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Asim, Muhammad; Imran, Muhammad; Leung, Michael K.H.; Kumar, N. T. Uday; Martin, Andrew R.; Kashif, Faiza

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Experimental analysis of solar thermal integrated MD system for cogeneration of drinking water and hot water for single family villa in Dubai using Flat Plate and Evacuated Tube Solar Collectors

Muhammad Asim[*a, b], Muhammad Imran[b,f], Michael K.H. Leung[a], Uday Kumar N. T.[c] ,
Andrew R. Martin[d], Faiza Kashif [e]

[*a]*Ability R&D Energy Research Centre (AERC), School of Energy and Environment, City University of Hong Kong, Hong Kong Special Administrative Region,*
Email: muhamasim2-c@my.cityu.edu.hk, Tel: +852 5909 3787

[b]*Department of Energy Engineering, School of Engineering, University of Management & Technology C-II Johar Town Lahore 54700, Pakistan*
Email: muhammadimran@umt.edu.pk, Tel: +92 345 5573234

[c]*RAK Research and Innovation Center, American University of Ras Al Khaimah (AURAK), Ras Al Khaimah, United Arab Emirates (UAE),*
Email: uday.kumar@aurak.ac.ae, Tel: +971 501954502

[d]*Department of Energy Technology, KTH Royal Institute of Technology, 100 44 Stockholm, Sweden,*
Email: andrew.martin@energy.kth.se, Tel: +46 87907473

[e]*Department of Structures & Environmental Engineering, University of Agriculture Faisalabad,*
Email: faizakashif054@gmail.com, Tel: +923314858833

[f]*Department of Mechanical Engineering, Technical University of Denmark, Building 403, 2800 Kongens Lyngby, Denmark,*
Email: mimran@mek.dtu.dk, Tel: +45 71323659

Corresponding Author:
Muhammad Asim
muhamasim2-c@my.cityu.edu.hk
Tel no.: +852 5909 3787

Abstract

This paper presents the experimental analysis performed on solar thermal integrated membrane distillation system using flat plate and evacuated tube collectors. The system will be utilized for cogeneration of drinking water and domestic hot water for single family in Dubai comprising of 4 to 5 members. Experiments have been performed in RAKRIC (Ras Al Khaimah Research and Innovation Centre) facility. The experimental setup has been installed to achieve the required production of 15-25 L/day of drinking water and 250L/day of hot water for domestic purposes. Experiments have been performed on membrane distillation setup at optimized flow rates of 6 L/min on hot side and 3 L/min on cold side for producing the desired distillate. The hot side and cold side MD temperature has been maintained between 60°C-70°Cand 20°C-30°C. The total annual energy demand comes out to be 8223kWh (6000 kWh is for pure water and 2223 kWh for hot water). The optimum aperture areas for flat plate and evacuated tube collector field have been identified as 8.5 m^2 and 7.5 m^2 respectively. Annual energy consumption per liter for pure water production is 1 kWh/L, 0.85kWh/L and 0.7kWh/L for different MD hot and cold inlet temperatures.

Keywords

Membrane Distillation, RAKRIC, Flat Plate Collectors, Evacuated Tube Collectors, Annual Energy Demand.

Nomenclature

MD	Membrane Distillation	DCMD	Direct contact membrane distillation
SDHW	Solar Domestic Hot Water	VMD	Vacuum membrane distillation
DHW	Domestic Hot Water	SGMD	Sweep gas membrane distillation
MENA	Middle East and North African	TDS	Total dissolved solids
AGMD	Air gap membrane distillation	m^o	mass flow rate of water (kg/s)
Q	Thermal Energy Consumed	T_{hout}	Hot Water Outlet Temperature (^{0}C)
T_{hin}	Hot Water Inlet Temperature	RO	Reverse Osmosis
RAKRIC	Ras Al Khaimah Research and Innovation Centre		

1 Introduction

The unavailability of potable water resources in Arab countries, specifically in UAE, has affected many lives and livelihood of inhabitants living there. In arid regions, water is very precious commodity. The issue of water shortage in these countries likely to approach the crisis level because the groundwater resources are nonrenewable and surface water resources and unavailable [1]. The drastic shortfall of rain and unavailability of the sufficient water resources are deteriorating the water quality in UAE [2].

UAE is one of the most rapidly growing countries in Middle East and North African (MENA) region showing the abrupt increase in population in past few decades. In 2013, the average consumption of bottled water per resident is 141 liters as compared to the global average of 37.5 liters per person. According to the survey of Euro monitor International, more than 1 billion liters of bottled water is sold every year in UAE generating total revenue of about 1.4 billion dirhams. By this growth rate, the bottled water will generate revenue of about 2 billion dirhams by the end of 2019 [3].

With a low average precipitation rate in UAE (78mm per year) as compared to United States (715mm per year) and Korea (1274mm per year) [5], the bottled water consumption is increasing creating alot of stress on underground aquifers. UAE is amongst the top ten countries having highest per capita domestic water consumption (550 liters per day per person) which is twice the global average (250 liters per day per person) [4].The water demand in UAE rises exponentially every year because of the high temperature, increase in domestic water consumption, rapid population, industrial growth and low rainfall. The low precipitation rates, scarce rainfall and limited water resources of UAE are some of the major problems that can only be solved by discovering new water resources.

According to a study conducted by Italian Trade Commission (ITC), the domestic household water consumption in UAE is about 24% and only 9% is utilized by the industrial sector whereas the agriculture sector consumes about 67% [5]. In future, the per capita availability of the water will be reduced to half and serious shortfall of the water will occur.

Therefore, in order to fulfill the demand of drinking water and domestic hot water, seawater desalination is considered the most suitable strategy. According to International Desalination Association (IDA) (as of 30th June 2015), the total number of desalination plants that has been installed worldwide over 150 countries counts 18426 with a total global desalination capacity of 86.8 million cubic meters of water per day. More than 300 million people around the world depend on desalinated water to fulfill their daily needs [6]. UAE is the world's

second largest producer of desalinated water after Saudi Arabia, which pumps nearly 2.02 billion cubic meters of desalinated water per year [7].

In UAE, people mostly use the bottled water for drinking purpose which is supplied to the end users in the form of 5 gallon containers. The yearly consumption of bottled water in UAE is about 1.2 billion liters out of which 60% are "home office delivery" in bulk supplies [8]. The bottled water consumption has been increasing day by day resulting in increasing demand for drinking water. Considering the above statistics regarding drinking water trends in UAE, a sustainable way needs to be adopted in order to fulfill the demand of pure drinking water and domestic hot water.

A lot of thermal and physical desalination technologies are well established commercially in order to desalinate water for its use in domestic as well as for industrial applications. Membrane distillation (MD) is a promising desalination technology which can be used for desalination as well as for recycling.MD processes can be classified into four basic configurations on the basis of the methods to induce vapor pressure gradient and to collect the transported vapors. Direct contact membrane distillation (DCMD) has been the most studied model due to its inherent simplicity [10]. On the other hand, vacuum membrane distillation (VMD) can be used for high output while air gap membrane distillation (AGMD) and sweep gas membrane distillation (SGMD) enjoy the benefit of low energy losses and high performance ratio [11-13]. Membrane Distillation (MD) technique involves the removal of water vapors from warm aqueous feed solution at a temperature below $100\,^{\circ}\mathrm{C}$ and has been proposed as an alternative for producing portable pure drinking water [24].

G.W. Meindersma et al. carried out an industrial research on solar driven membrane distillation system to produce pure water through Air gap membrane distillation (AGMD) to produce the pure drinking water at cost of about $0.50/m^3$, even as low as $0.26/m^3$depending on the thermal heat source [9]. Achmad Chafidz et al. [14] developed portable hybrid solar powered membrane distillation system for production of fresh water using Vacuum Multi-Effect Membrane Distillation. The total volume distillate output during the test was approximately 70 L with an approximate conductivity of 4.7 μS/cm. The average distillate output rate was 11.53 L/h with the maximum of 15.94 L/h at noon time, whereas the distillate flux was in the range of 1.5–2.6 L/m^2 h.

Kullab et al [15] studied the solar thermal integrated air-gap membrane distillation (AGMD) unit having non-concentrating solar thermal collectors. The trials were conducted on this test facility with different parametric analysis (feed stock, Total Dissolved Solid levels, temperature and flow rates)and the data from the experiments and related studies

demonstrated that the MD unit performance remain insensitive to variations in feedstock qualities (e.g. pH, TDS levels)..Banat and Simandl [16]used membranes of different porosities for desalinating water by using Air Gap Membrane Distillation (AGMD) technique. The results demonstrated that the permeate flux increased exponentially with the increase in hot side temperature. The mass flux was steady over time and was affected slightly by increase in salt concentration. Kullab, Alaa [17] performed the numerical and experimental assessment for water desalination using air gap membrane distillation (AGMD) technique. In this research study, the three stage AGMD system performance has been evaluated with saline water (35 g/l of NaCl).. The assessing parameters were water quality and energy consumption. The specific thermal energy consumption came out to be 950KWh$_t$/m^3 for a layout with no heat recovery whereas for a layout model with heat recovery, the specific thermal energy consumption was 850 KW$_t$/m^3.

