, A. A novel solar trigeneration system integrating PVT (photovoltaic/ thermal collectors) and SW (Seawater) desalination: Dynamic simulation and economic assessment. *Energy* 2014, *67*, 129-148.
5. Kullab, A. Desalination using Membrane Distillation: Experimental and Numerical study. Doctoral Thesis, KTH Royal Institute of technology, Sweden, 2011.-
6. Burrieza, E.G.; Blanco, J.; Zaragoza, G.; Alarcón, D.C.; Palenzuela, P.; Ibarra, M; Gerjak, W. Experimental analysis of an air gap membrane distillation solar desalination pilot plant system. *J. Membr. Sci.* 2011, *379*, 386-396.