Performance results of a solar adsorption cooling and heating unit

Tryfon C. Roumpedakis[1], Sotirios Karellas[1], Salvatore Vasta[2], Ursula Wittstadt[3] and Niels Harborth[4]

[1] National Technical University of Athens, Athens (Greece)

[2] Consiglio Nazionale delle Ricerche (CNR), Istituto di Tecnologie Avanzate per l'Energia "Nicola Giordano" (ITAE), Messina (Italy)

[3] Fahrenheit GmbH, Munich (Germany)

[4] AkoTec Produktionsgesellschaft mbH, Angermünde (Germany)

Abstract

The high environmental impact of conventional methods of cooling and heating has increased the need for renewable energy deployment for covering thermal loads. Towards that direction, the proposed system aims at offering an efficient solar powered alternative, coupling a zeolite-water adsorption chiller with a conventional vapor compression cycle. The system is designed to operate under intermittent heat supply of low-temperature solar thermal energy (<90 °C) provided by evacuated tube collectors. A prototype was developed and tested in cooling mode operation. The results of separate components testing showed that the adsorption chiller was operating efficiently, achieving a maximum coefficient of performance (COP) of 0.65. With respect to the combined performance of the system, evaluated on a typical week of summer in Athens, the maximum reported COP was approximately 0.575, mainly due to the lower driving temperatures at a range of 75 °C. The corresponding mean energy efficiency ratio (EER) obtained was 5.8.

Keywords: Solar Cooling, Adsorption, Evacuated tube collectors, Experimental testing

1. Introduction

The depletion of fossil fuel reserves and the growing concerns over the environmental impact of conventional cooling and heating technologies has turned attention towards alternative methods utilizing renewable energy sources. In this context, solar energy presents the most promising candidate to drive sustainable cooling and heating systems. In fact, given the concurrence between the solar availability and the peak building demands makes such systems as a field of great potential (Karellas et al. 2018).

With respect to solar driven heating/cooling there are two main technologies: photovoltaic driven reversible heat pumps and solar thermally driven sorption heat pumps (Calise et al. 2016, Sarbu and Sebarchievici 2013). Currently, the PV driven cooling/heating systems dominate the market, thanks to overall growth of the PV market, which is expected to gain a share of 16% of the total energy production by 2050, according to International Energy Agency (2014). This expansion of the PV market, along with the respective increased use of reversible heat pumps has resulted in low specific capital costs for the PV driven cooling/heating systems, making this technology the most competitive solar driven cooling/heating technology (Eicker et al. 2014).

On the other hand, the majority of commercially available solar thermally driven cooling/heating setups implement an absorption heat pump, mainly due to the fact that absorption is the most mature thermally driven cooling/heating technology (Infante Ferreira and Kim 2014). Several solar absorption applications have been developed and are currently in operation across the world. For instance, a solar driven absorption system has been installed at the Centre for Renewable Energy Sources and Saving (CRES) in Pikermi, Athens, Greece, and is in operation since December 2011. The solar field consists of flat plate collectors with a total surface of 149.5 m², while an underground energy storage system with a total volume of 58 m³ has also been installed. The $LiBr-H_2O$ absorption chiller has a nominal capacity of 35 kW, while a 18 kW conventional heat pump is installed as a

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backup. According to measurements conducted by Drosou et al. (2014), the achieved solar fraction is around 70%. The annual cooling demands were estimated to be 19.5 MWh/a, which refers to the period May-September, while the respective heating loads were 12.3 MWh/a for the period October-April (Drosou et al. 2016).

On the other hand, adsorption technology has gained attention over the past years, thanks to its potential to exploit very low grade heat sources, the absence of crystallization issues and the simplicity of the involved equipment due to the absence of solution pump and rectifier (Roumpedakis et al. 2019, Wang et al. 2009). Furthermore, compared to conventional electrically driven systems, the adsorption technology advantages in the lower operating costs, the absence of moving parts and the absence of vibrations (Otanicar et al. 2012). On the other hand, a key drawback for adsorption technology is the relatively low coefficient of performance (COP) (Wang and Oliveira 2006).