M.R. Qtaishat, F. Banat [18] tested several small and lab scale plants for MD desalination using solar energy (Photovoltaic panels and solar collectors) and is deemed suitable to operate in small capacities. Even though the main cost is the investment cost but once it is installed and become operational, the system become relatively inexpensive. A. Alkhudhiri et al [19] uses Air Gap Membrane Distillation (AGMD) technique to produce drinking water and analyzed the impact of different operating parameters on the performance of three different membranes (TF200, TF450 and TF1000), with different pore sizes of 0.2, 0.45 and 1μm respectively. He analyzed that with increase in feed temperature, the energy consumption and permeate flux of the membranes increases whereas the coolant temperature decreases.

In view of all the above reasons, a pilot plant setup has been commissioned and installed in UAE capable to fulfill the need of drinking water and domestic hot water for a single family in Dubai comprising of four to five members. The main concern of this study is to perform the experimental analysis and calculating the optimum collector area for solar thermal integrated membrane distillation setup where the thermal energy has been provided by two types of solar collector fields i.e. flat plate collectors and evacuated tube collectors. The experimental analysis has been performed on different solar collector aperture areas to determine the optimized collector area that is required to produce 15-25 L/day of pure drinking water and 250 L/day of domestic hot water under local conditions of UAE.

2   Membrane Distillation

Membrane distillation is a unique separation process based on the transportation of vapors across micro porous hydrophobic membrane ensuring high quality of pure water. This process is driven by the difference in partial pressure across the membrane. This process has been used extensively in research for various applications like seawater desalination, waste water

treatment etc. [24]. In AGMD, the partial pressure difference between the hot and cold side serves as a driving force which allows the molecular water vapors to pass through the micro porous hydrophobic membrane. The suitable hot side operating temperature in AGMD is below 90°C and this process is also very beneficial for recovering the heat from cold side. Even though the water recovery ratio is low for MD but it can operate continuously in batch mode.

H.C Doung et. al optimized the single pass pilot AGMD plant for sea water desalination with respect to distillate production as well as thermal and electrical energy consumption. Pilot setup delivered a better performance (i.e., higher distillate production rate and lower specific thermal and electrical energy consumption) when operating at elevated evaporator inlet temperature [26]. D U. Lawal et al studied the performance of double stage AGMD unit at various AGMD operating parameters. From experiments, it was observed that the double stage AGMD is capable of producing a maximum of 128 kg/m^{2}h of distillate production. The system uses the common cooling chamber to provide the sufficient cooling for two feed chambers [27].

This research study is based on small scale MD system which has some advantages over other conventional water purification techniques like Reverse Osmosis (RO). The MD process is capable to operate below atmospheric pressure (>1bar).... The main application areas for AGMD involve desalination, water treatment, food industry and chemical industry. Fig.1shows the basic idea behind the concept of air gap membrane distillation.
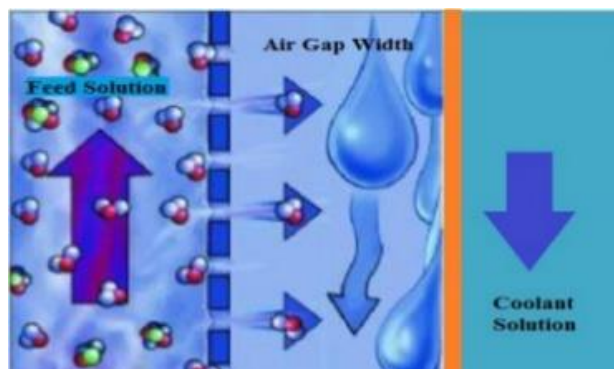

Figure 1: Air Gap Membrane Distillation Technique [20]

The air gap membrane distillation cassette that is used in the study is shown in the Fig.2. It has a plate and frame configuration with the following specifications.

- Cassette material is Hydrophobic Polytetrafluoroethylene (PTFE) membrane.
- Pore size is 0.2µm having 280µm thickness

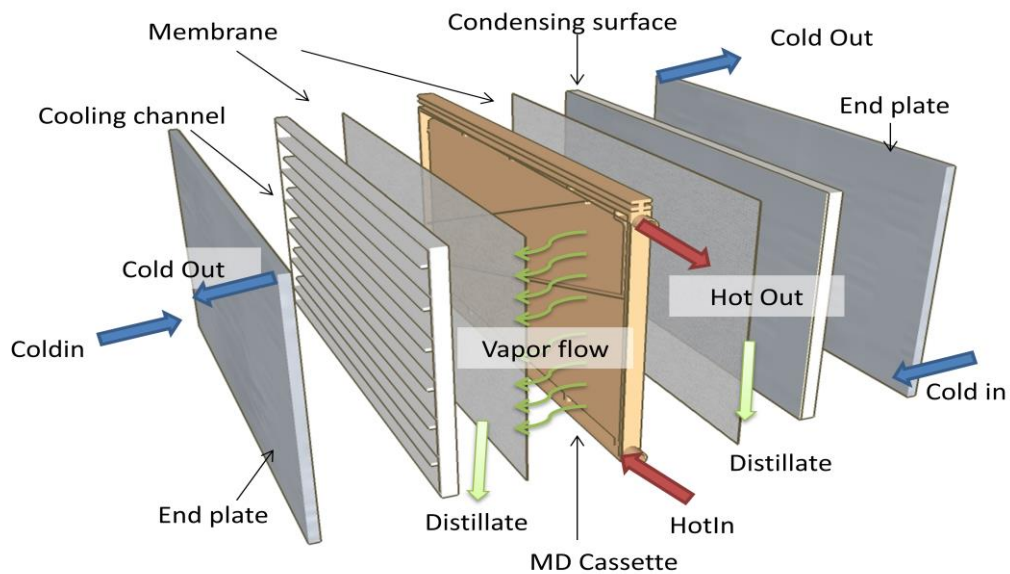- 80% Porosity having Membrane area of $0.2m^2$

Figure 2: Laboratory Sketch of Membrane Distillation (MD) Module [28]

The AGMD module shown in Fig 3 contains two aluminum condensing plates with 2.4cm gap between them. Cooling channels, in serpentine shapes, are present behind the condensing plates, and are covered with rigid aluminum end plates. The two membranes each having the surface area of $0.1m^2$ are thermally welded with the PTFE frame. The hot water enters from the bottom of the cassette and flows out from the top of the cassette after exchanging heat with the cold water that is entering into the cassette. An air gap of 5mm is maintained on both side of the cassette. The air gap is reduced to about 1mm when the cassette gets filled with water due to bulging of the membrane outwards.

The principle and laboratory sketch of air gap membrane distillation shown in Fig 3 is summarized in three different channels as:

- Hot Channel – Hot water enters into the cassette, makes contact with the membrane forming vapors which passes through the membrane.
- Air Gap – An air gap is maintained between the outer surface of the membrane and condensation plates which allows the vapors to condense resulting in distillate collection at the bottom.
- Cold Channel – The cold water flows from the other side of the condensation plate which absorbs the latent heat of vaporization of water.

Side view of the MD cassette and membrane are shown in the Fig.3(a) and 3(b)

Figure 3(a): Side View of MD Cassette [28]   Figure 3(b): PTFE Membrane Cassette inside module [28]

3   Methodology& Research Approach

For carrying out the research study and to perform the experimental analysis, a solar thermal integrated membrane distillation system prototype setup has been designed and installed in UAE. This system is capable of producing the pure drinking water and domestic hot water simultaneously in dry UAE region for a single family of 4 to 5 persons. The benchmark figures has been set as 15-25 L/day of pure drinking water and 250 L/day of domestic hot water using flat plate and evacuated tube collector arrays of varying aperture areas [23]. The objective is to design, install and perform the experimental analysis on this setup for achieving the required drinking water and domestic hot water for single family villa in UAE. Moreover, integrating the solar thermal system with the MD to purify the municipal water is one of the main objectives of the research study.

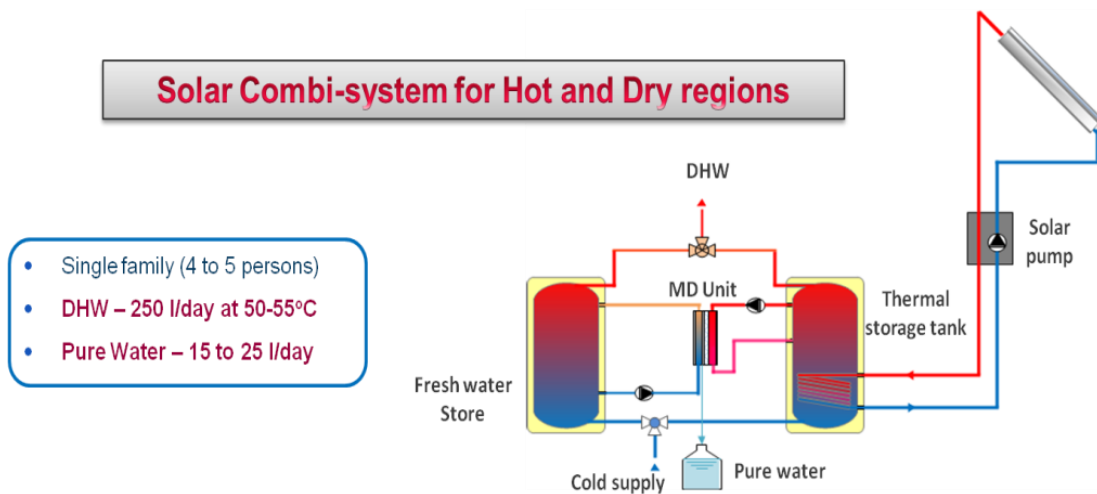Fig. 4shows the prototype of the solar thermal integrated membrane distillation system.

