An innovative solar-powered cooling system based on climate-friendly refrigerants, coupled with thermal energy storage: "COOLSPACES 4 LIFE" project

Innowacyjny, solarny system chłodzenia budynku oparty o ekologiczne czynniki chłodnicze i magazynowanie ciepła: projekt "COOLSPACES 4 LIFE"

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The article presents the concept as well as preliminary modeling and technical issues on the ongoing European project COOLSPACES 4 LIFE as a novel study of an innovative solar-powered building cooling (BC) system based on climate-friendly refrigerants (CFRs) operating in tandem with a short term energy storage. This novel BC system is being developed in collaboration with two institutions from Spain, namely University of Almeria and Hedera Helix Ingenieria y Biotecnologia as well as PROZON Fundacja Ochrony Klimatu from Poland. The prototype will supply one floor of Geocentrum building on the Wrocław University of Science and Technogy campus's institutional facility with a cooling power of 70 kW and will be powered by a photovoltaic system. Once we obtain satisfactory results in Poland this technology will be replicated in Spain in the University of Almeria campus's institutional facility, thus we aspire to develop a highly exploitable product applicable Europe wide. This technology will significantly reduce carbon emissions and produce significant economic benefits, therefore it will be a perfect climate change mitigation strategy.
Keywords: solar energy, photovoltaic system, building cooling system, climate-friendly refrigerants, phase-change material, climate change mitigation.

W artykule przedstawiono koncepcję, a także wstępne modelowanie i kwestie techniczne dotyczące realizowanego obecnie europejskiego projektu COOLSPACES 4 LIFE, w ramach którego prowadzone są badania nad innowacyjnym systemem chłodzenia budynków, zasilanym energią słoneczną, opartym na przyjaznym dla klimatu czynniku chłodniczym i współpracującym z krótkoterminowym magazynem energii. Ten nowatorski system chłodzenia jest opracowywany we współpracy z dwoma instytucjami z Hiszpanii, z Uniwersytetem w Almerii i Hedera Helix Ingenieria y Biotecnologia oraz z polską Fundacją Ochrony Klimatu PROZON. Prototyp o mocy chłodniczej 70 kW będzie dostarczał chłód do części budynku Geocentrum na terenie kampusu Politechniki Wrocławskiej i będzie zasilany z systemu fotowoltaicznego. Po uzyskaniu zadowalających wyników w Polsce, technologia ta zostanie zreplikowana w Hiszpanii na Uniwersytecie w Almerii, co pozwoli opracować produkt o szerokim zakresie eksploatacyjnym i umożliwi zastosowanie go w całej Europie. Technologia ta znacznie ograniczy emisję dwutlenku węgla i przyniesie znaczące korzyści ekonomiczne, dlatego będzie doskonałą strategią łagodzenia zmian klimatycznych.
Słowa kluczowe: energia słoneczna, fotowoltaika, system chłodzenia budynków, ekologiczny czynnik chłodniczy, materiał zmiennofazowy, łagodzenie zmian klimatu.

Introduction

Energy consumption in the building sector has increased significantly in the past years. The main factor of that increase is the space cooling, which in 2020 was accounted for 18.5% of the building sector final electricity consumption, and 6% of its total energy, which means nearly 2000 TWh of the global energy used for that part of our life (Fig. 1) [1, 2]. Narrowing the scope of that problem, including only European countries and analyzing the consumption in the different types of buildings, public buildings have even 60% higher demand of the energy than the residentiam ones, and this trend is stable since 2008 [3]. It gives opportunities to improve by looking for solutions in order to optimize the energy efficiency of the service buildings.

Another problem connected to the high energy demand for the cooling is the capacity of the national power grids and high fluctuations of the energy production and its need. Due to the problems described above and the continuous growth of the

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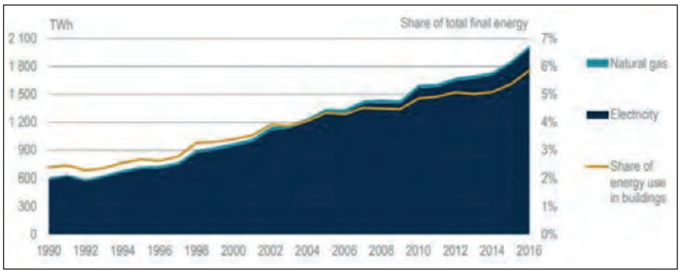