Solar adsorption systems have already been investigated thoroughly in terms of both their theoretical and experimental performance (Calise et al. 2016, Lu and Wang 2018). Habib et al. (2013) simulated the performance of a two stage four bed silica gel-water adsorption system, powered by evacuated tube collectors. For the needs of the simulations, the heat source temperature varied from 40 to 95 ^{o}C. In single stage mode (driving temperature of 80 ^{o}C, cooling water temperature of 30 ^{o}C and chilled water inlet temperature 14 ^{o}C), the COP was around 0.48. On the other hand, when the driving temperature is lower (50 ^{o}C), the system operates in two stage mode, with a COP of approximately 0.27. Lemmini and Errougani (2007) tested a single-bed methanol- activated carbon (AC-35) adsorption unit powered by a flat plate collector. Several experiments were conducted, achieving a maximum solar COP of 0.078 with a second law efficiency of 71%. Aristov et al. (2007) evaluated by simulations and developed a solar refrigeration system based on a closed adsorption cycle. Among several chemisorbents, $CaCl_2$ in silica gel composite sorbent was found to be the most efficient sorbent for water adsorption, resulting in a cycle's COP equal to 0.6-0.8 (θ_e=5 ^{o}C, θ_c=35 ^{o}C and θ_{des}=80 ^{o}C). Lattieff et al. (2019) evaluated experimentally a silica-gel single bed adsorption chiller driven by 4 m² evacuated tube collectors under the climatic conditions of Baghdad, Iraq. The nominal driving heat temperature was set at approximately 90 °C. Under varying experimental conditions, the optimal working point of the chiller was determined to be achieved at an evaporator temperature of 6.6 °C, which corresponded to a COP of 0.55. Due to the aforementioned drawbacks of adsorption technology, there are fewer applications of solar adsorption cooling. One of the earliest solar thermal system based on a 5.5 kW adsorption chiller was developed and installed at Institute for Solar Energy System (ISE) in Freiburg, Germany. The measurements conducted between August 2008 and July 2009, revealed an average COP was 0.43 (Kalkan et al. 2012).

Despite the attractiveness of the aforementioned solutions, the need to cover thermal loads on the absence of solar irradiance, results in the use of conventional backup systems. In order to overcome this issue, recently, several hybrid adsorption/compression solutions have been proposed (Vasta et al. 2018, Palomba et al. 2019a). In this context, ZEOSOL project is based on the hybridization of an adsorption chiller with a conventional vapor compression cycle. The implementation of the vapor compression cycle allows for covering of the peak loads allowing the adsorption chiller to operate at higher COP, while on the absence of the solar irradiance the conventional system is able to fully cover the loads of the residential building (Palomba et al. 2019b).

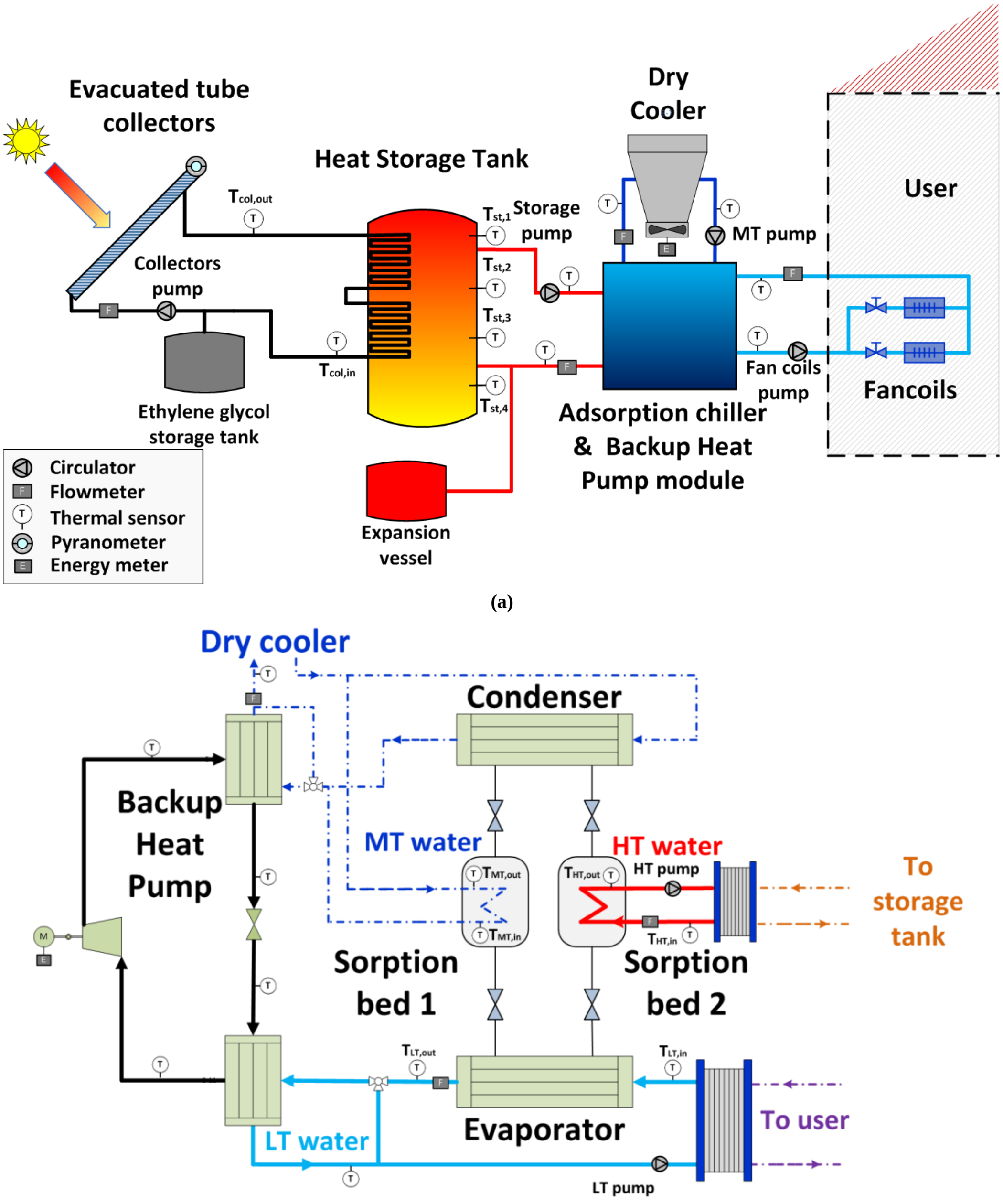
The system has been designed with particular attention on the environmental impact of the developed system, compared to conventional alternatives, as presented by Kallis et al. (2019). The life cycle assessment (LCA) of the investigated system, using the ReCiPe 2016 method, outlined the significant reduction in the system's impact on global warming and ozone depletion with respect to conventional reversible heat pumps.

