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Article

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Performance evaluation and life cycle analysis of new solar thermal absorption air conditioning system

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Abstract

The aim of this project is to design a solar thermal absorption air conditioning system that operates under UAE climate conditions. In absorption system, compressor which is normally used in conventional AC system, replaced by a chemical cycle that consists of a generator, absorber, pump, and expansion valve, while the rest of the components such as the evaporator, condenser, and expansion valve remain the same as conventional AC system. In this design, the water and lithium bromide pair is used as a refrigerant and absorbent, respectively. The generator is driven by an evacuated solar collector to heat the lithium bromide in the chemical cycle, while a solar PV panel, which ensures that the system works 100% by solar energy, drives the pumps and fans. An energy storage device also incorporated in the system to run it round the clock. An experimental investigation of the proposed design is presented in the paper. Results suggest that the proposed design match well to meet the cooling load demand which was about 300 watts. Furthermore, the system able to provide a desired as well as uniform comforts temperature at about 23 °C inside the room. The system COP was calculated to be 0.51. Life cycle analyses were also carried out using Eco Audit CES Edu pack software to study the viability of the new design. The results showed that the proposed new system is economically viable and environmentally friendly.

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Keywords: Absorption cooling; Water–liBr; Solar energy; Solar PV; COP; Life cycle analysis

1. Introduction

Air conditioning and refrigeration were one of the greatest engineering achievements that were developed in the 20th century. However, it is well-known that Refrigeration and air conditioning have a huge impact on the environment pollution and global warming due to the release of ozone-depleting refrigerants as well as high energy consumption [1]. Therefore, the effort is underway to find a suitable alternative for cooling applications. The developing history of Absorption chiller machine can be found in many scientific papers which can be a suitable

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alternative to resolve the above challenge. Absorption cooling was invented by the French scientist Ferdinand Carré in 1858, Lee et al. [2]. Solar energy constitutes a popular application of absorption refrigeration which is free, zero-emission as well as a clean energy source. Among other authors, Florides et al. [3] studied solar energy assisted water-LiBr absorption cooling is shown, estimated the hourly variations of the available free energy. However, the very minimum effort has been done on an environmentally friendly absorption system. Furthermore, according to the author's knowledge, no work proposed a complete study on an experimental and theoretical analysis together on life cycle analysis on a solar-powered absorption air-conditioning system. Therefore, the objective of this paper is to propose a novel absorption system which is fully operated by solar. The paper also focuses on an insight design methodology of various components of the system. A laboratory-scale setup was fabricated for validation of the proposed design. The sensitivity of the system was investigated along with the performance indicator (COP). Finally, an economic and life cycle analysis is performed by comparing the cost flows recurring throughout the lifetime of the solar and conventional systems.

2. Experimental apparatus

The schematic diagram shown in Fig. 1 represents the Lithium bromide–water (LiBr-H_2O) absorption refrigeration system, where water is the refrigerant and LiBr is the absorber. The system consists of eight major components that include an absorber, generator, condenser, evaporator, absorber heat exchanger, two expansion valves and the pump is as shown in Fig. 2. Compared with the conventional refrigeration cycle, the compressor is replaced by a chemical cycle in the absorption refrigeration system, where lithium bromide/water solution is reserved in between the absorber and generator (points 1 to 5 as shown in Fig. 1). The working fluid in the rest of the cycle is pure water. The solar collector is connected to the generator. The generator chamber contains a coil that carries the hot water from the collector and worked as a heat exchanger, while the photovoltaic panel is connected to the pumps and fans to supply electricity. The closed-loop cycle is started from the absorber, where the LiBr–water solution is pumped to the generator. Heat is transferred to the generator from the collector, as mentioned earlier, till pure water evaporates and leaves the generator to the condenser. Refrigerants, which are pure water vapor, then continue its journey through the rest of the cycle. Finally, refrigerants reach the evaporator to cool down the desired place and then travel to the absorber where the rest of the high concentration solution already back from the generator to the absorber and mix with water again.

