Performance of an Absorption Refrigerator Using a Solar Thermal Collector

Abir Hmida, Nihel Chekir, Ammar Ben Brahim

***Abstract*—**In the present paper, we investigate the feasibility of a thermal solar driven cold room in Gabes, southern region of Tunisia. The cold room of 109 m^3 is refrigerated using an ammonia absorption machine. It is destined to preserve dates during the hot months of the year. A detailed study of the cold room leads previously to the estimation of the cooling load of the proposed storage room in the operating conditions of the region. The next step consists of the estimation of the required heat in the generator of the absorption machine to ensure the desired cold temperature. A thermodynamic analysis was accomplished and complete description of the system is determined. We propose, here, to provide the needed heat thermally from the sun by using vacuum tube collectors. We found that at least 21m² of solar collectors are necessary to accomplish the work of the solar cold room.

***Keywords*—**Absorption, ammonia, cold room, solar collector, vacuum tube.

I. Introduction

DUE to growing in thermal loads and in changing building architectural modes, the energy demand for air-conditioning and refrigeration is increasing continuously nowadays [1], [2]. This growth leads to higher consumption of primary energy and emission of Green House Gases (GHG) due to the generation of electricity from primary energy sources such as fossil fuels [3]. An existing alternative to reduce the peak of electricity consumption is the possible use of renewable energies like biogas, ocean waves, wind, hydro and solar radiation, etc., which have been playing a major role in reforming the natural balance [4] and providing the needs of growing population demand [5].

As a kind of clean and renewable energy, solar energy is, today, one of the most distributed energy form in the world [6]. Thanks to its renewability and no pollution, solar energy has been paid much attention today. Likely, the availability of solar radiation's surplus amount offers an opportunity to use solar thermal technologies for cooling during summer season and heating during winter season [1]. The challenge lies in the selection of efficient and suitable technology to exploit maximum heat from the sun in order to fulfill the required energy demand [7]. In Europe, Balaras et al. [8] surveyed over 50 projects of solar powered cooling systems to evaluate the future needs of solar cooling technology. They found that 40–50% primary energy can be saved with 0.07 €/kW. Solar thermal cooling systems are energy saving systems; they convert directly thermal input into cooling output [9]-[11]. Among available solar thermal cooling systems, solar absorption cooling system is competitive due to its relatively high efficiency [9]. It is also environmentally safe since it works with natural refrigerants such water or ammonia [12].

Solar thermal driven refrigeration systems usually consist of solar thermal collectors connected to thermal driven chillers [13].

A crucial application of the solar thermal refrigeration systems is food refrigeration. Currently, and because of the lack of preservation methods, solar absorption thermal systems are used in the agriculture field, since many natural products have been rotten and lost during picking, storage and commercialization [14], [15]. Food refrigeration preserves physiological properties and blocks the development of pathogenic bacteria [16]. A solar absorption refrigeration system can be considered as a solution to improve the agricultural field, especially in the south of Tunisia where we find a good solar potential.

In this research, we propose a cold room driven by a solar absorption system destined to store fruits and vegetables, particularly dates. To prevent the food's perishability and to preserve all its benefits (nutritional value, quality and color) [16], it is important to pay attention to the cooling load, moisture and ventilation in the room.

The proposed system is composed of three parts: the cold room, the absorption machine and the solar collector. In previous studies, a real cold room was simulated to store dates for the hot months of the year. According to the climatic conditions of Gabes (South-East of Tunisia), an absorption machine working with ammonia as refrigerant and water as absorbent ensures the required cooling for this application. A thermodynamic analysis of the cycle of this machine at the indicated operating conditions leads to the estimation of the driven thermal energy required in the generator of the machine. We suggest here the use of solar energy to ensure the work of the absorption system through vacuum solar collectors.