In the present study the authors investigate the preliminary experimental performance of a solar driven hybrid cooling and heating system based on a small scale zeolite-water adsorption chiller at adsorption only mode. The prototype system has been designed to fully cover the thermal loads of a residential building of 12.5 kW peak cooling load.

2. System description

The proposed project focuses in the coupling of a zeolite-water adsorption chiller with solar thermal collectors. The cooling capacity of the developed sorption chiller is exceeding 10 kW with a maximum reported COP of 0.65. In order to reduce the chiller's capacity and thus the required solar field area, enhancing simultaneously the efficiency on part-load operation, a backup electrically driven heat pump is coupled with the adsorption chiller. The backup heat pump has a nominal cooling capacity of 10 kW and is used mainly to cover peak loads. The solar field consists of three rows of advanced evacuated tube collectors with a total surface of 40 m².

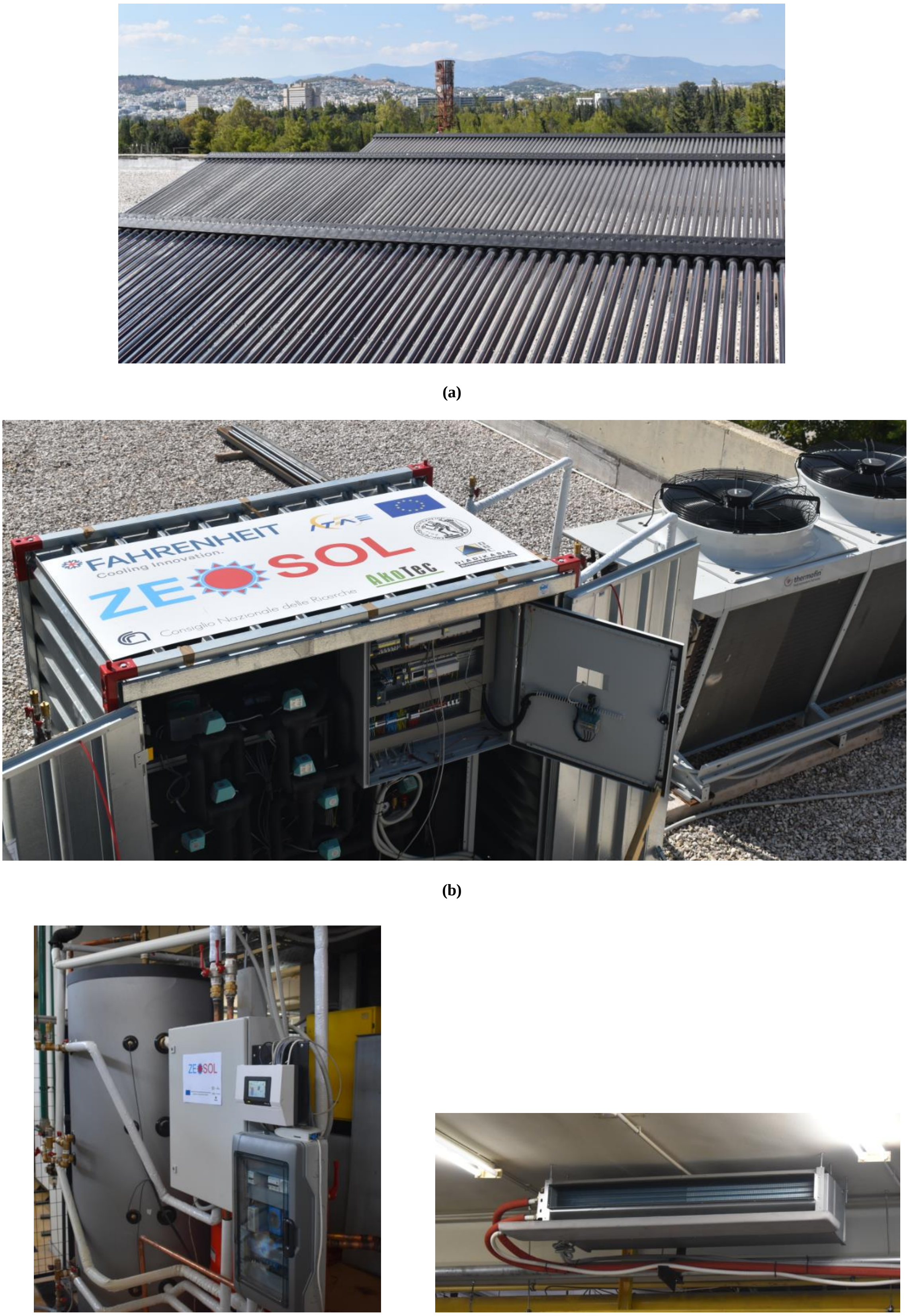
To enhance solar collector's performance and allow risk-free operation on low ambient temperatures, a propylene glycol solution is used as the working medium for the solar subsystem. Moreover, all secondary circuits of the adsorption chiller are using pure water. The 1 m³ heat storage tank is equipped with heat coils, via which heat is transferred from the glycol solution towards the hot water, which in turn drives the adsorption chiller. A "V shaped" dry cooler is implemented as the heat rejection unit for both the adsorption chiller and the backup heat pump, retrofitted for the specific application. An overview of the prototype, including the installed measuring devices is shown in Fig. 1, while images of the actual setup are also provided in Fig.2.