Fig. 1.
World energy consumption for space cooling in buildings [1]
Rys. 1. Globalne zużycie energii na chłodzenie pomieszczeń w budynkach

cooling branch the blackout becomes a really challenging problem for the European electricity systems [4]. A one of the solution which might improve national power grids capacity is a diverse energy mix and higher usage of renewable energy sources. Based on the Eurostat data [5] by the end of 2020 Poland has generated only slightly above 16% of its total energy demand from the various renewable energy sources [5] which is 6% less than the European average. Growth of the renewable energy sources sector is crucial to meet the targets about the shares established by European directives, but also to reduce greenhouse gases emission and then furthermore accomplish the Paris Agreement against the global temperature rise. That is why looking for the systems of green energy that get activated at the same time when the demand for the energy appears is one of the main area of investigation on renewable energy sources. One of that solution is a solar-powered building cooling (BC) system presented in this article.

Cooling devices commonly used in the air conditioning systems are mainly based on the F-gas refrigerants. Despite the emission produced by burning the fossil fuels, refrigerants are also a significant part of the emission of greenhouse gases. The impact of the greenhouse effect is represented by the global warming potential (GWP) factor, which is a calculated equivalent of the influence to the greenhouse effect of the given refrigerant in 100 years, compared to the impact that is caused by the same mass of CO_2 [6]. Reducing the GWP of commonly used refrigerants, by introducing the natural components, might importantly limit a negative impact of the widespread of usage of those substances in the European industry.

Prototype description and operation principle

The innovativeness of the proposed COOLSPACES 4 LIFE prototype manifests itself mainly in the refrigerants used. The prototype will use either a binary or a ternary mixture, the main component of which will be hydrocarbons (HC). By applying the above solution, it will be possible to obtain a low refrigerant impact on the environment (a GWP below 150), which is consistent with the provisions of Regulation (EU) No 517/2014 [6]. At the same time, it will be possible to improve the efficiency of the cooling cycle by improving the thermodynamic properties of the substances in relation to pure HC. Secondly, the prototype will use two refrigerant compression stages with full intercooling, which significantly reduces the amount of work necessary to implement the compression process, hence a high energy efficiency ratio will be obtained. The prototype design also assumes that the evaporator is fed through a liquid separator, which allows the heat exchanger to operate with zero superheat. Thirdly, operating the system in tandem with short-term energy storage extends the scope of operation beyond the hours of solar radiation necessary to start the air-conditioning system. This improves the building's energy performance by pre-cooling in the morning and improves overall system efficiency. It also reduces the cyclicality of the cooling device and minimizes temperatures changes in the cooling system's working medium. Another innovation of the system is the use of phase-change materials (PCMs) in the form of replaceable energy storage inserts, which will be placed in two short term energy storage tanks. Moreover, the possibility of PCM selection to a required phase-change temperature, will increase the possibility of cold accumulation for initial building cooling using latent heat, without the need for extensive technical interventions in the storage tank. Last, but not least, using photovoltaic panels as a power source for the inverter compressors and the autonomous operating control system will make it possible to use the harvested energy optimally and distribute it between cooling the building directly and energy storage. A further advantage of the solution is the reduction in energy losses from using the condensation heat discharge for water heating (pre-heating water for household use, etc.).

It has also to be highlighted that the BC system will possibly use waste refrigerants recovered from recycled refrigeration and air conditioning equipment. This will be possible due to collaboration with PROZON Fundacja Ochrony Klimatu, which is working on a waste separation installation for mixed refrigerants in another LIFE project (LIFE18 CCM/PL/001100). This installation will allow to separate refrigerant mixtures into basic components, from which we will choose those with a low global warming potential.

The BC system will supply one floor of Geocentrum building at the Wrocław University of Science and Technology campus with a cooling power of 70 kW and will be replicated in totally different climate conditions, namely at University of Almeria in southern Spain (Fig. 2), where need for cooling between May and October is extremely high. This leads to the main purpose of COOLSPACES 4 LIFE project, which is to develop a universal solution, that can be installed and effectively used at any latitude in Europe.