Fig. 1 shows the total working system, where the solar rays pass through the glass and then collected by an absorber that will be heated. The energy captured is transferred to the water circulating in the absorber. Next, hot water circulates through the generator, which contains an ammonia/water solution to evaporate the ammonia. The produced steam enters to the condenser where it liquefies by releasing heat [17]. Liquid refrigerant leaving the condenser passes from the high-

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pressure zone to the low-pressure evaporator through an expansion valve. The energy required for vaporization is extracted from the cold room and the fluid circulating in the evaporator will be cooled. Then, the ammonia enters the absorber; therein, refrigerant vapor recombines with the poor solution coming from generator [18]. Since this recombination is exothermic, it is necessary to extract heat from the absorber to maintain its temperature low enough to keep the high affinity needed between the ammonia and the poor solution. The resultant solution, rich in ammonia, is collected at the bottom of the absorber and then re-pumped into the generator. To minimize heat losses associated with fluid transfers between the generator and the absorber, we suggest the installation of a heat exchanger [19].

The main components of the solar cooling system are solar thermal collectors to produce heat from available radiation [1]. For such application, a high temperature is required in the generator to evaporate ammonia. As can be seen in the Fig. 2, at high-required temperatures, only vacuum tube collectors offer respectable efficiencies. Several technologies are available such as vacuum collectors with copper absorber and vacuum collectors with absorber on glass.

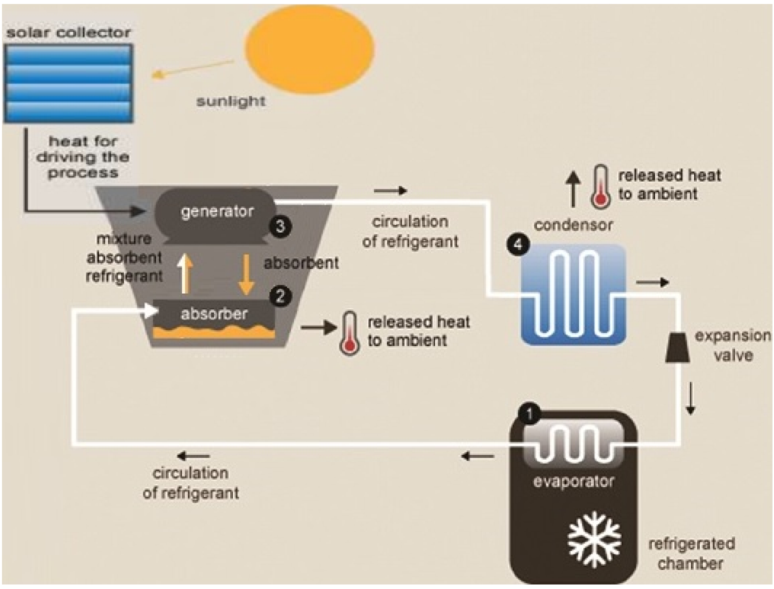

Fig. 1 Solar absorption refrigeration system

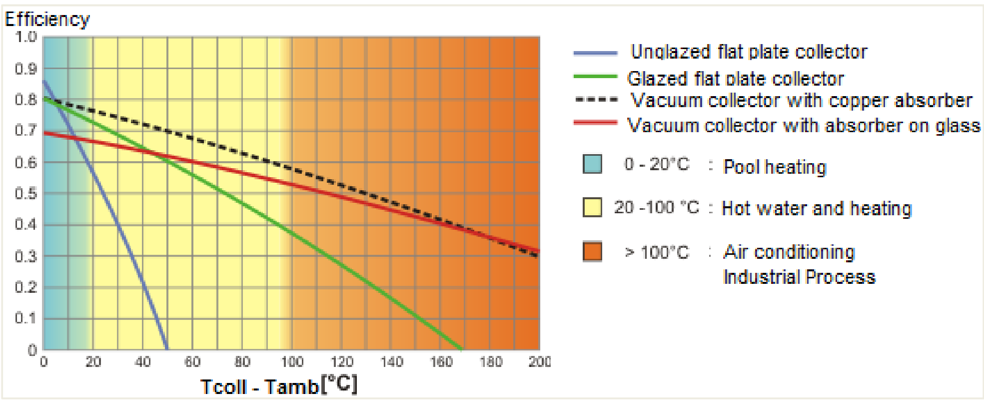

Fig. 2 Field of application of thermal collectors

When high temperatures for heating fluid are required, evacuated tube collectors possess a better performance in comparison with the flat plate collectors because of the elimination of convection heat loss due to the vacuum envelope around the absorber surface [20]. It represents excellent insulation. This feature illustrated in vacuum tube collectors focuses on their characteristics and leads to thermal losses substantially lower.