(a)

(b)

Fig. 1: (a) Schematic of system prototype with all the involved measuring devices and (b) detailed schematic of the hybrid adsorption chiller/backup heat pump module



(a)

(b)

(c) **(d)**

Fig. 2: Overview of the experimental setup components: (a) the ETCs solar field, (b) the hybrid chiller-dry cooler setup, (c) the solar station and the storage tank and (d) the hydronic ducted fan coil unit

3. Experimental measuring of separate components

The preliminary measuring of the proposed system was divided in three parts: (a) the experimental assessment of the solar collectors and the storage tank, (b) the performance testing of the hybrid adsorption chiller and (c) the dry cooler along with all the involved auxiliary equipment (e.g. circulations pumps).

The solar collectors used in the system are heat pipe evacuated tube collectors, manufactured by Akotec specifically for ZEOSOL system and being able to operate efficiently between 65-95 °C. The collectors were tested by a certified institute according to ISO 9806. The results of the testing with respect to the characteristic curve of the solar collectors are shown in Fig.3. The collector efficiency, shown in Fig.3, is calculated as follows:

$$\eta = \eta_0 - c_1 \frac{T_{col} - T_a}{\mathrm{G}} - c_2 \frac{(T_{col} - T_a)^2}{\mathrm{G}} \qquad \text{(eq. 1)}$$

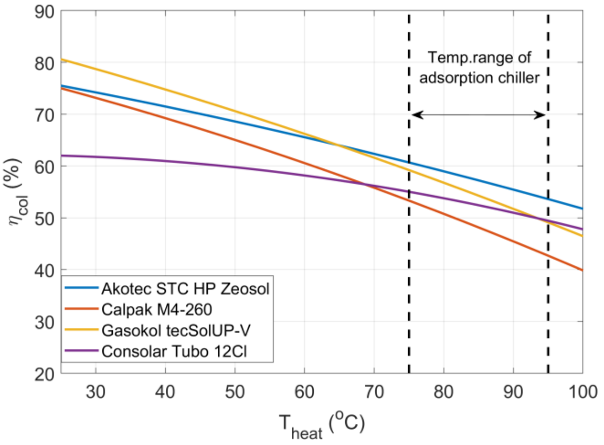


Fig. 3: Performance curve of the developed solar collectors for ZEOSOL system (blue line) in comparison to other commercial solar collectors

On the other hand, the adsorption chiller was developed and experimentally tested by the respective manufacturers, Fahrenheit GmbH. The performance results of the separate testing of the adsorption chiller, revealed a maximum thermal COP of 0.65, corresponding to an energy efficiency ratio (EER) as high as 45 for a driving temperature of 85 °C (Palomba et al. 2019b). The aforementioned COP for the adsorption chiller is defined by eq.2:

$$COP = \frac{\dot{Q}_{LT}}{\dot{Q}_{HT}} \qquad \text{(eq. 2)}$$

With HT referring to the driving heat supplied to adsorption chiller and LT to the low temperature stream which provides the cooling effect. On the other hand, the EER is defined as the ratio between the cooling capacity $\dot{Q}_{LT}$ and the total electric power consumption of the system $\dot{W}_{el}$:

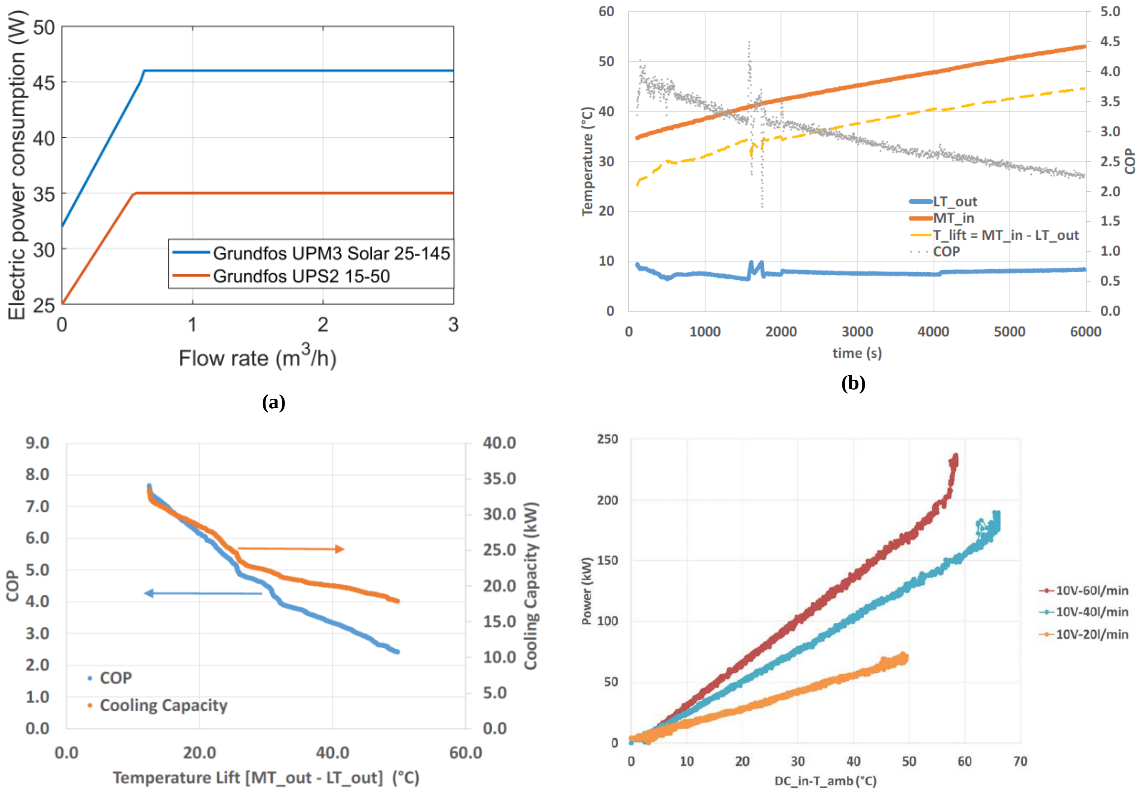
$$EER = \frac{\dot{Q}_{LT}}{\dot{W}_{el}} \qquad \text{(eq. 3)}$$

For the determination of the total electric power consumption of the system, apart from the electrical consumption of the dry cooler, $\dot{W}_{el,dc}$, are contributing also (i) the power consumption of the heat pump's compressor, $\dot{W}_{el,com}$, and (ii) the electrical consumption for the six pumps of the system, as shown in Fig.1. The total electrical power consumption is calculated as follows:

$$\dot{W}_{el,tot} = \dot{W}_{el,com} + \dot{W}_{el,dc} + \sum \dot{W}_{el,pumps} \qquad \text{(eq. 4)}$$

The equations for the power consumption of the HT, MT and LT pumps of Fig.1 can be found at Palomba et al. (2019b). Moreover, the fan coils pump is identical to the LT pump, thus the same power consumption profile is realized. The solar collector's circuit pump, installed at the solar station of the setup, Fig.2(c), is a Grundfos pump, model UPM3 Solar 25-145. On the other hand, the storage pump is a pump from the same manufacturer, model UPS2 15-50. The electric power consumption curves, as provided by the manufacturer, of the aforementioned pumps are shown in Fig. 4(a).