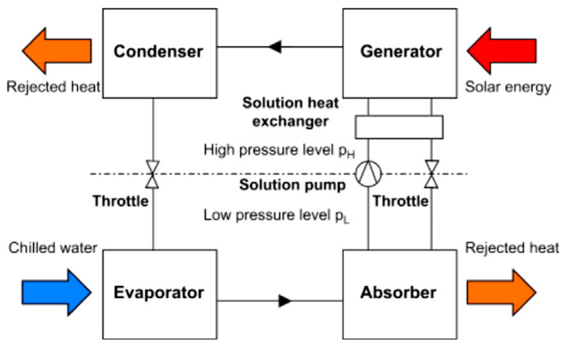


Fig. 1. Scheme diagram of the experimental setup.

3. System design

3.1. Cooling load

Cooling load calculations were performed for a plywood testing room. The dimension of the room was about 1 m × 1 m × 0.7 m. Hourly analysis program (HAP) was used to calculate the cooling load. The estimated cooling load of the room was about 300 watts.

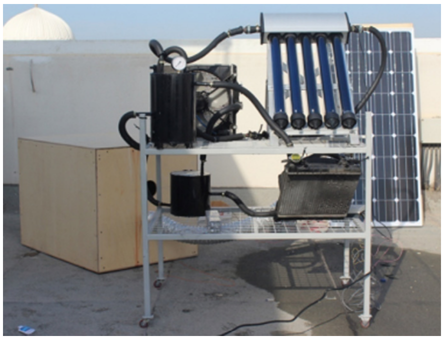


Fig. 2. Photograph of the experimental setup.

3.2. Mass–energy balance calculation

One of the biggest challenges of this work was to balance the system. Researchers utilized programs such as MATLAB, TRNSYS, etc. to design the absorption system. In this study, the analytical method by Ezzine et al. [4] was used to determine the properties at various state points based on the UAE climate conditions. All the system components were designed by using the parameters and tabulated in Table 1.

Table 1. Water LiBr absorption system calculations.

Description	Symbol	Watt
Capacity, evaporator output	$\dot{Q}_{Evap}$	300
Absorber, heat rejected to the environment	$\dot{Q}_{abs,chamber}$	382.349
Absorber HE, heat rejected	$\dot{Q}_{Abs,HE}$	189
Heat input to the generator	$\dot{Q}_{Gen}$	571.47
Condenser, heat rejected to the environment	$\dot{Q}_{Cond}$	321.15
Pump Work	$\dot{W}_{pump}$	20.24
Coefficient of performance (COP = QEvap/(QGen+WPump))	COP	0.51
Use of waste heat	COP_{waste}	14.822
Reversed Cycle	COP_{rev}	0.0685
Reversed effective Cycle	$ECOP$	7.418
Verification equation	–	−0.46

3.3. Generator

The generator was the first element to start components selection and sizing because the generator size cannot be determined theoretically by Granryd [5]. The generator generates sensible heat and latent heat of vaporization. The inlet temperature is raised up to saturation temperature by the sensible heat and it carries 13% of the total required for the heat of vaporization. Thereafter, the latent heat of solution plays the role to provide 11% heat of vaporization of the water–lithium bromide solution. Many studies were carried out on the pool boiling of liquids but very limited was found on lithium bromide water solution [6]. Experimental studies show that boiling is not significantly influenced by the tube diameter rather highly affected by the solution concentration. Generally, when solution concentration increases, the overall heat transfer coefficient decreases. Heat transfer coefficients for such a system vary between 1600 $W/m^2{}^\circ C$ and 7500 $W/m^2{}^\circ C$ [6]. The tubes of the generator were made of copper. The studies show that the tube material as presented in Kalogirou et al. [7] influences the heat transfer coefficient. To determine the heat transfer coefficient in the generator, the specific heat of the solution [7] was calculated from the molar mass fraction of water and lithium bromide [8] and the overall heat transfer coefficient was obtained from the equation $Q = UA\Delta T_m$. Kim et al. [8] The value was about 4205.6 $W/m^2{}^\circ C$, which is within an acceptable range between the values 1600 W/m^2-°C and 7500 W/m^2-°C [6].

3.4. Heat exchanger

Design of heat exchangers in the system such as condenser, evaporator, absorber and heat exchanger in the absorber was carried out by using the LMTD method. Flow pattern in all heat exchangers were fallen under turbulent flow therefore, a similar analysis was performed for the design of heat exchangers of the system. However, working fluid was the difference in different types of Heat Exchangers. Therefore, similar Nusselt number equation which captured the turbulent flow was used for design purpose [5,7–11].