The water-in-glass evacuated tube, presented in Fig. 3, is the most widely used form of evacuated tube collectors. It has higher thermal efficiency than the metal-in-glass evacuated tube. Besides, it has lower manufacturing costs thanks to its simpler construction requirements. A water-in-glass evacuated tubular solar water heater is usually consist of 15–40 flooded single-ended tubes in direct connection to a horizontal tank. The solar absorber tube consists of two concentric glass tubes sealed at one end [21]. The outer one is made of extremely strong transparent glass to withstand changing climatic conditions. The inner tube is coated with a special selective coating (ALN/AIN-SS/CU) which features excellent solar heat absorption and minimal heat reflection properties [22]. The air is evacuated from space between the two-glass tubes in order to form a vacuum, which is maintained by using a barium getter.

II. Thermodynamique Study

In this step, a thermodynamic study on the absorption machine will be handled. First of all, a mass balance and an enthalpy balance will be carried out in order to predict the heat released by the condenser (Qc) and the absorber (Qa) and the one absorbed by the evaporator (Qe) and the generator (Qg). The different points of the system are presented in Fig. 4.

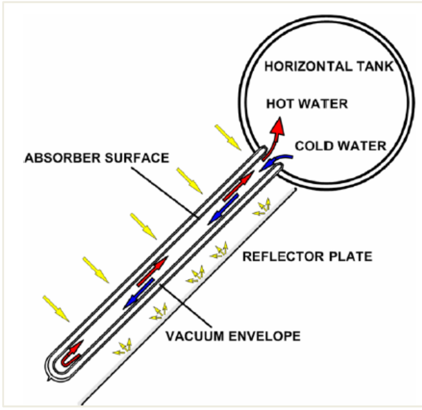

Fig. 3 Vacuum tube

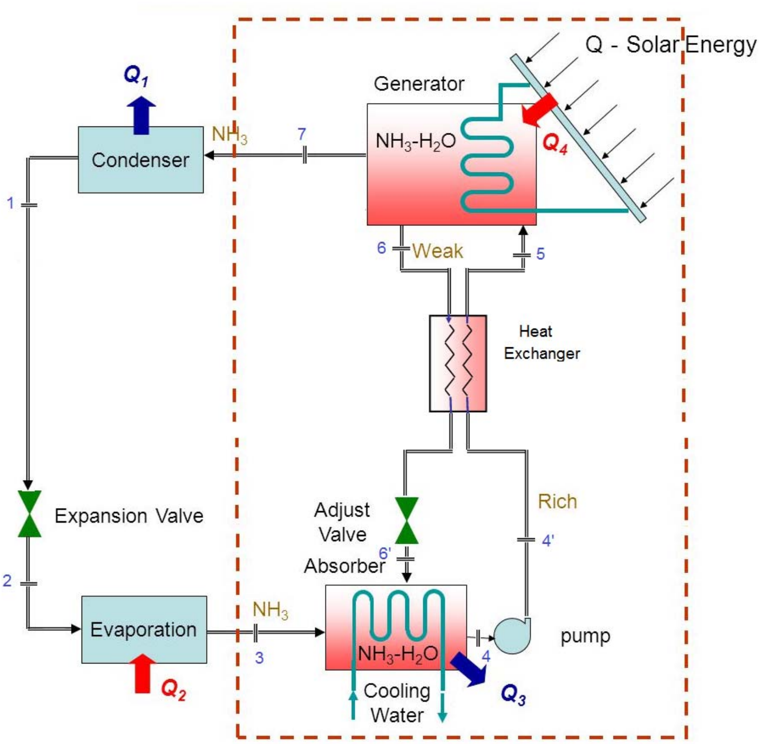

Fig. 4 Absorption Machine

A. Mass Balance

$$\dot{m} + \dot{p} - \dot{r} = 0 \text{ (Global)} \quad (1)$$

$$\dot{m} + x_p \dot{p} - x_r \dot{r} = 0 \text{ (Refrigerants)} \quad (2)$$

$$\dot{r} = \dot{m} \frac{1-xp}{xr - xp} \quad (3)$$

$$\dot{p} = \dot{m} \frac{1-xr}{xr - xp} \quad (4)$$

$\mathbf{x_p}$: Poor solution title of ammonia leaving the generator to the absorber. $\mathbf{x_r}$: Ammonia title in rich mixture leaving the absorber to the generator. $\dot{m}$: Refrigerant flow rate (kg/s). $\dot{p}$: Poor solution flow rate (kg/s). $\dot{r}$: Rich solution flow rate (kg/s).