The backup heat pump is a custom made module developed for this specific application and a series of experiments were conducted at CNR-ITAE to evaluate its performance in coupling with the dry cooler of the system. Fig.4 (b) and (c) show that the performance of the backup heat pump, operating with R134a at a cooling water temperature of 7 °C, is considered satisfactory, achieving COP values as high as 4.0. On the other hand, Fig.4 (c) presents the power dissipated by the dry cooler as a function of the temperature difference between the water input and air.



(a)

(b)

(c)

(d)

Fig. 4: Experimental results of (a) the electrical consumption of the pumps, the developed backup heat pump performance (b) at maximum flow rate and (c) as a function of the maximum temperature lift and (d) cooling map of the dry cooler for variable flow rates at maximum fan speed.

Regarding, the performance of the backup heat pump, its COP is defined by eq.5:

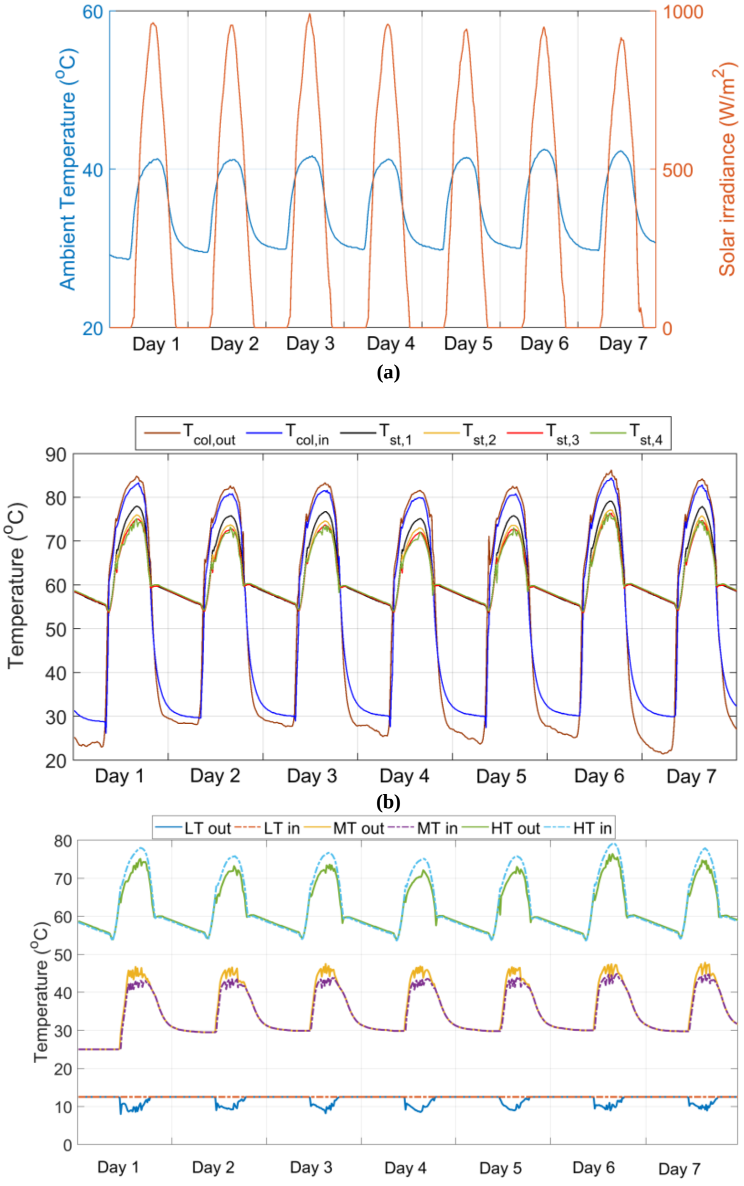
$$COP = \frac{\dot{Q}_{LT}}{\dot{W}_{el,com}} \qquad \text{(eq. 5)}$$

4. Results of solar adsorption cooling unit performance

In this section are presented the experimental results of the developed setup operating solely with the adsorption chiller. As the experimental testing of the ZEOSOL system is currently under progress, this study presents only the on- and off-design measurements of the solar driven adsorption chiller for a typical week in summer at Athens, Greece.

All temperature measurements were obtained using Pt100 thermal sensors, class A according to DIN/EN 60751. The flow sensors used are ultrasonic in-line flow meters with a 2% accuracy. The electrical power consumption of the dry cooler, the compressor and the circulation pumps was measured using energy analyzers. Finally, the solar radiation and the ambient conditions were monitored via a solar weather station, equipped with a second class (as ISO 9060) pyranometer, a Pt100 thermal sensor, an air humidity sensor and an anemometer.