Figure 4: Solar Thermal Integrated Membrane Distillation Prototype Setup [28]

Due to low conduction losses, temperature polarization effects and better internal heat recovery as compared to other membrane distillation techniques, the air gap membrane distillation technique has been used in this research study for experiments.

The whole experimental setup has been divided into three main circuits which are:

- Solar Thermal Heating Circuit
- Solar Domestic Hot Water Circuit
- Membrane Distillation Circuit

The experimental facility has been designed, installed, commissioned and operational in RAKRIC (Ras Al Khaimah Research and Innovation Centre).

4 Solar Domestic Hot Water Circuit

The availability of high solar radiation in MENA region enables us to use solar domestic hot water systems. Typically, the solar domestic hot water systems that have been installed are designed for the 60-70% annual solar fraction [22]. Back up electric heating is used for the rest of the time to gain energy. In MENA region, the solar fraction throughout the year is high enough to provide heat in order to produce hot water (with 90% solar fraction) but at such high temperatures and solar fraction, the designers have two main concerns.

- Due to the high stagnation temperature in peak summer times, the system remain idle most of the time and the demand is fulfilled by back up heaters.

- A Legionella bacterium is one of the main concerns in idle systems. The backup heating mechanism kills this bacterium by heating the water up to 60°C. This makes the solar domestic hot water systems inefficient. Since there is good possibility of operating the system at higher efficiencies [22].

Therefore, the proposed solar thermal integrated membrane distillation (MD) setup would be an ideal setup in order to enhance the annual solar fraction. This integrated setup also utilizes the extra heat in summers for the production of pure drinking water. In addition to this, mandatory rules and regulations by UAE local authorities encourages to use solar domestic hot water systems from energy conservation point of view.

ESTIDAMA, an urban planning council of Abu Dhabi, is very much interested to encourage people to use solar thermal systems. Therefore, ESTIDAMA has been working with distributors and manufacturers to design the standard sizes of solar thermal systems for variable sizes bedroom villas [25]. So, UAE region could be realized as one of the ideal region to use and implement the concept of solar thermal integrated system keeping in view the conditions, rules and regulations by local authorities.

5 Experimental Setup: Integrated MD System

5.1 Design of Experimental Field Setup

The whole experimental setup is based on the combination of three circuits as mentioned in methodology and research approach.

- Solar Thermal Circuit: This circuit includes solar collector (flat plate and evacuated tube) arrays, complete solar station and thermal storage tank.

- Domestic Hot Water Circuit: This circuit is comprised of two-way mixing valves, storage tank for collecting domestic hot water and cold water supply tank.

- Membrane Distillation Circuit: This circuit contains the single cassette MD module, storage container for distillate flux and storage tank for feed water.

These three circuits constitute the solar thermal integrated MD system with required sensors to monitor the temperature, pressure and flow rate shown in Fig.5.
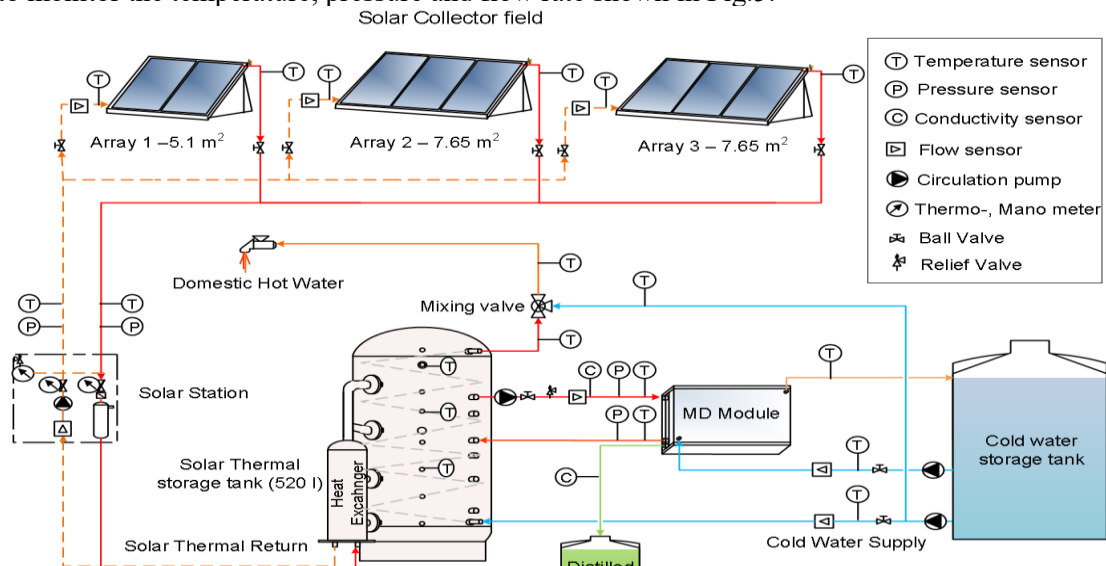

Figure 1:Solar Thermal Integrated MD Experimental Field Setup at RAKRIC Site [21,28,29]

Since the evacuated tube collector field has already been installed onsite, so only flat plate collector design of various aperture areas has been shown in the Fig. 5.

5.1.1 Solar Thermal Circuit

As mentioned earlier, solar thermal circuit comprised of the flat plate and evacuated tube solar collectors. Each flat plate collector has an absorber area of 2.55 m^2. In total, there are total 8 flat plate collectors of 20.5 m^2 absorber area and they have been arranged into the arrays of different configurations in order to have more operation options for finding out the feasibility of different experiments for co-generation. As shown in Fig 5, the first array has an area of 5.1 m^2, the second and third arrays have the respective areas of 7.65m^2. Similarly, for evacuated tube collectors, RAKRIC facilities have an evacuated tubular collector field having aperture area of 9.024m^2 (3 collectors, 16 tube) as shown in Fig 6(e). In this research study,

the experimental results for flat plate collector having aperture area of 11.85 m^2 and 7.08 m^2 and evacuated tube collector having aperture area of9.024m^2 have been investigated. In this circuit, the energy transfer mechanism is same for both type of collectors and piping is done in such a manner so that we can operate the flat plate collectors and evacuated tube collectors in variety of arrays combination. The energy from the solar collectors has been transferred to the storage tank to the membrane distillation circuit and domestic hot water circuit. To start the solar thermal circuit, the solar collector circuit has been pressurized and solar station pump circulates the water in solar collector arrays and thermal storage tank. The flow rate, temperature and pressure in the solar circuit is continuously monitored and adjusted by the inline flow meters, pressure and temperature sensors. The water flow rate has been adjusted and available solar radiation heats the water inside the collectors. Thermal energy from the collectors is transferred to a stratified thermal storage tank.

5.1.2   Solar Domestic Hot Water Circuit

Solar domestic hot water system consists of storage tank and control valves. Control valves includes solenoid valve to control quantitative draw off the domestic hot water as per requirement of the user and mixing valve for control of desired temperature and mass flow rate of the domestic hot water. Copper pipes insulated with Poly-isocyanurate have been used to connect the domestic hot water circuit with thermal storage tank. The cold water is drawn off from the cold water storage tank by hydraulic pump. The hot water is drawn off from the hot water storage tank at a flow rate of 3L/min. The cold and hot water are mixed together manually using 3-way valve to get the desired temperature of domestic hot water (45-55°C). The desired temperature is achieved by the manual operation of the mixing valve. Once the desired temperature level has been achieved, the mixing valve position is fixed. The domestic hot water is collected in a separate storage tank.

5.1.3   Membrane Distillation Circuit

Single cassette MD module has been used in experimental setup. For hot and cold water inflow into the cassette, both hot water storage tank and cold water storage tank have been connected with cassette. Municipal water supply has been used as feed water. The circulation of hot water in the circuit is ensured by the hot water circulation pump. The measurement system consists of pressure sensor, temperature sensor, flow meter, and conductivity sensor and are installed in all major measuring points as shown in Figure 5. Initially, the different components in MD circuit have been set to specific values for producing the drinking water and domestic hot water as per the energy available from the solar collectors. The experimental results were based on the input conditions fed into the MD system. The results were used as a comparative measure to estimate that their deviation from the standard benchmarks or desired results.

In order to transfer the hot water from storage tank to the MD system, pumps are used. There is also a solar thermal return line from MD to the low temperature zone of the storage tank to conserve energy from water after exchanging heat in MD module. Due to this efficient energy recovery from the return line, the energy demand of MD will be reduced since we are recovering the heat and sending the water back to the thermal storage tank.