B. Enthalpy Balance

$$Q_a + Q_c = Q_e + Q_g + W \quad (5)$$

- In the generator

$$Qg = \dot{m}\, h_7 + \dot{p}\, h_6 - \dot{r}\, h_5 \quad (6)$$

- In the evaporator

$$Q_e = \dot{m}\,(h_3 - h_2) \tag{7}$$

- In the absorber

$$Q_a = \dot{p}\, h_{6'} + \dot{r}\, h_4 - \dot{m}\, h_3 \tag{8}$$

- In the condenser

$$Q_c = \dot{m}\,(h_1 - h_7) \tag{9}$$

- In the pump

$$W = \dot{r}\,(h_{4'} - h_4) = V\,(P_{4'} - P_4) \tag{10}$$

The performance coefficient of the machine is calculated by the following equation.

$$COP = \frac{Qe}{Qg - W} \tag{11}$$

In order to calculate the enthalpy at each point of the system, the Gibbs energy formula is used. It predicts the thermodynamic properties of pure ammonia and water as well as the ammonia-water mixture. This equation is valid for the gaseous phase and liquid. Enthalpy, entropy and molar volume are related to Gibbs energy:

$$H = -R\,T_B\,T_r^2\,\left[\left(\frac{\partial\left(\frac{G_r}{T_r}\right)}{\partial T_r}\right)\right] \tag{12}$$

$$S = -R\left[\frac{\partial G_r}{\partial T_r}\right] \tag{13}$$

$$V = \frac{RT_B}{P_B}\left[\frac{\partial G_r}{\partial P_r}\right] \tag{14}$$

In a second step, and in order to ensure heat for the generator, a prediction of the exact area of the thermal collector is a necessity. Therefore, the useful power of the solar collector depends on its surface and the local global radiation. The surface can be calculated using (15).

$$A = \frac{Pu}{G*\beta - G*K*(Tfm - Te)} \tag{15}$$

where Pu is the useful power (kW) of the solar collector. In our application the useful power is estimated to be:

$$Pu = 1.1*Qg \tag{16}$$

where, Qg is the heat absorbed by the generator (kW). K is the heat loss coefficient, generally between 1.5 and 3 W/m²° C, β is optical coefficient for vacuum tube collector which is between 0.5 and 0.8, and finally, G is the global radiation either calculated by different models or got directly from the Nation Institute of Meteorology.

In this research, a MATLAB code was developed to determine the enthalpy of each point of the system as well as the heat consumed by all the equipment (generator, condenser, evaporator and absorber). The following table represents the necessary operation conditions for the system simulation.

TABLE I
OPERATING CONDITIONS

Generator Temperature, °C	120
Condenser and Absorber temperature, °C	50
Evaporator Temperature, °C	2
Vapor phase composition	≥95
Heat exchanger pinch , °C	5

III. RESULTS

The storage room, as shown in Fig. 5, has a total volume of 109 m³. Inside the room dates are packed in plastic boxes disposed in blocks. This room has a capacity of 40 tons and is located in Gabes southern zone in Tunisia. To prevent shock of the products, the fruits are firstly pre-cooled in an adjacent room with an indoor temperature of 6°C and then stored in the cold room at a temperature of 2°C.