3.5. Solar collector

The solar collector sizing was determined by the energy requirements in the generator. The solar collector was connected in order to supply the required amount of energy for the evaporation of H_2O from the Lithium bromide-water solution. The maximum temperature in the generator was calculated to be about 100 °C. To obtain the desired temperature in the generator evacuated tubes solar collector was chosen which could provide more than 100 °C compared to the flat plate collector. A controller was used to control the temperature of the collector by simply controlling the water temperature leaving and coming back to the collector. To control the outlet temperature close to 100 °C; the set temperature was about between 105 °C to 110 °C. By fixing the temperature difference between the inlet and outlet of the collector, mass flow rate through the collector was calculated by the using equation $\dot{Q} = \dot{m} C_p \Delta T$ and was about 0.04 kg/s.

3.6. PV module and storage system

The system was designed based on renewable sources round the year powered by the Solar PV modules along with the storage system by using batteries. A storage system is needed to store energy from the PV system at day time and meet the demand on a cloudy day, rainy day and at night when sunlight is not available.

Required array output per day $= \left(\frac{Total\, energy\, demand\, per\, day}{Battery\, round\, trip\, efficiency}\right) = \frac{292.8}{0.70} = 418.3$ watt-hours

-Peak sun hours = 6.37 h

-Energy output per module per day = (selected PV module guaranteed power output at STC × peak sun hours) = 108 × 6.3 = 680.4 watt-hours

Module energy output at operating temperature = (DF × Energy output per module per day) where DF = 0.80 for hot climate = (×0.80) = 0.80 × 680.4 = 544 watt-hours

Number of modules required to meet the energy requirements = (Required array output per day \Module energy output at operating temperature) $= \frac{418.3}{544} = 0.77 = 1$ modules

4. Performance analysis of the system

Before testing, lithium bromide was dissolved in the water in the laboratories and injected it into the absorber chamber. The lithium bromide was injected directly before the final testing to avoid corrosion. Prior testing, the collector was placed under the sun from early morning until the temperature reached above 100 °C degree. Once the temperature was reached to the desired level, the system was turned on and the chemical was started to circulate. The pressure was adjusted manually through the expansion values. The ambient temperature was about 27 °C.

As expected and it can be seen in Fig. 3, that with the increases of collector temperature, room temperature decreases. The minimum temperature in the testing room was obtained at about 21 °C corresponding to maximum air temperature about 27 °C. Fig. 4 revealed that the system has good response with the variation of solar collector temperature. Furthermore, a good agreement between the designed and experimental results on room temperature, the prime target of the project, demonstrates the accuracy of the proposed design method of the system

5. Life cycle analysis

A life cycle analysis was performed for the baseline prototype using electrical power from the grid and the new prototype powered with solar PV/battery system. The goal of the life cycle analysis was to determine the total energy, CO_2 emissions and the cost over life (20 years) of the baseline and solar prototypes. A bill of material with the type of material and mass of each part was determined the system will get electrical power from the grid,

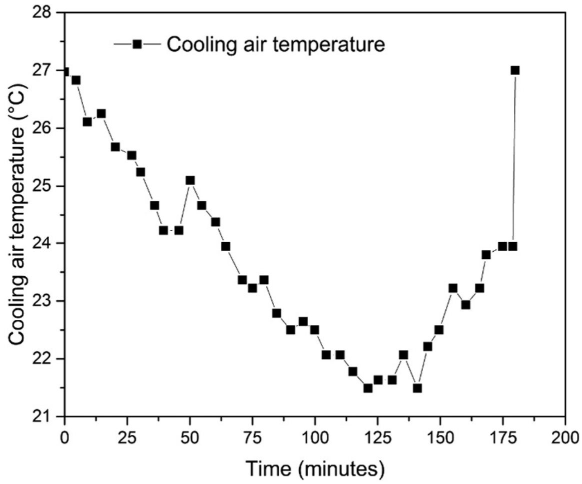


Fig. 3. Variation of cooling air temperature with time.