6   Installation and Commissioning

The flat plate collector frames were designed and fabricated as per geometrical details of the solar collectors. The installation of flat plate collector frames is shown in Figure 6 (a). To achieve maximum solar radiation over the year, especially in winter, solar collectors are installed facing south with tilt angle of 35°, as shown in Figure 6 (b). In next step,   copper piping is used to connect solar arrays with solar station. To reduce heat loss form copper piping, the whole copper piping network is insulated with Poly-Isocyanurate insulation with insulation thickness of 50mm thickness and density of 35-40 kg/m^3. The solar circuit is connected to stratified solar thermal storage tank, as shown in Figure 6 (c). For simultaneous production of hot water and pure drinking water, storage tank is further connected to MD system and Solar Domestic Hot Water (SDHW) system. Thermal storage tank is connected with MD system and cold water storage tank via Chlorinated Polyvinyl Chloride (CPVC) piping, as shown in Figure 6(d). Furthermore, the experimental setup is also integrated with an array of evacuated tubular collectors at RAKRIC facility for comparative analysis during the experimental investigation of MD system, as shown in Figure 6(e).
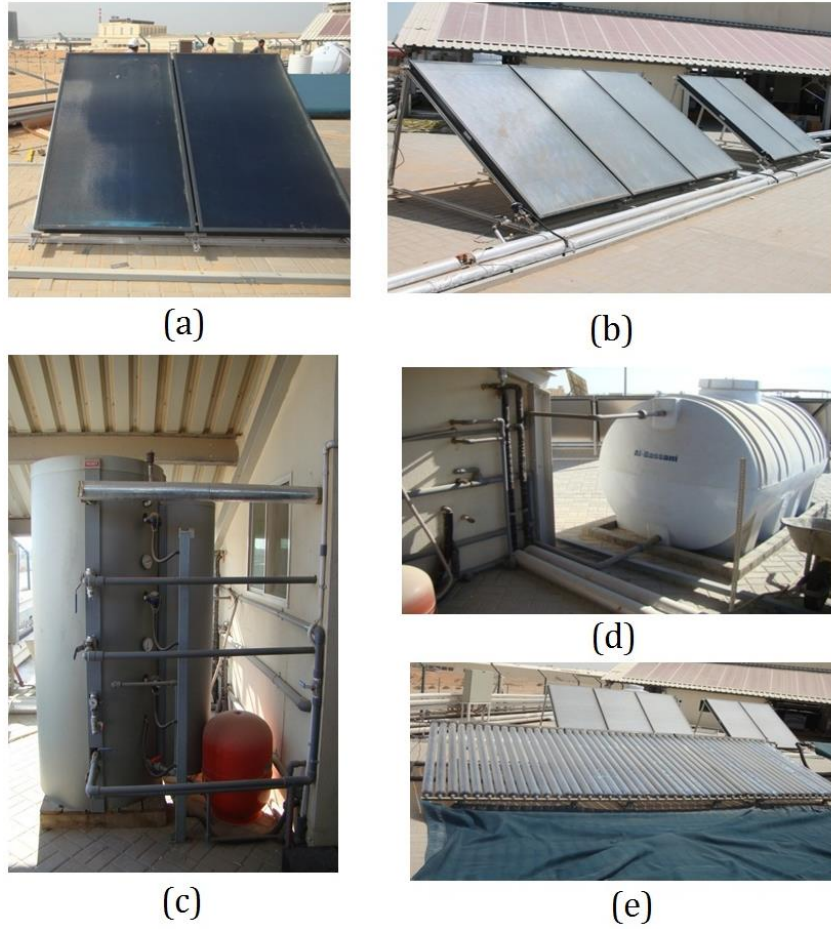.

Figure 2: [a] Flat Plate Collector Installation [b] Angle Adjustment for Collectors

[c] Stratified Thermal Storage Tank [d] Municipal Water Storage Tank

[e] Installed Evacuated Tube Collectors at RAKRIC [28,30]

Experimental facility with complete MD unit and the solar station circuit is shown Figure 7.

Figure 3: Solar Station and MD Circuit [28,30]

7 Experimental Analysis

In next phase, comprehensive experimentation has been performed to investigate the effect of different parameters on distillate production of the integrated pilot plant. Thermal performance of the flat plate and evacuated tube collectors based on their aperture areas has been investigated for feasibility assessment. The optimum area of the flat plate and evacuated tube collectors of integrated pilot plant is estimated for benchmark production. A detailed simulation model has been developed in simulation environment of PolySun. The simulations results of the model are compared with the experimental results. The detail procedure is described below.

7.1 MD Operational Parameters

For experimental analysis, detailed experimental approach has been prepared. The operating parameters and their logical bounds of the integrated pilot plant are shown in Table 1.

Table 1: MD Operation parameters for experimental analysis [28]

Operational Paramentes of MD	Range
Concentration of Muncipal Feed Water	750 -1000 ppm
Flow Rate of MuncipalFeed Water	4-8 l/min
Flow Rate of Coolant	2.5 l/min, 3 l/min, 3.5 l/min
MD Hot Inlet Water Temperature	50°C - 75°C
MD Cold Water Temperature e	30°C - 40°C

7.2 PolySun Simulation Model

The PolySun simulation model has been shown in Fig. 8. This model is the replica of the
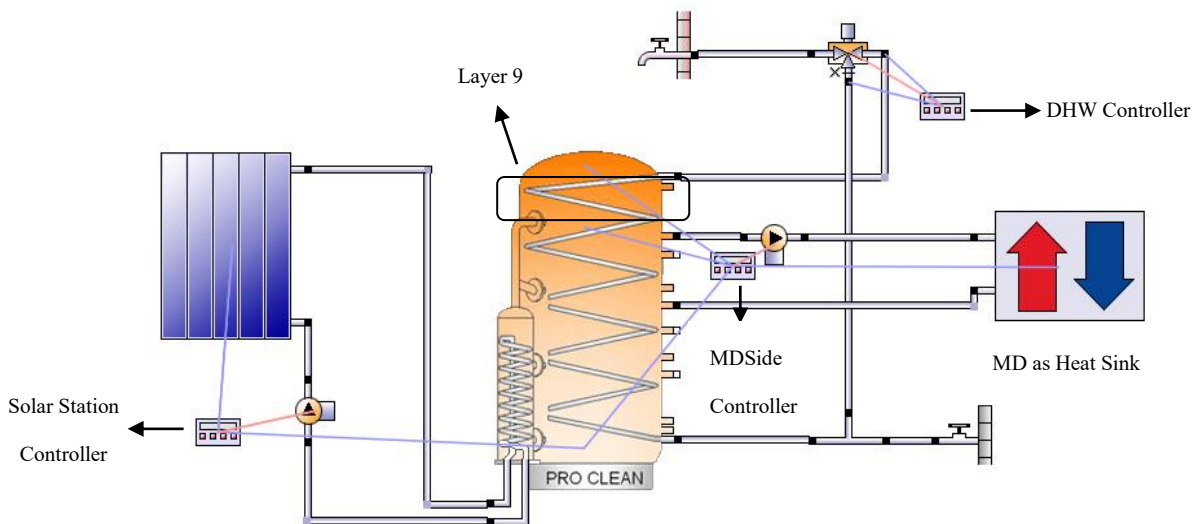
Figure 4: Schematic diagram of PolySun Simulation Model [28]

experimental setup installed onsite for experimentation purpose. For replicating solar thermal circuit, the inbuilt system components in PolySun has been selected and exact specifications, (as were in experimental setup) like pipe lengths, flow rates, temperature settings, insulation thickness etc, has been provided to simulate the system. Solar pump will be switched ON when the temperature difference between the collector outlet and tank lower level will be 6°C and switches OFF when the temperature difference will be less than 4°C. Since there is no inbuilt MD system present in the PolySun simulation environment, so it is experimentally replicated with energy sink having specific annual demand profile. In the simulated model, the controllers for MD sink and DHW have also been used along with the solar station circuit.

7.2.1   MD Energy Sink Profile

As mentioned in section 7.2, there is no inbuilt component to model the MD sink in PolySun environment. So a heat sink component has been used to estimate the energy consumption of MD. A monthly demand profile for the sink has been generated which is based on the minimum temperature levels that could be obtained from the storage tank layer from where the hot water is fed into the MD. With a minimum aperture area of 7 m^2, the annual daily simulations for tank layer 9, MD hot in and hot out temperatures have been shown in Fig.9. Using this profile, the average hot in temperature profile has been shown in green color in the same figure.

With the increase in the solar radiation, the tank starts to charge resulting in the increase in the tank top layer temperature. It is obvious that as the tank top layer increases, MD hot in temperature also increases resulting in better heat exchange rate.
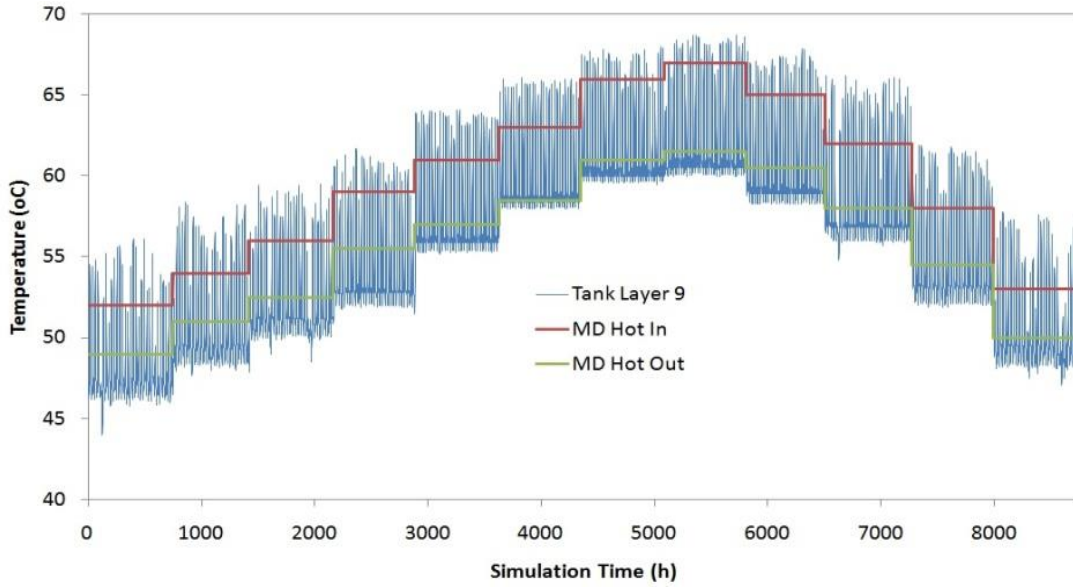
Figure 5: MD Energy Sink Temperature Profile [28]

7.2.2   Domestic Hot Water Profile

For technical viability of the system, it is important to estimate the annual and monthly temperature profiles of the hot and cold water to meet required domestic hot water demand. The standard value of hot water consumption is taken as 50 liters/day at 50°C based on the single person in UAE [23]. This data is further extended to a single family of 5 members, 250l/day, and used in the simulation and experimentation.