Fig 5(a) presents an overview of the ambient conditions, with respect to the temperature and the solar irradiance for the week of the measurements. As shown in Fig. 5(a), the solar irradiance in the evaluated week is a rather lower than the average peak values for the summer of the typical year in Athens, not exceeding 1000 W/m². On the other hand, the simultaneous higher ambient temperatures that occurred in the investigated days resulted in operating all the components at higher temperature levels, which decreased their efficiency. Fig. 5 (b) and (c) present the temperature profiles for the solar collectors-storage tank module and for the adsorption chiller secondary streams, respectively. The adsorption chiller was set to start its operation at 65 °C for the HT in stream, resulting -in combination with the available solar irradiance- in operating only a few hours per day close to the solar noon. Despite the less optimal conditions, the system is able to cool down the water to 7.5 °C, which is the setpoint for the low temperature circuit, even though the driving temperature was less than 80 °C on all cases. The profiles of Fig. 5(c) outline the necessity for a modification of the control strategy for the involved circulating pumps so that higher driving temperatures are obtained ensuring maximum efficiency of the chiller. At this point, it has to be highlighted that Fig. 5 refers to adsorption only mode, thus at the absence of driving solar heat the system is off, which results in no operation at night.



(a)

(b)

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Fig. 5: (a) Ambient conditions at the period of the experiments (b) experimental results with respect to the solar subcircuit temperatures and (c) with respect to the chiller's secondary streams' temperatures

Fig. 6 presents the performance results for the entire ZEOSOL system, on adsorption-only mode, based on the definitions of eq. (2)-(3). Fig.6 (a) shows the cooling power production of the chiller during the investigated week and the total electrical power consumption, as defined by eq. (4). As shown in Fig. 6(a) the maximum obtained cooling power output is around 5 kW, which is approximately 40% of the nominal chiller's cooling capacity and is mainly attributed to the lower driving temperatures during the period of the measurements. On the other hand, the electrical power consumption is significantly low, with a maximum of 900 W, mainly due to the operation of the dry cooler, which accounts for more than 60% of the total power consumption of the system, on adsorption-only mode. The corresponding performance indicators are presented in Fig.6 (b). The maximum obtained thermal COP is approximately 0.575, for a maximum reported driving temperature of 79 °C, while the corresponding maximum EER was as high as 12, with an average operation at approximately 5.8. As these figures present only preliminary results of the system's performance on real-time conditions, there cannot be conclusive outcomes at this point. However, the first results with respect to the COP and the EER, at driving temperatures more than 10 °C lower than the nominal driving temperatures are rather promising. Furthermore, as a next step in the experimental evaluation of the system is also considered the operation of the backup heat pump as either an efficiency boost to the adsorption chiller as well as to cover the thermal loads at periods with no solar availability.

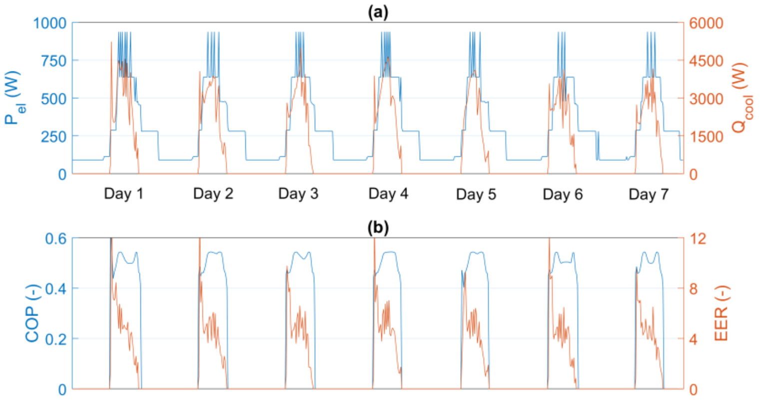

Fig. 6: Performance results of proposed system prototype with respect to (a) the produced cooling output and the respective electrical consumption and (b) the corresponding COP and EER values

5. Conclusions

In this study, the preliminary performance results of a solar driven hybrid adsorption chiller coupled with a backup heat pump were presented. The experimental analysis of the solar driven adsorption chiller revealed that the system despite non optimal conditions (smaller solar irradiance, high ambient temperatures) operated at a satisfactory level, with a maximum COP of 0.575. The developed system was proven to decrease significantly the electrical power consumption, achieving a maximum EER of 5.83 (with more than 60% of the total consumption coming from the system's dry cooler). These results are considered optimistic for the upcoming phases of the experimental evaluation of the system, not only on cooling but also for heating mode operation. However, as the experimental testing is at preliminary phase, there cannot be objective conclusions towards the system's performance, especially prior to the evaluation of the combined adsorption chiller-backup heat pump operation, which allows for even higher EER values under an optimized operational strategy. At the combined operation the system is expected to fully cover the loads of a 12.5 kW peak building, with an optimum solar fraction of around 60%, depending on the climatic conditions of the site of installation. An alternative to further enhance the solar fraction of the system it would be the addition of photovoltaic (PV) panels; however, this option was not evaluated within the framework of this project as it would increase the capital costs and add further complexity to the system.