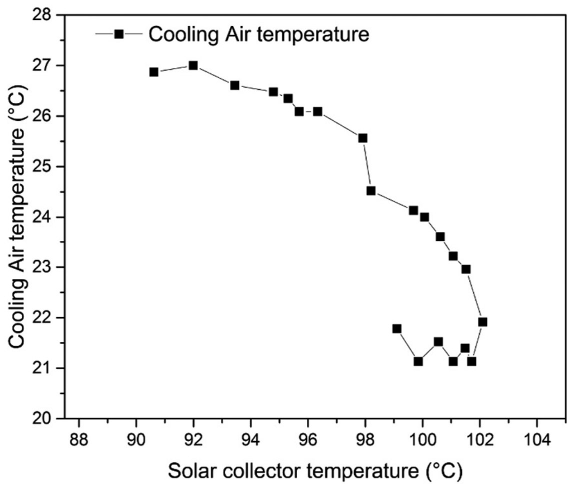


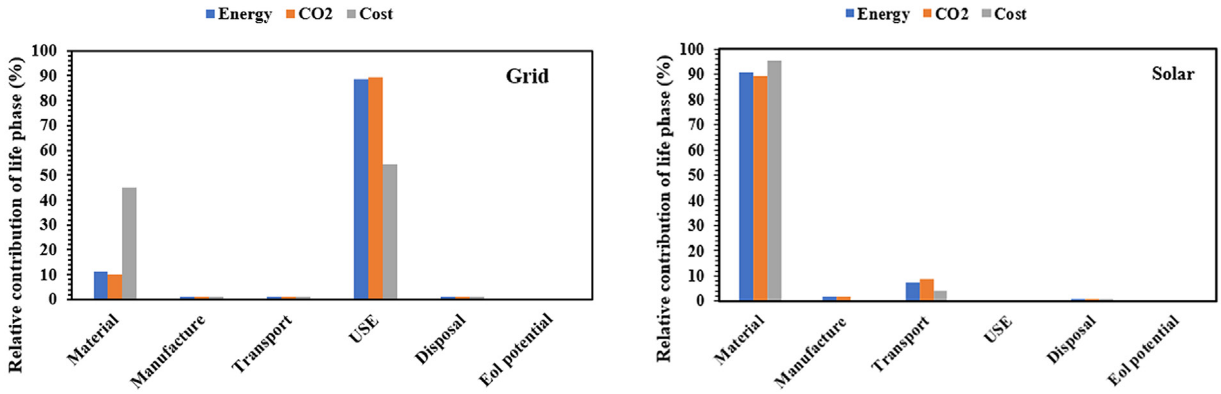
Fig. 4. Variation of cooling air temperature over solar collector temperature.

and it is assumed that the system will be running 365 days/year and for 24 hours/day over the life of the system. The results of the life cycle analysis is shown in Fig. 5(a) and Fig. 5(b). The results show that the main phase is consuming more energy (89.7%), producing more carbon dioxide CO_2 (90.5%), with the high cost (72.3%) during the usage phase.

A summary of the life cycle cost analysis of the baseline absorption chiller and the chiller using solar PV/battery system is shown in Fig. 6a and Fig. 6b. The total cost of the baseline prototype system is $2100/year (45.4% for material, 0.14% for manufacturing, 0.058% for transportation and 54.4% during the use). For the solar-powered absorption chiller, the total cost of the system is $1010/year (95.3% for material, 0.294% for manufacturing, 4.36% for transportation and $0 during the use). The life cycle analysis results show clearly the benefits of using a solar energy system for powering the absorption chiller concerning life energy usage, CO_2 emissions, and cost [12–14]. The new proposed system is very competitive from an environmental and economic point of view .