For a single family in UAE, daily hot water consumption profile is shown in Figure 10. The results were obtained from the simulation model developed in PolySun. The constant daily hot water consumption of 250l/day is assumed over the year. However, three peek of hot water consumption are observed in a single day. As already discussed, the desired temperature of hot water of 50°C is controlled via mixing valve, shown in Figure 8
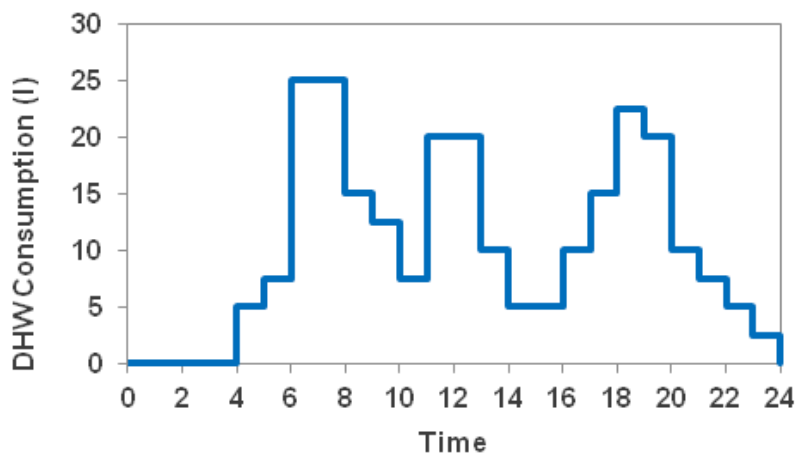

Figure 6: Daily DHW Withdrawal Profile [28]

7.2.3 Cold Water Profile

The annual temperature profile of cold water plays a significant role in the DHW demand. In present study, average tap cold water temperatures are taken as 14°C for winter and 30°C for summer as per ESTIDAMA recommendation [23]. These recommended temperatures are used in the simulation model in PolySun and the annual profile of monthly averages temperature were obtained, shown in Figure 11. The simulation results of the annual profile of monthly averages temperature were compared with daily ambient temperature of corresponding month. The simulation results show reasonable agreement with the real-time average monthly ambient temperature. As discussed earlier, heat recovery from cold side of MD effects the overall thermal energy demand. Therefore, it is of crucial importance to analyze the temperature profile of return cold water from MD unit. The lab experimental results indicate that the temperature profile of return cold water from MD unit will increase by 4°C in winter and 10°C in summer under local conditions of UAE. The temperature profile of return cold water from MD unit is shown in red line in Figure 11.
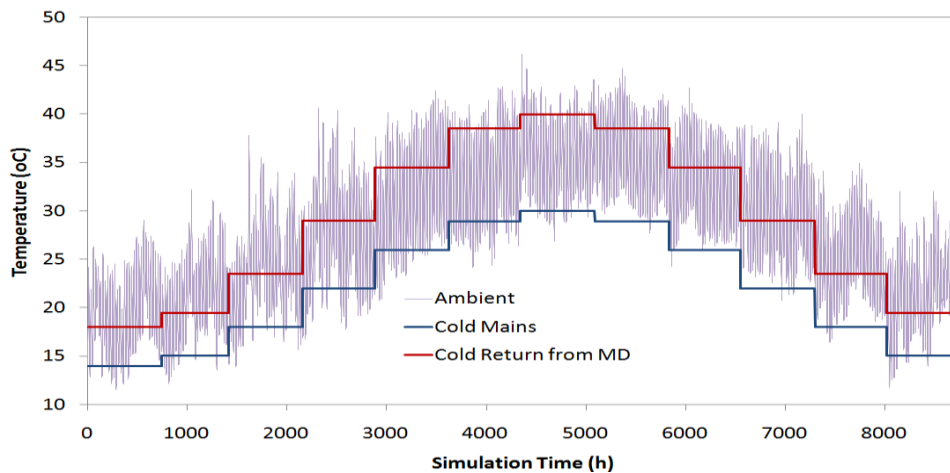

Figure 7: Cold Water Temperature Profile [28]

7.3 Comparison of Experimental and Simulation Data:

Keeping in view the abovementioned profiles, the experimental analysis have been performed on the setup and real experimentation data inputs have been used to simulate the results. The experiments have been performed on different days in the month of July. Different configurations of flat plate collectors and evacuated tube collectors with different aperture areas have been employed for experimentation purpose. The simulated and experimental results have been compared to determine real energy demand of MD in comparison with

energy sink profile used in simulations. MD hot inlet and outlet temperatures are very crucial and depend on various parameters including solar radiation, collector outlet temperature and thermal storage tank top layer temperature.

7.3.1 Flat Plate Collectors

Aperture area 11.85m²: The flat plate collectors have arranged in such a way so as to form the two arrays (5 collectors). One array has two collectors whereas the other array has three collectors. The total aperture area of the collectors is 11.85m². To achieve the high outlet water temperature, the specific flow rate in solar circuit is kept low. The simulations and experimental data for energy consumption estimates on 11th July is provided in Table 2. From the simulations, for 12 hours operation, the total solar yield is 31.3 KWh. It is important to notice that MD uses 20 KWh (64% of total solar yield) of energy whereas for DHW, the energy usage is only 5.85 KWh (18.5% of total solar yield).

Table 2: Simulation and Experimental Data: Flat Plate Collector (FPC) Aperture Area 11.85m²[28]

Parameter	Value	Remarks
Specific Flow Rate	11.2 l/h/m²	Low for achieving high outlet temperature
Simulation Data		
Total Solar Yield	31.3 KWh	12 Hours
MD Energy Use	20 KWh	64% of total solar yield
DHW Energy Use	5.85 KWh	18.5 KWh
Losses %	17.5%	Long length piping-more losses
Experimental Data		
Distillate Collected	16 liters	10 Hours Plant Operation
MD Energy Use	12.92 KWh	0.804 KWh/liter
DHW Energy Use	5.63 KWh	Not withdrawn according to domestic hot water profile
Estimated Values		
Extra Available Energy	7.3 KWh	Total$_{Sim}$-Total$_{Exp}$
Estimated Distillate Volume	25 Liters	36% more water production

From experiments, assuming the same solar yield, it has been found that MD utilizes 12.92 KWh (41% of total solar yield) of energy whereas the energy utilization for DHW is 5.63 KWh (18% of total solar yield). Assuming the same solar yield for the experiments, only 41% of total yield has been utilized by MD and 18% for DHW production. The total volume of distillate collected was 16 Liters with energy consumption of 0.804kWh/liter. Practically

the losses could be avoided by proper insulation around the copper piping and by installing the thermal storage tank near to the collectors.

If we assume the simulation results as real case scenario, then it is obvious that extra available energy used for MD is 7.3 KWh (23.3% of total solar yield). By utilizing this energy, more pure water can be produced. It has been estimated that 36% more water production can be obtained with same operational hours of MD. The experimental and simulation plots for MD hourly energy consumption along with collector outlet temperature, tank top temperature and MD hot inlet temperature have been shown in Fig. 12. It can be observed that there is a difference of 5°C between the simulated and experimental values of collector outlet temperatures and MD energy consumption trend is also greater in simulated data.
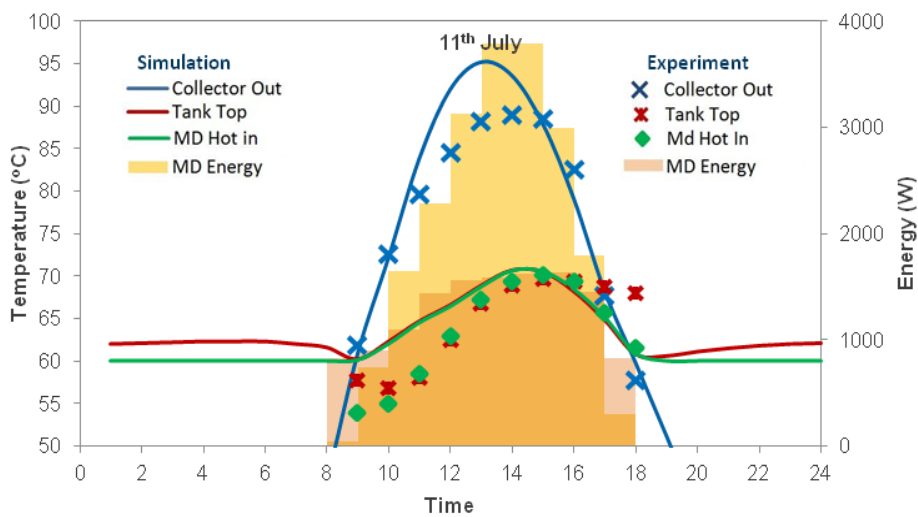