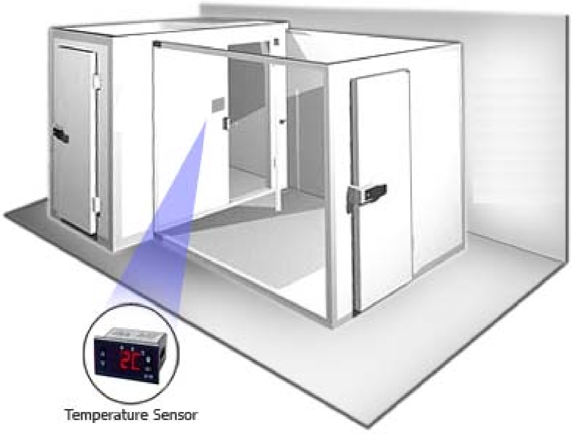

Fig. 5 Cold room for fruits refrigeration

In a previous step, a study on sizing a cold room was established where the major input data, as shown in Fig. 6, are the heat gained by walls; room capacity; dates respiration and heat released by lights, fans and people. A MATLAB code was established to predict the cooling load needed for the refrigeration of the dates. We found that between March and October, the average power is 8 kW, which were enough for the chamber operation.

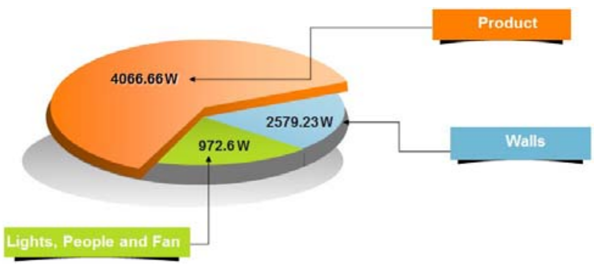

Fig. 6 Cooling thermal load

In the next step, a study on the absorption chiller was elaborated in order to find the operated condition such as the rich and the poor ammonia mass fraction (x_r and x_p), heat released or absorbed by different equipment (Q_i) and finally, the most important parameter, the COP of the machine. The following figure illustrates those results. As can be seen in Fig. 7, the system works under a high pressure equal to 20 bar and low pressure equal to 4 bar. For a COP equal to 0.74, and cooling load of 8 kW, the heat needed for the generator is 10.6 kW. This heat will be provided by the vacuum tube collector which will have useful power of 11.1 kW.

The calculation of the solar collector area depends on the available global radiation. The design of the solar collector requires either a numerical model such as the Eufrat model, Capderou model or Brichambaut model, or direct data from stations installed in the region. In this case, this data were obtained from the National Institute of Meteorology, where they provided a monthly measurement, and is presented in Fig. 8. As it can be seen, between April and September, the cooling demand is in its maximum.