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7. References

Aristov, Y.I., Chalaev, D.M., Dawoud, B., Heifets, L.I., Popel, O.S., and Restuccia, G. 2007. "Simulation and design of a solar driven thermochemical refrigerator using new chemisorbents." *Chemical Engineering Journal* 134 (1–3):58-65.

Calise, F., Dentice d'Accadia, M., Figaj, R.D., and Vanoli, L. 2016. "A novel solar-assisted heat pump driven by photovoltaic/thermal collectors: Dynamic simulation and thermoeconomic optimization." *Energy* 95 (Supplement C):346-366.

Drosou, V., Kosmopoulos, P., and Papadopoulos, A. 2016. "Solar cooling system using concentrating collectors for office buildings: A case study for Greece." *Renewable Energy* 97 (Supplement C):697-708.

Drosou, V.N., Tsekouras, P.D., Oikonomou, T.I., Kosmopoulos, P.I., and Karytsas, C.S. 2014. "The HIGH-COMBI project: High solar fraction heating and cooling systems with combination of innovative components and methods." *Renewable and Sustainable Energy Reviews* 29 (Supplement C):463-472.

Eicker, U., Pietruschka, D., Haag, M., and Schmitt, A. 2014. "Energy and Economic Performance of Solar Cooling Systems World Wide." *Energy Procedia* 57:2581-2589.

Habib, K., Choudhury, B., Chatterjee, P.K., and Saha, B.B. 2013. "Study on a solar heat driven dual-mode adsorption chiller." *Energy* 63:133-141.

Infante Ferreira, C., and Kim, D.-S. 2014. "Techno-economic review of solar cooling technologies based on location-specific data." *International Journal of Refrigeration* 39 (Supplement C):23-37.

International Energy Agency. 2014. Technology Roadmap. Solar Photovoltaic Energy.

Kalkan, N., Young, E.A., and Celiktas, A. 2012. "Solar thermal air conditioning technology reducing the footprint of solar thermal air conditioning." *Renewable and Sustainable Energy Reviews* 16 (8):6352-6383.

Kallis, G., Roumpedakis, T.C., Magiri-Skouloudi, D., and Karellas, S. 2019. "Environmental performance of ZEOSOL solar cooling setup." ECOS 2019, Wroclaw, Poland, 23-28 June.

Karellas, S., Roumpedakis, T.C., Tzouganatos, N., and Braimakis, K. 2018. *Solar Cooling Technologies*: CRC Press.

Lattieff, F.A., Atiya, M.A., and Al-Hemiri, A.A. 2019. "Test of solar adsorption air-conditioning powered by evacuated tube collectors under the climatic conditions of Iraq." *Renewable Energy* 142:20-29.

Lemmini, F., and Errougani, A. 2007. "Experimentation of a solar adsorption refrigerator in Morocco." *Renewable Energy* 32 (15):2629-2641.

Lu, Z., and Wang, R. 2018. "Experimental and simulation analysis of low temperature heat sources driven adsorption air conditioning, refrigeration, integrating ammonia, and organic expanding power generation." *International Journal of Energy Research* 42 (13):4157-4169.

Otanicar, T., Taylor, R.A., and Phelan, P.E. 2012. "Prospects for solar cooling – An economic and environmental assessment." *Solar Energy* 86 (5):1287-1299.

Palomba, V., Varvagiannis, E., Karellas, S., and Frazzica, A. 2019a. "Hybrid Adsorption-Compression Systems for Air Conditioning in Efficient Buildings: Design through Validated Dynamic Models." *Energies* 12 (6):1161.

Palomba, V., Wittstadt, U., Bonanno, A., Tanne, M., Harborth, N., and Vasta, S. 2019b. "Components and design guidelines for solar cooling systems: The experience of ZEOSOL." *Renewable Energy* 141:678-692.

Roumpedakis, T.C., Christou, T., Monokrousou, E., Braimakis, K., and Karellas, S. 2019. "Integrated ORC-Adsorption cycle: A first and second law analysis of potential configurations." *Energy* 179:46-58.

Sarbu, I., and Sebarchievici, C. 2013. "Review of solar refrigeration and cooling systems." *Energy and Buildings* 67:286-297.

Vasta, S., Palomba, V., La Rosa, D., and Mittelbach, W. 2018. "Adsorption-compression cascade cycles: An experimental study." *Energy Conversion and Management* 156:365-375.

Wang, L.W., Wang, R.Z., and Oliveira, R.G. 2009. "A review on adsorption working pairs for refrigeration." *Renewable and Sustainable Energy Reviews* 13 (3):518-534.

Wang, R.Z., and Oliveira, R.G. 2006. "Adsorption refrigeration—An efficient way to make good use of waste heat and solar energy." *Progress in Energy and Combustion Science* 32 (4):424-458.