Figure 8: MD Temperature and Energy Profile [28]

During the early hours of plant operation, the MD hot inlet and tank top temperature also shows the slight drop. The reason for the drop could be explained due to the fact that the DHW has been withdrawn in the morning hours instead of following the proper withdrawal profile as shown in Fig. 13. This sudden drop in the tank top temperature is due to the uncontrolled draw off of the DHW. The vertical green bars show the hourly simulated values for DHW energy profile whereas the pink vertical bars are the experimental values. The average domestic hot water that has been withdrawn from experiments was 273 Liters at an average temperature of about 50°C.
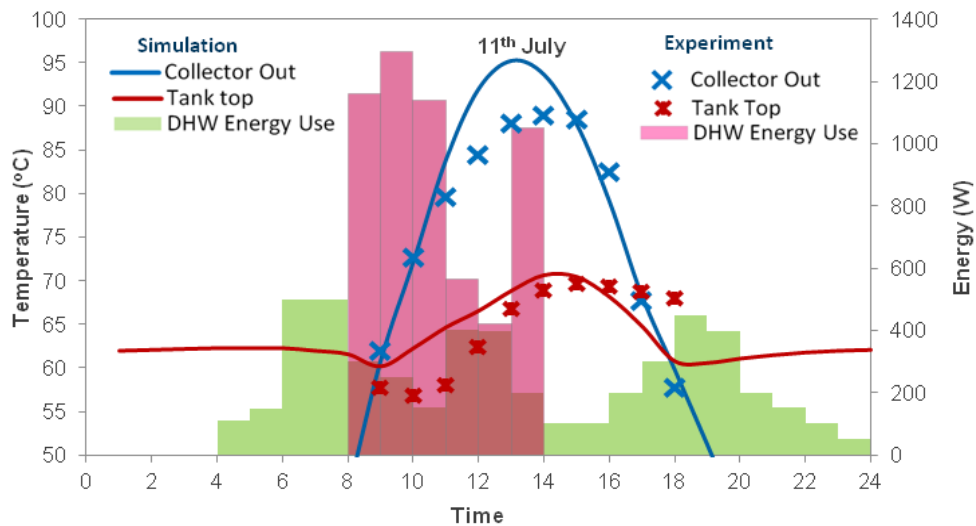
Figure 9: Domestic Hot Water (DHW) Temperature and Energy Profile [28]

Aperture area – 7.08m^2: The 3 flat plate collectors have been aligned now into a single array constituting a total aperture area of 7.08m^2 which is the lower aperture area. To maintain a balance between the outlet temperature and harvested thermal energy, the specific flow rate has been adjusted slightly higher from previous experiments. From Table 3, the values clearly show that the solar yield reduced due to less collector area. The simulated results for 10 hours plant operation shows the total solar yield of 21.2KWh. Out of this, MD uses 11.3 KWh of energy (53.5% of total solar yield) whereas DHW uses 5.85 KWh (27.5% of total solar yield) of energy to produce the fixed volume of hot water. Similarly, from experimental analysis for 9.25 hours of plant operation, MD energy consumption is 8.3 KWh (39% of total solar yield) whereas DHW consumes 5.2 KWh (24.5% of total solar yield) of energy. The total volume of distillate collected was 8.5 Liters with energy consumption of 0.975kWh/liter at MD hot inlet temperatures ranging from 50-55°C.

Table 3: Simulation and Experimental Data for Flat Plate Collector of Aperture Area 7.08m^2[28]

Parameter	Value	Remarks
Specific Flow Rate	17 l/h/m^2	Medium flow conditions
Simulation Data		
Solar Yield	21.2 kWh	12 Hours
MD Energy Use	11.3 kWh	53.5% of total solar yield
DHW Energy Use	5.85 kWh	27.5% of total solar yield
% of losses	19%	Long lecgth piping
Experimental Data		
Distillate Collected	8.5 liters	9.25 Hours of Operation
MD Energy Use	8.3 kWh	0.975 kWh/l
DHW Energy Use	5.2 kWh	3 Peak Withdrawal
Estimated Values		
Extra Available Energy	3.7 kWh	Total$_{Sim}$ − Total $_{Exp}$
Estimated V$_{Dis}$	12.5 liters	32% more production

As compared to the previous experiments, the temperature profiles obtained for the simulation and experiment results shows large variation as shown in Fig. 14. There is a temperature difference of around 10°C between MD hot inlet and tank top. The low tank temperature is merely due to increase in flow rate and pipe losses collectively. Therefore, it's reasonable to estimate excess energy taking simulation as actual case and hence 32% more distillate production could be obtained. However, the actual demand of 20liters/day has not been fulfilled by this collector array configuration which further suggests the fact that MD system must need to be operated for more hours.
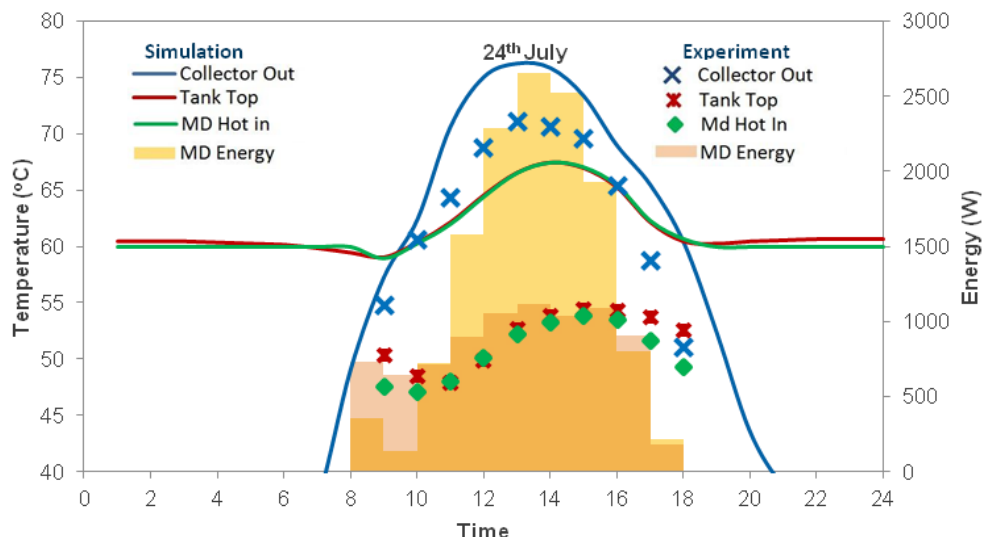

Figure 10:MD Temperature and Energy Profile [28]

Instead of random withdrawal of DHW as in previous case, DHW has been withdrawn following 3 peaks of demand profile. The experimental data for tank top shows the dips in the morning plant operation and rapid discharge of the storage tank. This is because of the simultaneous operation of MD and DHW circuits.

Around the noon time, the temperature starts to stabilize approaching to a trend similar to the simulation data. So from the results obtained, it is obvious that the aperture area of 7.08m^{2}for the flat plate collector is insufficient to fulfill the benchmark demand for MD and DHW.

7.3.2   Evacuated Tube Collectors

The RAKRIC facility have an evacuated tubular collector field array consisting of 3 collectors 16 tubes with aperture area of 9.024m^2. In order to maximize the thermal energy yield, the specific flow rate has set high (manufacturer's recommendation). The experimentation results have been summarized in Table 4. It is obvious from the simulation results that the obtained solar yield from evacuated tube collectors is higher than the yield obtained with flat plate collectors having more aperture area (Section 7.3.1) which confirms fact that higher flow

rates leads to high thermal yield. From total solar yield of 36.4 kWh, MD system consumed 26kWh (71.5% of total yield) and DHW system consumed 5.85 kWh (16% of total yield) whereas the 12.5% of energy has been lost due to long length of piping installation. The heat losses have been minimized due to turbulent flow conditions. Moreover, from the experimental results, it was observed that 44% of the total yield has been utilized for MD (16 kWh) and 14.3% (5.2 kWh) for DHW. Since the estimated production of distillate is 28 liters which means that 40% more production can be possible with this setup of ETC of aperture area of 9.024m^2.