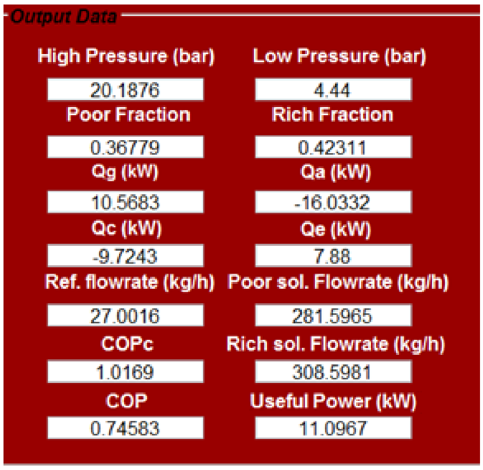

Fig. 7 Simulation result of the absorption chiller

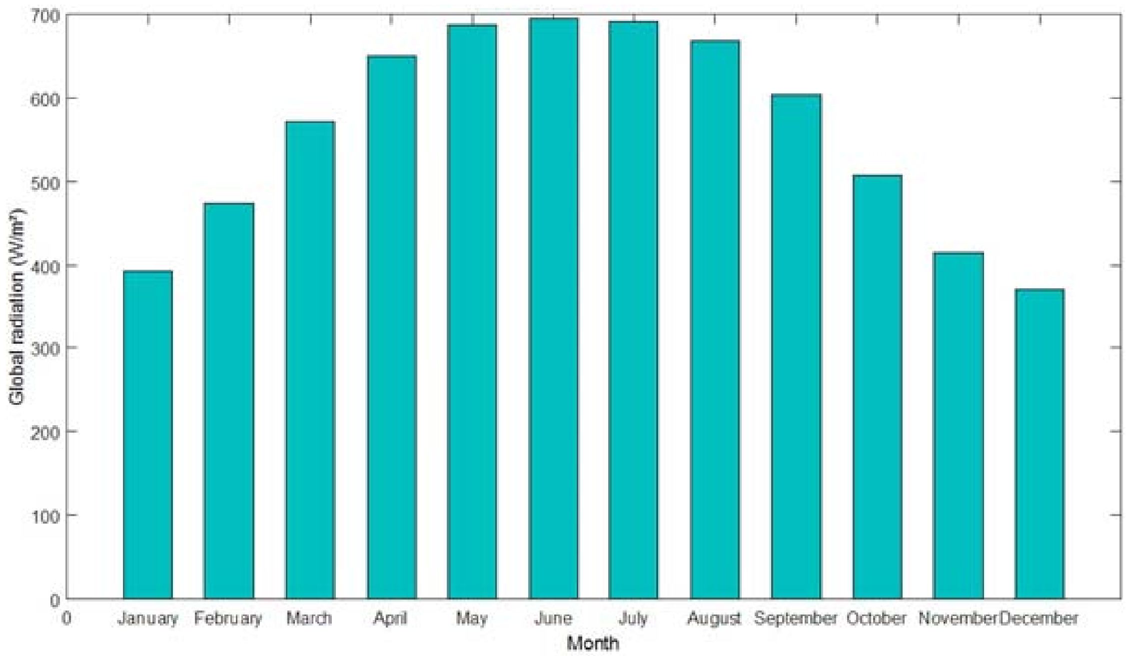

Fig. 8 Global radiation in the region of Gabes, Tunisia

Finally, the simulation of the absorption machine has led, in the first step, to finding the cooling load needed to the cold room, which was 8 kW. In the second step, to identify the heat required in each component and specially that absorbed by the generator, it helped us to design the solar collector. Using (15), we found that a surface of 21 m² of solar collector can ensure the evaporation of the ammonia in the generator at 120°C.

In fact, after obtaining the global radiation of the region of Gabes, we used some commercial collector characteristics to size the solar collector. Optical coefficient and the heat loss coefficient are the most used input data. We chose four different types of commercial collector with the available sizes. As can be seen in Table II, the collector surfaces are practically the same, and in general, 21 m² were enough to ensure the working of the absorption machine and the cooling of the products.

IV. Conclusion

An absorption refrigeration machine is simulated and studied to ensure the frigorific power required for a storage cold room destined for preserving foods in the south of Tunisia. The result of the simulation of the solar chiller offers a respectable COP about 0.74.

TABLE II
COLLECTOR AREA AND NUMBER

Collector type	Availability (m²)	K	β	S (m²)	N
Vitsol 200T	1,26	1,522	0.785	21.47	17
	1,51	1.443	0.801	20.59	14
	3,03	1.103	0.801	19.3	7
Thermomax HP100	2	1	0.39	48.04	24
	3	1	0.739	20.85	7
Thermomax HP200	2	1.36	0.761	21.62	11
	3	1.36	0.761	21.62	7
Thermomax DF100	2	1.45	0.773	21.59	11
	3	1.45	0.773	21.59	7

The use of solar energy, as the heat source, makes such system as a more economical alternative. For storage rooms of 109m^3, approximately 21m² of vacuum tube collectors are required. This number can be decreased if we consider the solar radiation of the summer months when the need of refrigerator is crucial and the solar radiation is more important.

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REFERENCES

[1] A. Ghafoor, A. Munir, "Worldwide overview of solar thermal cooling technologies", Renewable and Sustainable Energy Reviews. Vol 43, pp 763–774, 2015.

[2] Kalkan N, Young EA, Celiktas A. Solar thermal air conditioning technology reducing the footprint of solar thermal air conditioning. Renew Sustain Energy Rev, vol 16, pp 6352-83, 2012.

[3] Saman W, Krause M, Vajen M, Solar cooling technologies: status and recent developments. In: Proc 42th annu. conference of the Australian and New Zealand solar energy society. Pearth, Australia; 1-3 Decemeber 2004

[4] Mohammed Mumtaz A. Khana , R. Saidura, Fahad A. Al-Sulaimana, "A review for phase change materials (PCMs) in solar absorption refrigeration systems", Renewable and Sustainable Energy Reviews vol 76, pp 105–137, 2017

[5] Sorensen B. Chapter 3- The individual Energy Source. In: Sorensen D, editor Renewable Energy Third Edition. Burlington: Academic press. pp. 210-317. 2004.

