DOI: 10.17512/bozpe.2019.1.07

Budownictwo o zoptymalizowanym potencjale energetycznym
Construction of optimized energy potential

ISSN 2299-8535 e-ISSN 2544-963X

Building solar cooling systems based on thermally driven chillers as an alternative approach to classic electrical cooling systems

Mariusz Filipowicz[1] (*orcid id: 0000-0002-1931-9383*)
Rafał Damian Figaj[2] (*orcid id: 0000-0002-2746-1299*)
Estera Przenzak[3] (*orcid id: 0000-0002-7000-6876*)
[1,2,3] AGH University of Science and Technology, Faculty of Energy and Fuels, Cracow

Abstract: Recently, the cooling market has witnessed a significant growth resulting in a considerable increase in the demand for electricity. Demand peaks during the hottest days and has become a serious problem in terms of power network stability. This can be seen during summer in Poland, where electricity demand over those few days, is greater than compared to winter. In general, the summer peak in electrical demand due to space cooling installations is a common problem in European countries. Fortunately, the high availability of solar energy is correlated with the cooling demands of buildings. A condition that creates an opportunity for the application of solar cooling systems. Thus, solar energy may reduce the consumption of power produced from conventional energy sources and at the same time reduce the peak of electrical energy demand. The available solar thermal collectors with sufficient and insufficient temperature output to drive the solar cooling process are presented. In the case of insufficient temperature output, auxiliary units have been considered. The absorption technology has been reviewed. Some simulation and experimental results of systems presented in literature are discussed in the paper. Finally, an example simulation of a hybrid solar system of heat generation, including flat plate collectors, a solar concentrator and an absorption chiller, is presented.

Keywords: solar space cooling, solar concentrator, absorption cooling, building installation, dynamic simulation

Access to the content of article only on the base of Creative Commons licence CC BY-NC-ND 4.0

Please, quote this article as follows:

M. Filipowicz, R.D. Figaj, E. Przenzak, Building solar cooling systems based on thermally driven chillers as an alternative approach to classic electrical cooling systems, Budownictwo o zoptymalizowanym potencjale energetycznym, vol. 8, 1, 2019, 67-76, DOI: 10.17512/bozpe.2019.1.07

Introduction

A significant growth in the cooling market has been observed in the recent years, due to continuous improvement of living standards. Therefore, the significant increase in the electrical demand due to space conditioning, especially during the hottest days, has become a serious problem in the view of power system operation.

High availability of solar energy in the summer is correlated with the cooling demands of buildings, which creates an opportunity for the application of solar cooling systems. The application of solar energy may reduce the consumption of power from conventional energy sources and also reduce peak demand.

The interest given to solar cooling technologies in recent years is significant. In (Wang et al., 2016), a detailed review of selected absorption and adsorption units was presented, where five different sorption units able to be driven by solar heating were described. In this paper, design schematics, design methods and experimental results are discussed. In (Choudhury et al., 2013) several systems based on adsorption cooling were presented. The authors stated that low-temperature adsorption cooling systems are emerging and are expected as a solution for electricity demand problems. Thermally activated adsorption cooling technologies are attractive alternatives in that they: i) serve the need for air-conditioning and refrigeration, ii) meet the demand for energy conservation and iii) achieve significant environmental benefits.

Solar cooling installations are a mature technology and many facilities are currently in operation, e.g.:

– Installation of the Fraunhoffer Institute Building in Germany (Ali et al., 2008). The system includes a 35 kW hot water cooling absorption chiller supplied by vacuum tube collectors, hot water storage, cold water storage and a cooling tower. A floor area of 270 m^2 is air-conditioned by the installation. In some months where cooling is required, the demand covered by solar energy reaches 70%, while the value was about 25% during the 5 years period of the installation's operation.
– Facility in Madrid, Spain (Venegas et al., 2011), where a commercial single-effect water-lithium bromide absorption chiller and 20 flat plate solar collectors arranged in four parallel straight lines are installed. A commercial-grade thermal storage tank of 2000 l capacity, heat exchanger and the corresponding insulated piping were included in the installation. The obtained maximal thermal power was above 45 kW and maximal cooling power ranged between 5 and 7 kW.
– Plant developed in Hong-Kong (Fong et al., 2012). The installation consists of two solar cooling systems: with building-integrated (BI) solar collectors and collectors installed on the roof for absorption refrigeration, and with PV panels for DC-driven vapor compression refrigeration. The end user is considered to be a typical office area ca. 200 m^2. For this installation, the building integrated solar collectors achieve a lower solar fraction (SF) and consequently a higher primary energy consumption compared to the conventional system.