Table 4:   Simulation and Experimental Data Comparison for Evacuated Tube Collectors (ETC) Aperture Area 9.024m^2 [28]

Parameter	Value	Remarks
Specific Flow Rate	28 l/h/m^2	High to maximize energy
Simulation Data		
Solar Yield	36.4 kWh	12 Hours
MD Energy Use	26 kWh	71.5% of total yield
DHW Energy Use	5.85 kWh	16% of total yield
% of losses	12.5%	Long length piping
Experimental Data		
Distillate Collected	17 liters	9.67 Hours of Operation
MD Energy Use	16 kWh	0.94 kWh/l
DHW Energy Use	5.2 kWh	3 Peak Withdrawal
Estimated Values		
Extra Available Energy	10.6 kWh	$Total_{Sim} - Total_{Exp}$
Estimated V_{Dis}	28 Liters	40% more production

According to the data available from the experimentation results from 22nd July, the MD
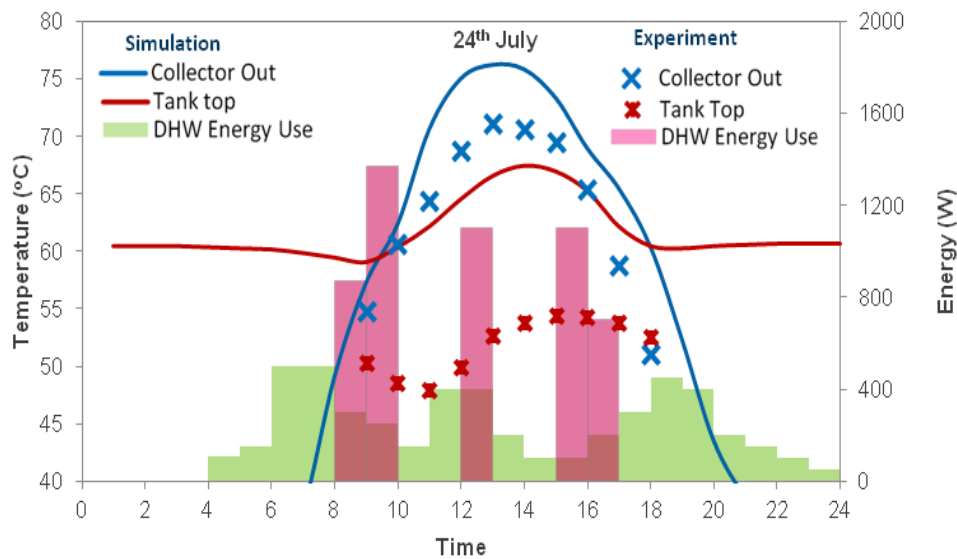
Figure 11: DHW Temperature and Energy Profile [28]

energy and temperature profile have been drawn and is shown in Fig.16. Moreover the Domestic Hot Water temperature and energy profile has been shown in Fig.15.

The temperature profiles of MD hot inlet and storage tank top layer shows the interesting results during experimentation. The trend explains that the top layer of the storage tank charges more rapidly due to high specific flow rates and the layer from which the MD hot inlet water is taken gets much more heated than top layers of the storage tank. This gives us an advantage of getting hot water at higher temperature for MD. The domestic hot water energy profile and temperature profile is shown in Fig. 17. Due to dual demand (hot water and drinking water), low radiation and unstable operation in the morning hours, there is a sudden temperature drop in the tank top layer. During the complete plant run, the domestic hot water has been drawn in 3 peaks:

- First peak between 8AM to 10AM
- Second peak between 12PM to 1PM
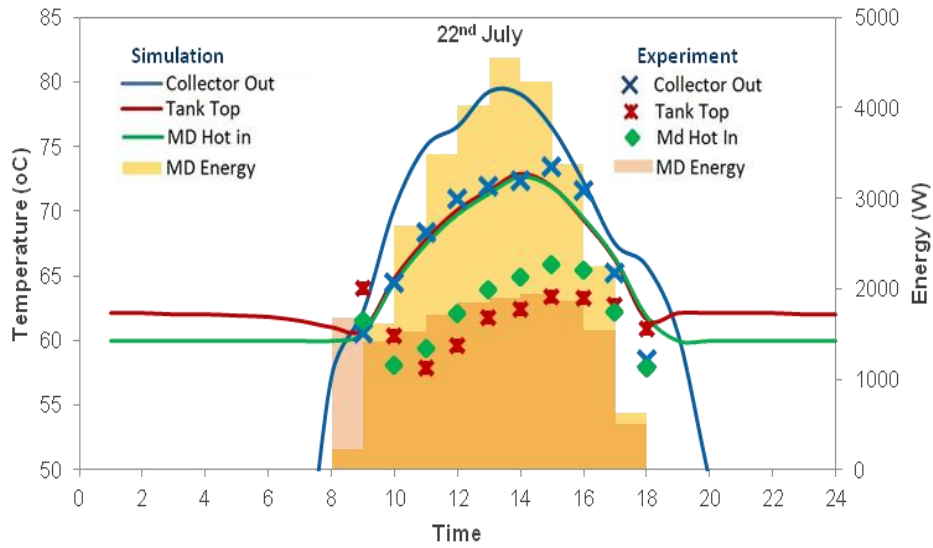- Third peak between 4PM to 5PM

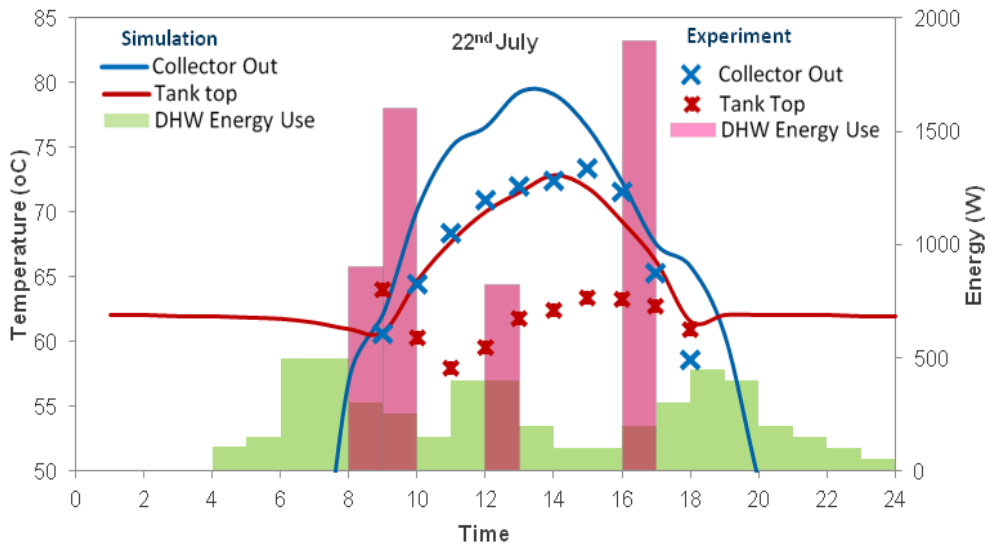**Figure 12: MD Temperature and Energy Profile [28]**

Figure 13: Domestic Hot Water Temperature and Energy Profile [28]

From Table 4, it is obvious that we can obtain the excess energy as per simulation data which contributes to about 40% more distillate production. The simulated results show that we can produce 28 liters of pure water for 10 hours of plant operation compared to 16 liters of pure water during real time experimentation. In real time situations, the key is to minimize the losses and operating the plant at reasonably high flow rates. So, the aperture area of 9.024m² is ideal to fulfil the fulfill the overall demand of MD and DHW as well

8 Determination of Optimum Collector Area

8.1 Annual water production and energy demand profiles

The lab scale experimentation research has been performed in RAKRIC facility on solar thermal integrated MD system. Based on the results, the thermal energy consumption patterns for variable ranges of MD inlet hot and cold temperatures have been determined. Table 5 provides the thermal energy consumption per liter of pure water for different MD hot inlet and cold inlet temperature ranges for different periods (values indicated italics) using the equation:

$$Q = m^{\circ}C_p \, (T_{hin} - T_{hout})$$

The consumption of pure water varies yearly i-e, pure water consumption is more in summers than in winters. So, 15 liters/day of pure water consumption is estimated in winter days i-e from December to February, 20 liters/day is estimated from March to June and in October and November and 25 liters/day of pure water consumption is estimated in peak summer days i-e from July to September. Therefore, the total estimated yearly volume of pure water or distillate is 7300 liters. Assuming that the temperature ranges mentioned in Table. 5 would be available for MD in the periods mentioned above; the annual energy demand for pure water production will be around 6000 kWh as shown in Fig.18. The plot has also been drawn in Fig. 19.