[6] Q. F. Chen S. W. Du Z. X. Yuan T. B. Sun Y. X. Li, "Experimental study on performance change with time of solar adsorption refrigeration system", Appl. Thermal Eng. Vol 138, pp 386-393 , 2018.

[7] Henning hm. Solar assisted air conditioning in buildings. A Handbook for planner. 2nd ed. Wien. Austria: Springer-Verlag: 2007.

[8] Balaras CA, Grossman G, Henning HM, Infante Ferreira CA, Podesser E, Wang L, et al. "Solar air conditioning in Europe- an overview". Renew Sustain Energy Rev, vol 11, pp 299-314.2007

[9] Z. Y. Xu, R. Z. Wang, "Comparison of CPC driven solar absorption cooling systems with single, double and variable effect absorption chillers", Solar energy, vol 158, pp 511-519.2017

[10] Ullah, K. R., Saidur, R., Ping, H. W., Akikur, R. K., Shuvo, N. H. "A review of solar thermal refrigeration and cooling methods". Renew. Sust. Energy Rev. vol 24, pp 499–513. 2013.

[11] Wang, R. Z., Ge, T. S., Chen, C. J., Ma, Q., Xiong, Z. Q., "Solar sorption cooling systems for residential applications: options and guidelines". Int. J. Refrig. Vol 32, pp638–660.2009.

[12] Eicker, U., Pietruschka, D., Haag, M., Schmitt, A. "Systematic design and analysis of solar thermal cooling systems in different climates". Renew. Energy, vol 80, pp 827–836.2015.

[13] Boopathi V. Raja, Shanmugam V. A, "A review and new approach to minimize the cost of solar assisted absorption cooling system". Renew Sustain Energy Rev. vol 16, pp6725-31.2012.

[14] Abbes F, Bouaziz MA, Blecher C, Masmoudi M, Attia H, Besbes S., "Date syrup: effect of hydrolytic enzymes (pectinase/cellulose) on physicochemical characteristics, sensory and functional properties". LWT Food Sci Technol, Vol 44(8), pp 1827-1834. 2011.

[15] Masmoudi M, Besbes S, Chaabouni M, Robert C, Paquot M, Blecker C, et al. "Optimization of pectin extraction from lemon by-product with acidified date juice using response surface methodology". Carbohyd Polym, Vol 74(2), pp185-192. 2008.

[16] Foroogh Biglari, Abbas F. M. AlKarkhi, Azhar Mat Easa, "Cluster analysis of antioxidant compounds in dates (Phoenix dactylifera): Effect of long-term cold storage", Food Chemistry, Vol 112, pp 998–1001. 2009

[17] Marıa S. Mazzei, Miguel C. Mussati, Sergio F. Mussati "NLP model-based optimal design of LiBr/H_2O absorption refrigeration systems" International Journal of Refrigeration; Vol 38, pp 58-70.2014.

[18] Rabah Gomri; "Second law comparison of single effect and double effect vapour absorption refrigeration systems" Energy Conversion and Management; Vol 50, pp 1279–1287. 2009.

[19] André Aleixo Manzela, Sérgio Morais Hanriot, Luben Cabezas-Gómez, José Ricardo Sodré, "Using engine exhaust gas as energy source for an absorption refrigeration system" Applied Energy, Vol 87, pp 1141-1148. 2010.

[20] Indra Budihardjo, Graham L. Morrison, Masud Behnia, Natural circulation flow through water-in-glass evacuated tube solar collector, Solar Energy, Vol 81, pp 1460-1472 2007.

[21] I. Budihardjo, G. L. Morrison, Performance of water-in-glass evacuated tube solar water heaters, Solar Energy, Vol 83 pp 49–56. 2009.

[22] Dr. S. P. Vendan, L. P. A. Shunmuganathan, T. Manojkumar, C. Shiva Thanu, "Study on design of an evacuated tube solar collector for high temperature steam generation", International Journal of Emerging Technology and Advanced Engineering. Vol 2 pp 539-541, 2012.