The entire prototype is based on three components: an innovative climate-friendly refrigerants (CFRs) based solar cooling

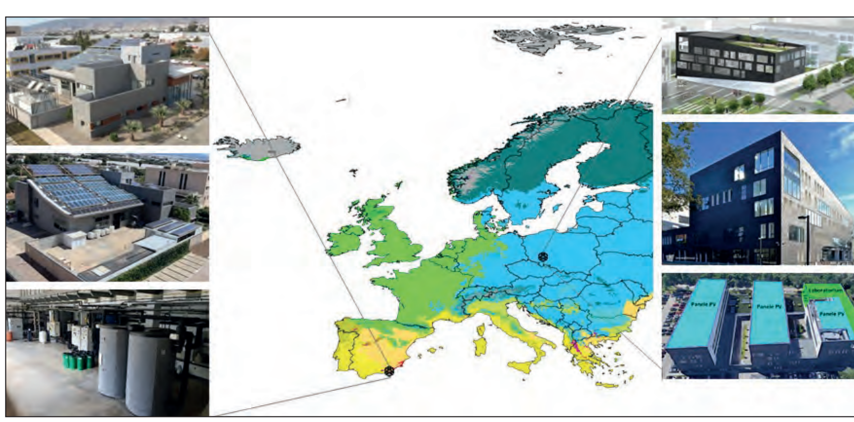

Fig. 2.
Geographical locations of COOLSPACES 4 LIFE installation (University of Almeria in Spain and Wrocław University of Science and Technology in Poland)
Rys. 2. Lokalizacje geograficzne instalacji COOLSPACES 4 LIFE (Uniwersytet w Almerii w Hiszpanii i Politechnika Wrocławska w Polsce)

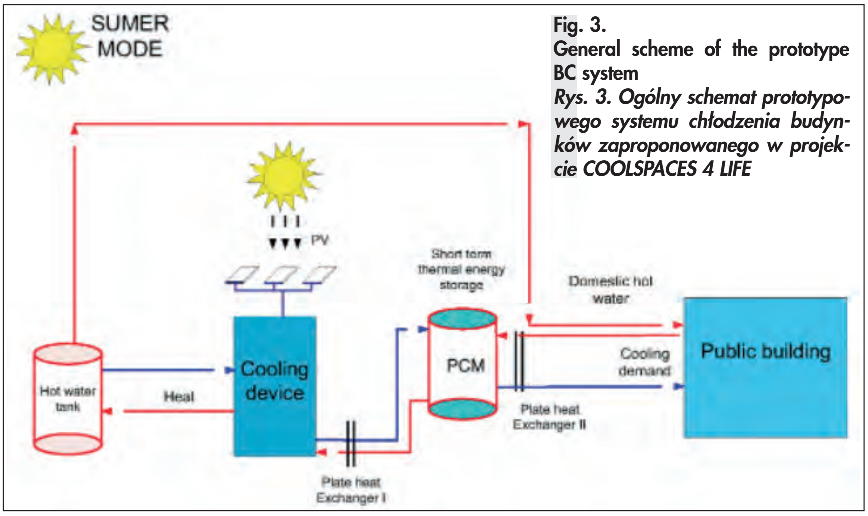

Fig. 3.
General scheme of the prototype BC system
Rys. 3. Ogólny schemat prototypowego systemu chłodzenia budynków zaproponowanego w projekcie COOLSPACES 4 LIFE

device prototype powered by photovoltaic panels, a short-term energy storage based on phase-change materials and cooling and domestic hot water (DHW) subsystems (Fig. 3). During summer, the premises cooling demand will be covered by the cold generated through the solar-powered cooling device, coupled to the PCM tank, and supplied to the building by a cooling water subsystem. On cloudy days the cooling demand will be covered by cold accumulated in the PCM tank, which will be stored the day before. Using a battery set, coupled to the photovoltaic panels, will allow to store electric energy and therefore eliminate any additional fossil fuel energy consumption. During cold days the premises will be extra supplied by heat produced in condenser coupled to DHW subsystem.

The cooling device will consist of two compression stages with full intercooling obtained in a diaphragm less cooler. The air-cooled condenser will allow for a wider use of the device in practice. The evaporator will be supplied with liquid refrigerant in a pumping system, where the liquid will flow from the equalizing drum, which is also a liquid separator for the first stage compressors (Fig. 4).

The prototype will be equipped with numerous systems for monitoring the operation of both the entire device and individual components. All signals collected from the pressure and temperature transducers, signals from expansion and electromagnetic valves (opening states), data from flow meters and current parameters of compressors will be collected and analyzed by the system. This will allow the development of an effective control strategy for the operation of the device.