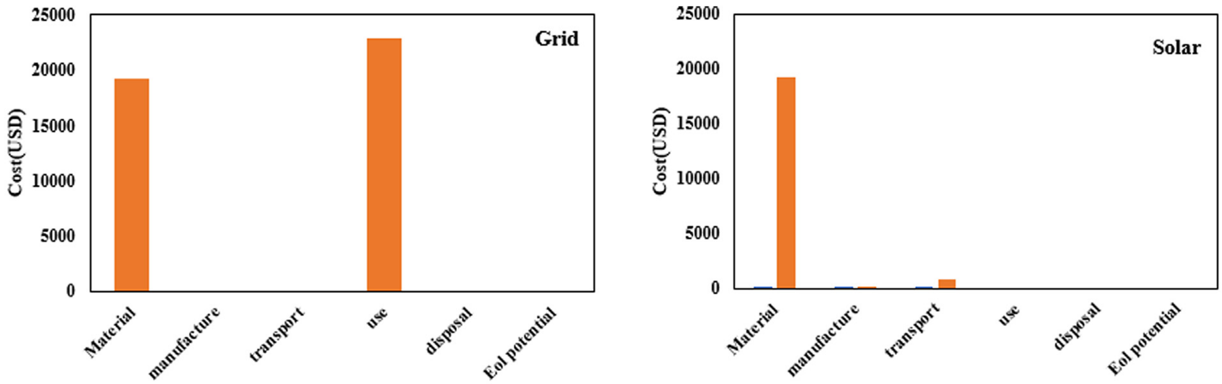
6. Conclusion

In this paper, a new portable absorption refrigeration system was designed, fabricated and tested. Experimental results illustrated that the proposed system achieved and maintained the target temperature inside the cooling



(a) (b)

Fig. 5. Life Cycle Analysis of the solar absorption refrigerator: (a) baseline with electrical power and (b) solar PV/Battery system.



(a) (b)

Fig. 6. (a) Summary of the life cycle cost analysis of the solar absorption refrigerator baseline with electrical power; (b) solar PV/battery system.

chamber during day time as well as at night. Furthermore, the design parameter well matched with the experimental results that prove the accuracy of the design approach. The coefficient of performance was obtained at about 0.51, which is a bit lower compared to the conventional refrigerator. However, the solar absorption refrigerator is environmentally friendly that does not produce chlorofluorocarbon (CFC) as in the conventional thermoelectric refrigerator which contributes to ozone depletion in the upper atmosphere. The life cycle analysis showed clearly the benefits of using a solar energy system for powering the system concerning the total energy, CO_2 emissions, and cost. Hence, the solar-assisted thermoelectric refrigerator would be less harmful to the environment as well as economically viable.

References

[1] Bowman M, Debray SK, Peterson. Cengel, heat and mass transfer, a practical approach. Mc Graw Hill; 1993.

[2] Lee RJ, Di Guilio RM, Jeter SM. Properties of lithium bromide–water solutions at high temperatures and concentration. II. Density and viscosity. ASHRAE Trans 1990;96(1990):709–28.

[3] Florides GA, Kalogirou SA, Tassou SA. Design and construction of a LiBr-water absorption machine. Energy Convers Manage 2003;44(15):2483–508.

[4] Ezzine NB, Barhoumi M, Mejbri K, Chemkhi S, Bellagi A. Solar cooling with the absorption principle: first and second law analysis of an ammonia-water double-generator absorption chiller. Desalination 2004;168:137–44.

[5] Granryd E. Refrigerating engineering. Stockholm: Department of energy technology; 2005, ch3-4.

[6] Herold KE, Radermacher R, Klein SA. Absorption chillers and heat pumps. Boca Raton: CRC Press; 1996.

[7] Kalogirou S, Florides G, Tassou S. Design and construction of a Lithium Bromide water absorption refrigerator. 2001.

[8] Kim, Kim, Joshi. Thermodynamic analysis of an absorption refrigeration system with ionic-liquid/refrigerant mixture as a working fluid. 2012; 44: 1005–15.
[9] Sauer HJ, Howell RH, Coad WJ. Principles of HVAC. ASHRAE Refrigeration Equipment 1998 (chap 8, 11).
[10] Kreith F, Bohn MS. Principles of heat transfer. Boston: PWS; 1997.
[11] Onan C, Ozcan B, Erdem S. Energy analysis of a solar assisted absorption cooling on an hourly basis in villa application. Energy 2010;35(12):5277–85.
[12] Mehmood A, Waqas A, Said Z, Rahman SMA, Akram M. Performance evaluation of solar water heating system with heat pipe evacuated tubes provided with natural gas backup. Energy Reports 2019;5:1432–44.
[13] Rahman S, Issa S, Said Z, Assad MEH, Zadeh R, Barani Y. Performance enhancement of a solar powered air conditioning system using passive techniques and SWCNT/R-407c nano refrigerant. Case Stud. Thermal Eng. 2019;100565.
[14] Sabiha MA, Saidur R, Hassani S, Said Z, Mekhilef S. Energy performance of an evacuated tube solar collector using single walled carbon nanotubes nanofluids. Energy Conversion Manag. 2015;105:1377–88.