In many applications, the amount of heat generated from solar radiation is not sufficient to obtain the required temperature of the working medium. Therefore various methods of heating up the working medium are applied, e.g. gas burner (Vargas et al., 2009), electric heater (Izquierdo et al., 2014).

The scope of this paper is the investigation of a hybrid solar cooling system that integrates flat plate solar collectors, a solar dish concentrator and an absorption chiller. The system is entirely powered by solar energy, without auxiliary units to drive the absorption chiller in the event of scarce availability of solar radiation.

1. Description of the system

The solar hybrid system used as a base for the present study is installed at the Faculty of Energy and Fuels, AGH UST (Fig. 1). The absorption chiller is a Yazaki unit of 17 kW, with a coefficient of performance of 0.74. The Yazaki unit is installed at the Center of Energy, where several experimental activities are performed.

Fig. 1. Installation of the absorption chiller

The installed unit is equipped with thermal storage, used in order to allow proper and stable operation of the chiller in case of variations in the driving thermal power source. The experimental installation also consists of a fan coil, piping, auxiliary electric heating and control system.

However, for the purpose of the simulation in this paper, the chiller unit was operated at a reduced thermal power of 7 kW, since the maximum power was limited by the solar field capacity and by the thermal demand of the considered user.

The second element of the system was a hybrid solar thermal collector system, including flat plate collectors and a solar dish concentrator. The system allows one to increase the operational temperature of the solar loop compared to the flat plate collectors. The installation of the system is located on the roof of the faculty buildings (Fig. 2).

Fig. 2. Solar installation (left image available in Przenzak et al., 2016)

2. Simulation model

The simulations performed in this paper are based on the previously presented installations. The object of the simulation is a typical Polish household. In particular, the case study consists of a typical single floor house with sloped roof. The developed case study building is shown in Figure 3.

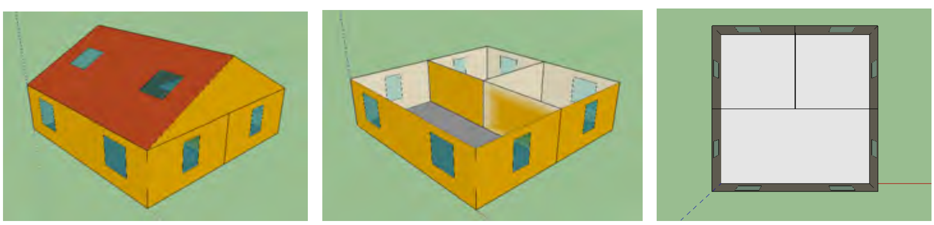

Fig. 3. Building structure

Four zones are used to develop the model of the building. Three of them located on the ground floor and one located in the attic. The slope of the roof is 30°, the ground floor area is equal to 100 m^2 and the height is 2.70 m. For the glazed surfaces, double-glass insulated windows were adopted. The building envelope components were implemented with the assumption that they consist of several series of layers. The transmittances of windows, walls, roof and floor are reported in Table 1.

Each zone of the house is equipped with an independent fan coil unit that provides the required space conditioning during winter and summer periods. Obviously, due to the scope of the performed study, only the cooling of the house was simulated. The space cooling period is assumed to be from May 1st to October 31st, while the chilling equipment (ACH, ECH and FC) is set to operate from 8.00 am to 8:00 pm. During that time, the hybrid space cooling system ensures air temperatures in each zone ranges between 24 and 26°C, as described in the model section.

Table 1. Building elements transmittances

Building envelop element	$W/(m^2K)$
External window	2.83
External wall	0.40
Adjacent wall	2.20
Ceiling	1.58
Roof	0.32
Ground floor	0.37

The layout of the simulated system is shown in Figure 4. Please note that the system integrates an electrical chiller, included in order to match the space cooling demand of the user in the case of scarce solar energy availability.