The short term energy storage system, as part of a cooling system, improves the efficiency of the system as a whole. Designed system will consist of two tanks storing

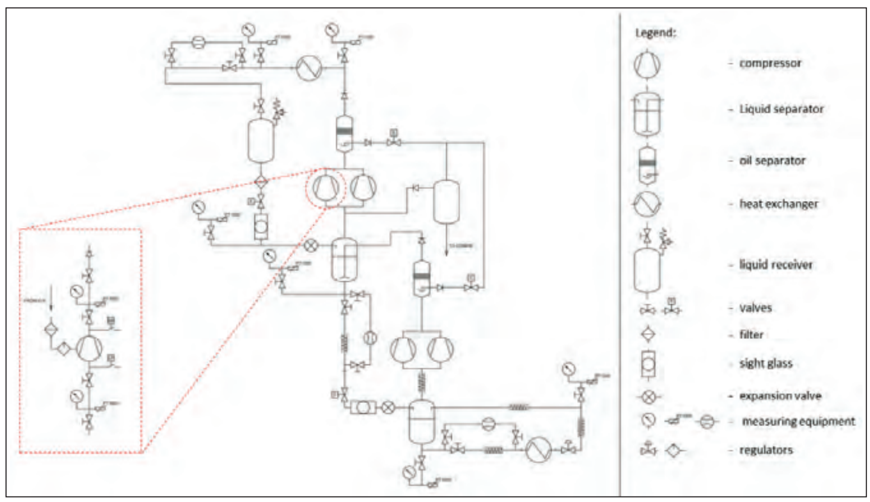

Fig. 4.
Process flow diagram of the cooling prototype
Rys. 4. Schemat układu procesowego prototypu instalacji chłodniczej

energy in the form of sensible heat by using the intermediate fluid and latent heat resulting from the phase transition of PCM, thus ensuring a high heat storage density.

Two unconventional pressure vessels made of stainless steel with high thermal insulation suitable for low temperatures will be made. Initial studies of the phase change material led to the selection of two potential tank fillings. The first is a sleeve-shaped structure 310 mm long and 42 mm in diameter (Fig. 5a), the second is a flanche-shaped PCM structure similar to a cuboid with dimensions 185 x 185 x 32 mm (Fig. 5b). The tank will have 4 flange connections for the inlet and outlet of the intermediate fluid, along with digital flow measurement and a stratified temperature measurement, enabling the energy balance of the tank to be made. Freezing temperature of PCMs in both containers will be – 3 °C.

Measurement of the tanks and the data acquisition system will enable the monitoring of the process of charging and discharging energy from the tank to the air-conditioned building, ensuring the selection of the optimal cooling strategy.

The entire newly design cooling system will be supplied by a photovoltaic system installed on the roof of the building (Figs. 6 and 7) belonging to the Renewable Energy Laboratory of the Wrocław University of Technology. It is planned to provide a minimum of 20 kWe of electricity to the cooling device during the summer season, which in the climatic conditions of Poland will allow for the production of approx. 70 kW of cooling power. The potential excess

Fig. 5.
Types of the PCM containers evaluated in the simulation;
a) sleeve-shaped,
b) flanche-shaped
Rys. 5. Typy zbiorników PCM ewaluowanych w symulacji:
a) w kształcie elipsoidy obrotowej,
b) w kształcie kołnierza

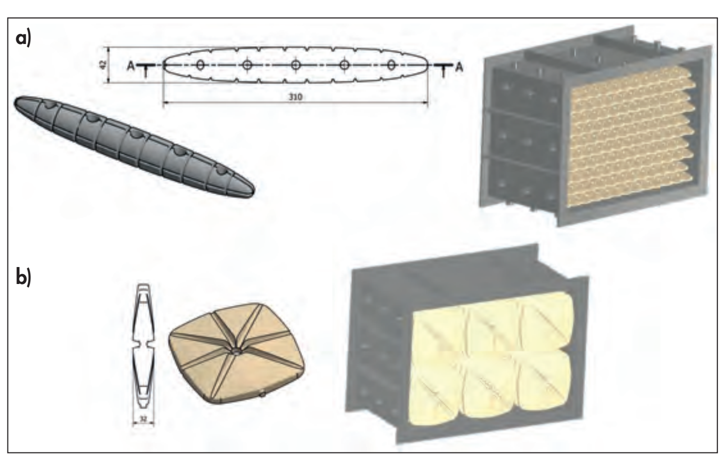

Fig. 6.
Location of photovoltaic panels on the middle roof of Geocentrum building
Rys. 6. Lokalizacja paneli fotowoltaicznych na środkowym dachu budynku Geocentrum