Table 5: Temperature and Energy Estimations for yearly pure water profile [28]

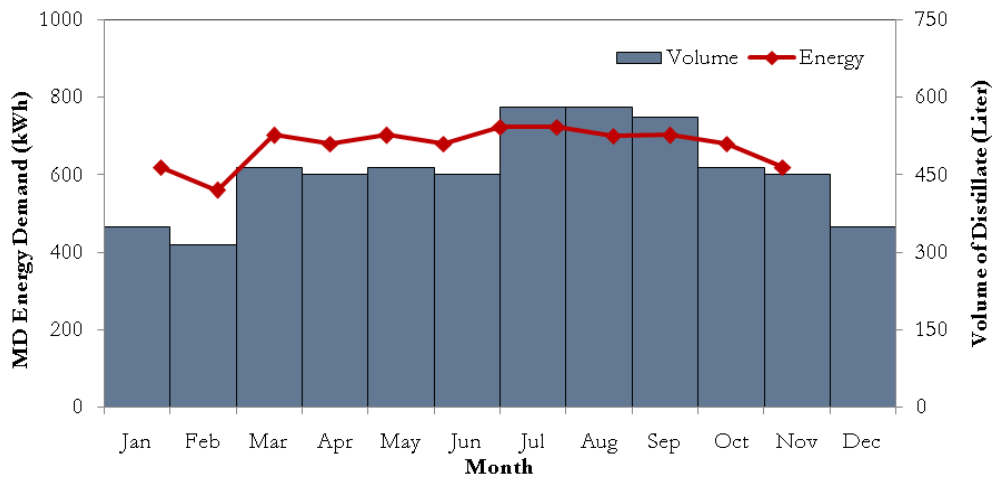| Parameter	Operational Range/Energy/Months		
MD Hot In Temperature	50 to 55°C	55 to 60°C	60 to 65°C
MD Cold In Temperature	14 to 16°C	18 to 25°C	28 to 30°C
Energy consumed for pure water kWh/L production	*1*	*0.85*	*0.7*
Period during which temperatures are available	Dec, Jan, Feb	Mar-Jun, Oct, Nov	Jul, Aug, Sep

Figure 14: Annual pure water production profile and MD Energy demand [28]

Similarly, according to ESTIDAMA standards, the annual energy demand for domestic hot water has also been calculated. With the fixed volume of 250 liters/day at 50-55°C, the cold water temperature of 14°C in winters and 30°C in summers the annual demand for domestic hot water is 2968 KWh. By recirculating and recovering the heat from MD cold side return, we can preheat the water for DHW circuit and thus the total annual energy demand will be reduced to 2223 kWh. It means that from waste heat recovery from MD cold side return, we can save about 25% of energy for domestic hot water production resulting in reduced energy demand. Table 6 provides annual energy demand values for MD and DHW.

Table 6: Annual Energy demand for MD and DHW [28]

Parameter	Value
MD Annual Energy Demand	6000 kWh
DHW Annual Energy Demand	2968 kWh
DHW demand with MD heat recovery	2223 kWh

8.2 Optimum collector area determination

For determining the collector area to fulfil the energy demand of solar thermal integrated system, PolySun simulation software has been used. The calculations are based on 10 hours of daily plant operation assuming 100% annual solar fraction. It means that the MD system would be operated in sunlight hours and the domestic hot water requirement would be

fulfilled through the thermal storage system. Following models of flat plat collectors and evacuated tube collectors have been used for experimentation:

- Flat Plate Collector– Tison FMS-2.55
- Evacuated Tube Collector - Sunda SolarSiedo 1-16

Fig. 19 shows the graphs of the flat plate collector efficiency and aperture area against the annual energy demand. The trends have been drawn for both MD cold side waste heat recovery and without MD cold side waste heat recovery. A careful consideration shows that the flat plate aperture area of 8 to 9m^2 is sufficient to achieve the benchmark production and overall energy demand for both MD and DHW. The highlighted area shows the optimum flat plate collector area to fulfill the desired energy demand for MD and DHW.
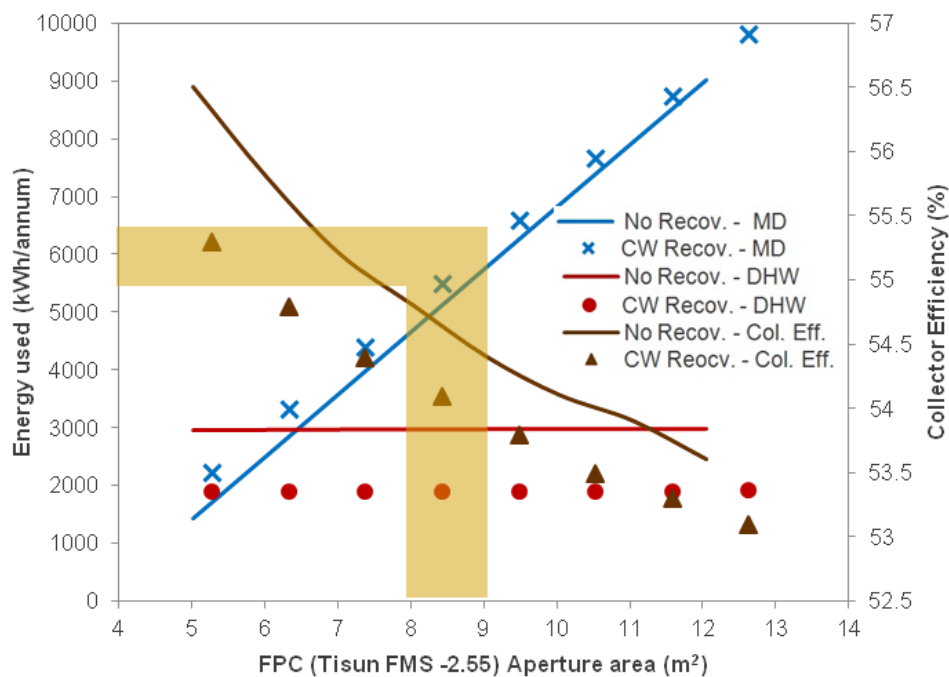

Figure 15: Optimum Flat Plate Collector Area for Solar Thermal Integrated MD system [28]

In a similar way, Fig. 20 shows the graph for the evacuated tube collector aperture area against collector efficiency. It can be seen that the collector area of 7 to 8m^2 is sufficient to meet overall energy demand for MD and DHW.
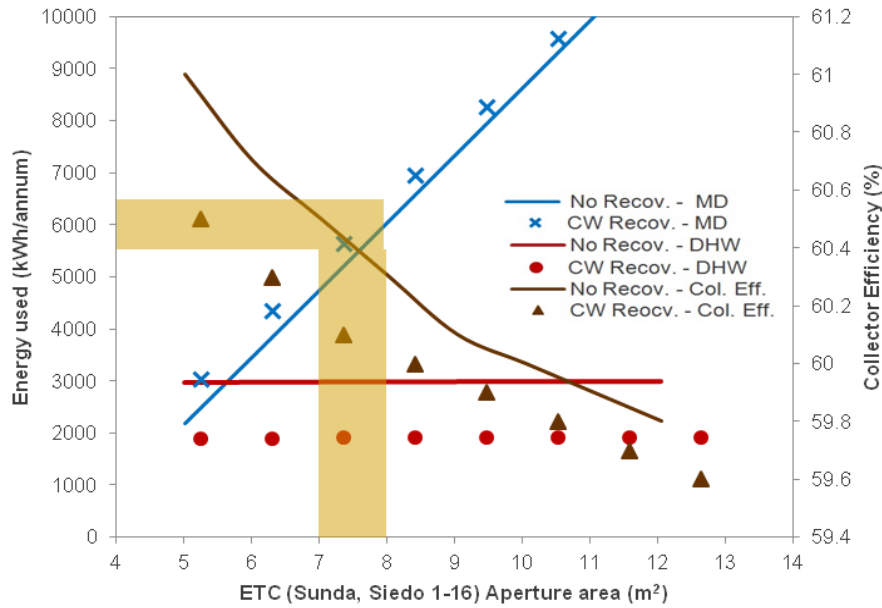
Figure 16: Optimum Evacuated Tube Collector Area for Solar Thermal Integrated MD system [28]

In MENA region, the collector field of normally 5m^2 is used for the production of hot water to meet the hot water demand for domestic purposes. So, by this study, the addition of minimum 3m^{2}aperture area will be sufficient to meet the pure water demand for a single family villa. Table 7 summarizes the average area required for SDHW-MD system for a system installed on top of a villa in UAE region.

Table 7: Summary of optimum collector area required [28]

Collector Type	Aperture Area (m²)	Solar Yield (kWh/annum)	Energy Use for MD(kWh/annum)	Energy Use for DHW(kWh/annum)	Total Losses (kWh/annum)
FPC	8.5 m²	9800	5900 (60%)	2100 (21.5 %)	1800 (18.5%)
ETC	7.5 m²	9700	5700 (58.5%)	2100 (22%)	1900 (19.5%)

9 Conclusions

The whole experimental analysis and study performed on the solar thermal integrated system installed in RAKRIC has been concluded and following results have been drawn based on the experiments performed for benchmark production and optimum collector area.

- The integration of MD with solar domestic hot water system is feasible for the cogeneration and sustainable production of 15-25 liters per day per person of pure drinking water along with domestic hot water. Based on pure water usage pattern, the

production of distillate will be less in winter, i-e from December to January and more in peak summer, i-e from July to September.

- For the simultaneous production of 15-25 liters/day of pure drinking water, 250 Liters/day of domestic hot water and to meet the annual energy demand, the optimum flat plate and evacuated tube collector area is found to be 8.5 m^2 and 7.5 m^2 respectively for producing the required pure water and domestic hot water for single family.

- From AGMD unit used in the MD system for distillate production, the optimum hot water side and cold water side flow rates are 6 liters/min and 3 liters/min. The hot side temperature and cold side temperature should be maintained between 60°C-70°C and 20°C-30°C respectively.

- The integrated system leads to efficient utilization of the standard domestic hot water system in summer time by reducing the backup heating and pure water production. Moreover, the domestic hot water energy demand can be reduced to about 25% by recovering the energy from MD cold side which maximizes the energy input to MD, thereby, increasing the distillate production.

- For solar thermal integrated MD system for production of hot water and drinking water, the total annual energy demand is 8223KWhout of which 6000 KWh is for pure water and 2223 KWh is for hot water. So, by recovering the hot water from MD cold side, the energy demand for pure water will only be 73%.

Acknowledgments

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