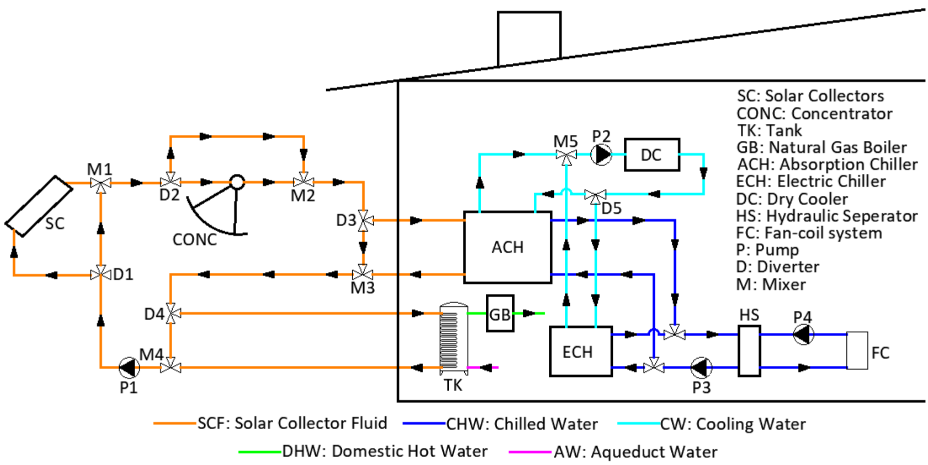

Fig. 4. Building structure

The building and the hybrid space cooling system were modelled and simulated in the TRNSYS 17 software. The model of the system was developed using both built-in library components and user defined components. The software library components are experimentally validated and/or are based on real operational/manufacturer data, thus, they are intrinsically validated. In particular, in order to simulate the yearly climatic conditions, the Meteonorm weather data for Cracow, Southern Poland, was implemented.

In order to calculate the system's economic profitability, a comparison was made with a conventional system consisting of a natural gas boiler and an electrical chiller for domestic hot water preparation and space cooling, respectively. The calculation of the Simple Pay back (SPB) index was introduced. In detail, the economic assessment of the system was carried out assuming manufacturers data costs for all the components of the system and actual prices for natural gas and electrical energy (Eurostat). The adopted costs are: 118 €/m^2 of concentrator area, 825 € for biaxial tracking system, 300 €/kW of absorption chiller power.

3. Results

The dynamic simulation of the system produced an enormous quantity of data, thus for reasons of brevity only some results are presented here. The results of the daily and weekly operation of the system were carried out by the dynamic simulation of the system and with the integration of the data over the selected time period (week). Moreover, the effect of the concentrator area on the system energy and economic performance is analyzed by means of a sensitivity analysis.

The dynamic trends of the main thermal power of the system during a typical summer day are shown in Figure 5. The activation/deactivation of the absorption chiller occurs during the first and lasts hours of the unit operation. This occurs because the temperature of the solar fluid oscillates and in some time periods it is not high enough to drive the absorption unit. In fact, during the first morning hours the solar thermal energy is entirely supplied to the TK, since the temperate is below 80°C. Moreover, it is worth noting that the solar concentrator is able to produce useful heat earlier in the morning and late evening hours compared to the solar field, due to the two-axis tracking system. However, the solar field thermal power produced during the day is significantly higher than the one of the concentrator, due to the difference of aperture area between the solar devices. The graph also points out that the domestic hot water demand of the user was matched by the gas boiler only during the first morning hours, when the production of solar thermal energy is scarce.

The results show that the solar cooling systems is capable of driving the absorption chiller once the solar loop fluid achieves an adequate temperature. Only some oscillations occur due to the variation of the returning temperature of the space cooling distribution system and to the oscillation of the solar fluid temperature.