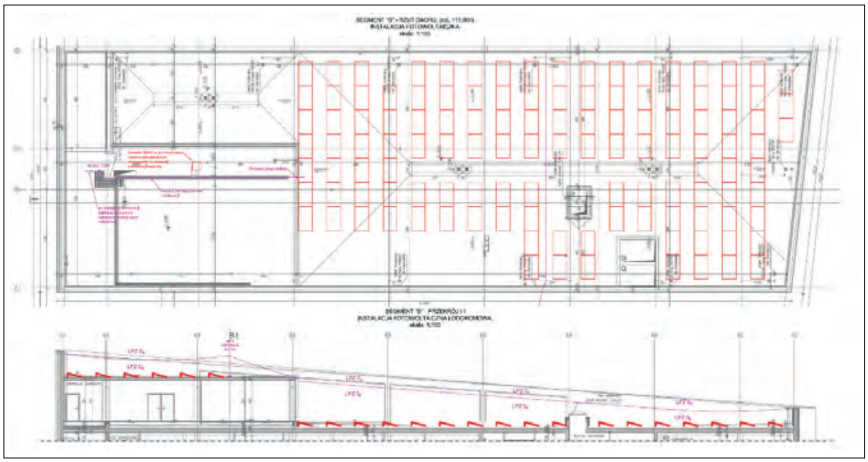

Fig. 7.
A detailed scheme of photovoltaic panels location on the roof of Geocentrum building
Rys. 7. Szczegółowy schemat rozmieszczenia paneli fotowoltaicznych na dachu budynku Geocentrum

of electricity produced will be stored in the battery system.

The entire system will be controlled by a building management system, allowing for a smart control and to even more optimize the use of cold supplied to the building. Together allowing for a summer-round cover of the building's partial cooling and DHW demand. Through this project we will demonstrate, that it is possible to use buildings as an environmental source of energy production, storage and conservation.

Expected results

The expected results of COOLSPACES 4 LIFE project are as follow:

- Reduction of CO_2 emissions due to lower primary energy consumption trough the decreased use of fossil fuels and therefore local pollution from power generation, leading to reductions in both negative health and climate effects. A 41.06 tons/year reduction in CO_2 emissions will also reduce SO_x, NO_x and dust emissions by 0.0365, 0.0338 and 0.002 tons/year, respectively.
- Reduction of primary energy consumption by at least 60% compared to a conventional BC system, thereby offering an ultra-high sustainable solution for the building sector.
- Use of as an climate-friendly refrigerants rather than conventional refrigerants.
- Design, execution and testing of an innovative prototype solar-powered CFR-based cooling device and refinement of the technical parameters of its operation.
- Geographical replication of the prototype in Spain.
- Development of a highly exploitable product applicable Europe wide.

Summary

Currently there are ongoing works on adjustment of infrastructure of Geocentrum building to supply 3rd floor of the building with cold produced by a new prototype cooling system, which will be installed in next stages of the project. After successfully built, optimized and verified the operation of the prototype at Wrocław University of Science and Technology campus's institutional facility, a next twin system is going to be built in an another climate region which is southern Spain, at the University of Almeria campus, as a prove that proposed novel cooling solution might be replicated in different climate conditions. It is aimed to create a highly exploitable product applicable Europe wide, which may be an ideal solution for cooling buildings in the era of the European green deal.

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REFERENCES

[1] IEA (2018), The Future of Cooling, IEA, Paris https://www.iea.org/reports/the-future-of-cooling
[2] IEA (2021), Cooling, IEA, Paris https://www.iea.org/reports/cooling
[3] https://www.odyssee-mure.eu/publications/policy-brief/buildings-energy-efficiency-trends.pdf, 15.05.2022
[4] RAP (2018): Report on the Polish Power System. Version 2.0 Study commissioned by Agora Energiewende
[5] https://ec.europa.eu/eurostat/web/energy/data/shares, 15.05.2022
[6] Regulation (EU) No 517/2014 of the European Parliament and of the Council of 16 April 2014 on fluorinated greenhouse gases and repealing Regulation (EC) No 842/2006.

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