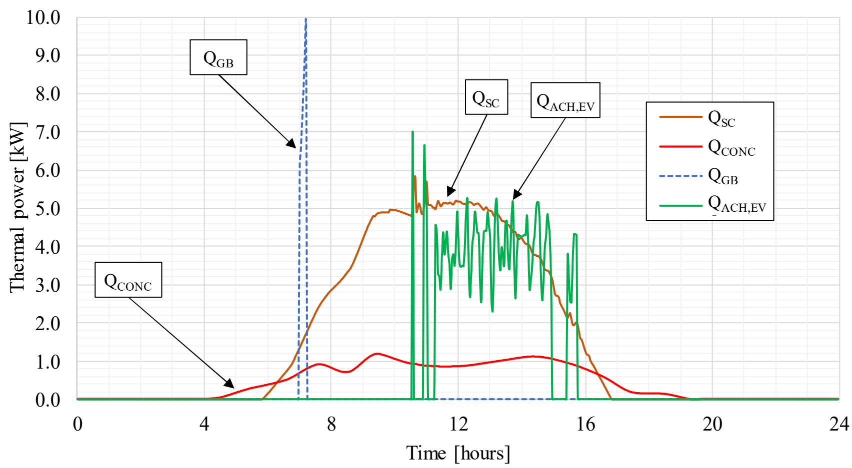

Fig. 5. Dynamic trends of the main thermal power of the system: solar collectors, concentrator, gas boiler for domestic hot water, evaporator of the absorption chiller

The weekly trends from Figure 6 show the operation of the system during the year. All the energy flows reported follow the trend of the solar radiation (not reported for sake of clarity). As highlighted by the daily graph, the magnitude of the produced thermal energy by the solar collector is significantly higher than that of the concentrator.

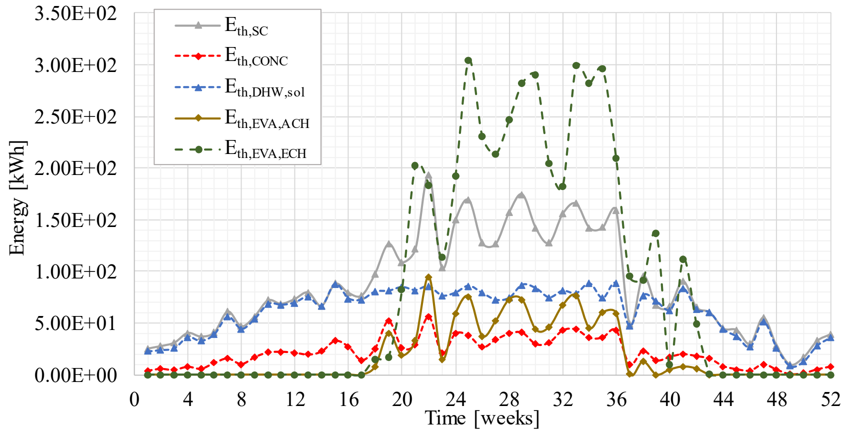

Fig. 6. Weekly trends of the main thermal power of the system: solar collectors, concentrator, solar energy supplied to domestic hot water production, evaporator of the absorption chiller, evaporator of the electric chiller

The trend of the solar energy supplied to domestic hot water is almost constant during summer. This occurs because the solar system matches almost the entire demand of the user, as a consequence, the operation of the gas boiler is only marginal. The solar cooling system provides only part of the energy for space cooling, while the most part of the user's demand is matched by the electric chiller. This is due to the limited extension of solar field and concentrator area, which allows one to match the cooling demand during the central hours of the day when the solar radiation is relatively high.

The main results of the sensitivity analysis are shown in Figure 7. The results show that the maximum efficiency of the concentrator is achieved in the range of between 4 and 5 m^2. Over such a range the efficiency decreases due to the increase of the operational temperature of the solar loop fluid. In fact, the higher the operational temperature, the higher the thermal losses. This effect is also present in the flat plate collectors, leading to a significant reduction of the efficiency. Moreover, a larger concentrator determines a slight decrease of the Coefficient of Performance of the absorption chiller, accordingly to the performance of the unit.

The increase of the concentrator area determines an increase of the space cooling demand matched by the solar system, as outlined by the solar factor. For a concentrator area of 20 m^2, the solar factor for cooling increases above 55%. Furthermore, for a larger concentrator aperture, the Primary Energy Saving increases due to the higher production of domestic hot water by solar energy and to the reduction of electrical energy consumption (less frequent activation) of the electric chiller.

For 20 m^2, the system allows one to save more than 60% of Primary Energy compared to the traditional system consisting of a gas boiler for domestic hot water production and the electric chiller for space cooling purposes.

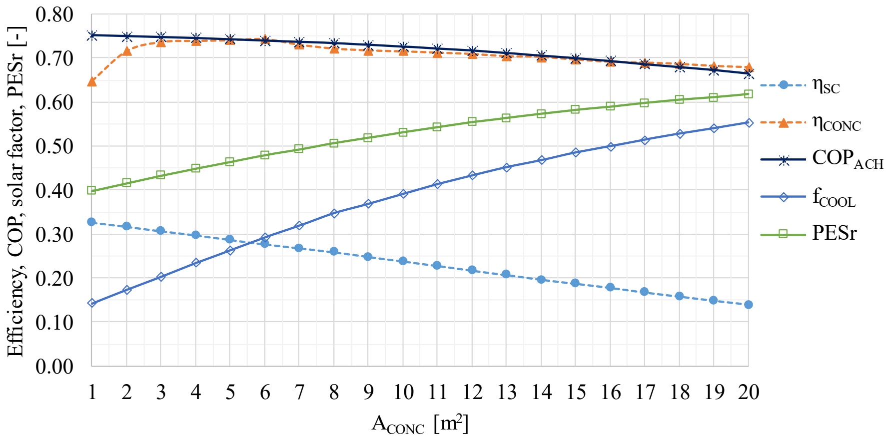

Fig. 7. Energy parameters as a function of the concentrator area: collector efficiency, concentrator efficiency, absorption chiller Coefficient Of Performance, solar factor for cooling, Primary Energy Saving ratio

The results of the economic analysis are shown in Figure 8. The values of SPB show that the system is not profitable from the economic point of view for the considered concentrator area values. In fact, more than 20 years are required to repay the investment to the user. This is due to the high cost of the equipment and relatively low thermal and electrical energy tariffs. It is worth noting, that the optimum concentrator area is about 11 m^2. Such configuration allows to achieve the best balance between the energy savings/consumption and the economic savings.

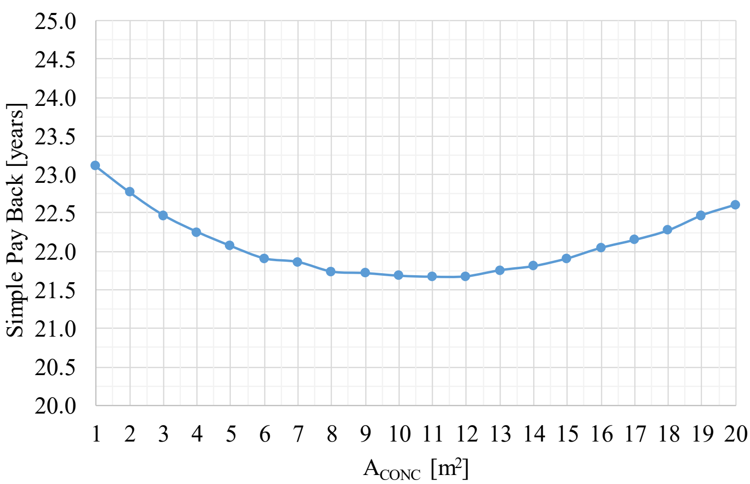

Fig. 8. Simple Pay Back as a function of the concentrator area

Furthermore, it is important to note that the economic performance of the proposed system improves when locations with higher availability of solar energy, space cooling demand and energy prices compared to Cracow are considered. For example, in the case of Madrid, SPB is 7.9 years, which starts to be an acceptable value from the economic feasibility point of view. Such a value, could be reduced by taking into account a possible incentive policy allowing the reduction of the investment cost. In this way, even in the case of Cracow, the system could be economically profitable. In fact, adopting an aggressive policy funding of 80% of the total cost of the system, a SPB of less than 5 years can be reached. Finally, it must also be considered that the increase in energy prices results in a better condition for the applicability of the proposed system.

Conclusions

The simulation of the hybrid solar cooling system allowed the investigation of its dynamic operation for daily and weekly operation, as well as determine the effect of the concentrator area parameter on the system performance. In particular, the system allows one to drive the absorption chiller unit for several hours during the central hours of the day, avoiding the operation of the electrical chiller unit. For the considered case study of Cracow, the system energy yield increases significantly during the summer, however the operation of the electrical chiller is mandatory to match the user's demand during off-peak hours of solar radiation. The parametric analysis showed that the increase of the concentrator area allows one to increase the part of the space cooling demand matched by the absorption unit. The concentrator area must reach about 17 m^2 to match 50% of the space cooling with the use of solar energy. The economic performance of the system is relatively poor, since the Simple Pay Back is more than 20 years, due to the high cost of the system and relatively low energy tariffs. Better performance can be achieved in the case of Madrid, where a Simple Pay Back value lower than 8 years can be reached.

Acknowledgments

This work was carried out under statutory research of AGH WEiP. The infrastructure of the Center of Energy, AGH UST in Cracow was used.

Bibliography

Ali, A.H.H. et al. (2008) *Performance assessment of an integrated free cooling and solar powered single-effect lithium bromide-water absorption chiller*. Solar Energy, 82(11), 1021-1030.

Choudhury, B. et al. (2013) *An overview of developments in adsorption refrigeration systems towards a sustainable way of cooling*. Applied Energy, 104, 554-567.

Eurostat - European Comission, *http://ec.europa.eu/eurostat*, accessed on December 2018.

Fong, K. et al. (2012) *Comparative study of solar cooling systems with building-integrated solar collectors for use in sub-tropical regions like Hong Kong*. Applied Energy, 90(1), 189-195.

Izquierdo, M. et al. (2014) *Solar-powered single-and double-effect directly air-cooled LiBr-H_2O absorption prototype built as a single unit*. Applied Energy, 130, 7-19.

Przenzak, E. et al. (2016) *The numerical model of the high temperature receiver for concentrated solar radiation*. Energy Conversion and Management, 125, 97-106.

Vargas, J. et al. (2009) *Modeling, simulation and optimization of a solar collector driven water heating and absorption cooling plant*. Solar Energy, 83(8), 1232-1244.

Venegas, M. et al. (2011) *Experimental diagnosis of the influence of operational variables on the performance of a solar absorption cooling system*. Applied Energy, 88(4), 1447-1454.

Wang, R. et al. (2016) *Solar driven air conditioning and refrigeration systems corresponding to various heating source temperatures*. Applied Energy, 169, 846-856.

Chłodzenie słoneczne jako alternatywa tradycyjnych technologii chłodzenia w budynkach

Streszczenie: Ostatnio na rynku chłodniczym odnotowano znaczny wzrost zainstalowanych jednostek, determinujący znaczne zwiększenie konsumpcji energii elektrycznej. Dlatego szczytowe zapotrzebowanie w najgorętsze dni stało się poważnym problemem ze względu na stabilność sieci energetycznych. Na przykład, podczas obecnego lata w Polsce popyt na energię elektryczną w ciągu kilku dni był większy niż w dni zimowe. Ogólnie, letni szczyt zapotrzebowania na energię ze względu na instalacje do chłodzenia pomieszczeń jest powszechnym problemem w krajach europejskich. Na szczęście wysoka dostępność energii słonecznej jest skorelowana z zapotrzebowaniem na chłód budynków w lecie. Taki stan stwarza okazję do zastosowania systemów energii słonecznej do celów chłodzenia, co może obniżyć zużycie energii wytwarzanej z konwencjonalnych źródeł energii, a jednocześnie zmniejszyć szczyt zapotrzebowania na energię elektryczną. W artykule opisano dostępne kolektory słoneczne o wystarczającym i niewystarczającym wydatku temperatury do napędzania procesu chłodzenia energią słoneczną. W przypadku niewystarczającej wydajności cieplnej uwzględnia się jednostki pomocnicze (takie jak kotły elektryczne i biomasowe). Przedstawiono niektóre symulacje i wyniki eksperymentalne systemów prezentowanych w literaturze. Na zakończenie zaprezentowano wyniki symulacji hybrydowego układu słonecznego wytwarzania ciepła i chłodu z kolektorami płaskimi, koncentratorem słonecznym i chłodziarką absorpcyjną.

Słowa kluczowe: chłodzenie słoneczne, koncentrator solarny, chłodzenie absorpcyjne, budynek, symulacja dynamiczna