The Concept of Zero-Emission Cooling

Alois Resch[1] and Harald Dehner[1]

[1] University of Applied Sciences Upper Austria, Stelzhamerstrasse 23, 4600 Wels, Austria

Abstract

Cooling demand in residential and industrial applications causes a tremendous consumption of electrical energy due to the conventional technology of compression chillers. Furthermore, future scenarios depict a significant increase of the cooling demand for the year 2050, so that 16% of the entire global electricity consumption is originated by the cooling sector by then, with the consequence of emitting enormous amounts of CO_2 emissions. Therefore, renewable and emission-free solutions for satisfying the worldwide cooling demand are highly important. The concept of "Zero-Emission Cooling" proposed in this paper considers the combination of an adsorption chiller and a double-glazed PVT collector in order to generate emission-free cold. The chiller under investigation already starts to work at a driving temperature of 55°C, and the double-glazing of the PVT collector makes it capable of providing temperatures up to 80°C more efficiently than others. The electrical output of the collector supplies all electric components and provides excess energy to be fed into the grid. The performed investigation showed that the concept basically works from the technical point of view, although a big collector area is required in order to provide enough driving power for the chiller. Most of the produced electrical energy can be fed into the grid, as only 13% are required to supply the internal electric consumers.

Keywords: Cooling demand, solar cooling, PVT collector, emission-free cooling

1. Introduction

Cooling demand is growing drastically all over the world, both in the residential sector and in commercial applications. The global cooling output capacity (measured in GW) has almost tripled between the years 1990 and 2016, leading to an electricity demand of around 2,000 TWh respectively nearly 10% of the global total electricity consumption in 2016. Moreover, the cooling sector has a severe impact on the electricity network, as this huge number of electrically driven chillers are more and more contributing to peak load within the grids (OECD/IEA, 2018).

Solar thermal cooling systems provide an efficient and renewable alternative to electrically driven cooling devices. As the thermal driving power for sorption chillers is taken from the sun, electricity from the grid is only necessary to drive pumps and valves, making it possible to reduce the electric energy demand by around 80% compared to conventional compression chillers. A number of 1800 solar cooling systems have been in operation in the year 2018 with cooling capacities up to the MW-range (Weiss and Spörk-Dür, 2019).

Scenarios of the further development of the cooling sector pointed out that for the year 2050 the electrical energy demand will triple to an amount of around 6,200 TWh, causing 16% of the total global electricity demand by then (OECD/IEA, 2018). With respect to the climate crisis, this increasing energy demand for cooling applications should not be accepted. Renewable cooling solutions must be pushed forward to achieve faster and deeper market penetration.

The concept of "Zero-Emission Cooling" discussed in this paper can provide such a renewable way for covering the cooling demand of residential or office buildings. The intention of this concept is to supply an adsorption chiller not only thermally by a solar thermal collector, as it is done by the established technology of solar cooling, but also electrically by the combination with a PVT-collector. In this way, the energy demand from conventional sources like fossil fuels or the electrical grid and therefore the corresponding greenhouse gas emissions could be reduced to zero.

Research activities in this field of solar combined cooling, heating and power systems (S-CCHP) have achieved promising results (e.g. Herrando et al., 2019). One of the research outcomes so far is the fact that on the one

doi:10.18086/eurosun.2020.05.08 Available at http://proceedings.ises.org

hand sorption chillers need a certain driving temperature in the range of 70°C upwards in order to reach a reasonable coefficient of performance (COP). On the other hand, most of the available non-concentrating PVT-collectors are designed to reach optimal performance in low-temperature applications, but show considerable efficiency reduction at temperature differences above 50 K to ambient air (Zenhäusern et al., 2017). Therefore, the central aim of this presented work is to analyze a novel configuration of components for providing an S-CCHP system that can have the potential to be more competitive to conventional cooling technologies. Analysis was done theoretically and experimentally.

2. System configuration and pre-dimensioning of components

This section describes the configuration of the considered S-CCHP system and summarizes the performed pre-dimensioning of the relevant components.

2.1 System configuration

The S-CCHP under investigation is illustrated schematically in Figure 1 below. The PVT collector field supplies its thermal power via the high-temperature (HT) storage tank to the HT-circuit of the adsorption chiller ($\dot{Q}_{HT}$). The HT storage tank is required to compensate fluctuations of the solar energy delivery as well as of the energy demand from the chiller. The cooling load is represented by an office building. The thermal power extracted from the building is transferred to the low-temperature (LT) storage tank that is connected to the LT circuit of the chiller. Similarly as on the HT side, also this tank serves as a hydraulic compensator for occurring fluctuations in the available cooling power $\dot{Q}_{LT}$. The entire thermal power $\dot{Q}_{MT}$ is released to ambient air by the heat rejection tower.

The electrical power P_{el} generated by the PVT collector field is used to supply all electric components of the system like pumps, fans, valves, control units, sensors and so on. If excess energy occurs, it can be fed into the grid.

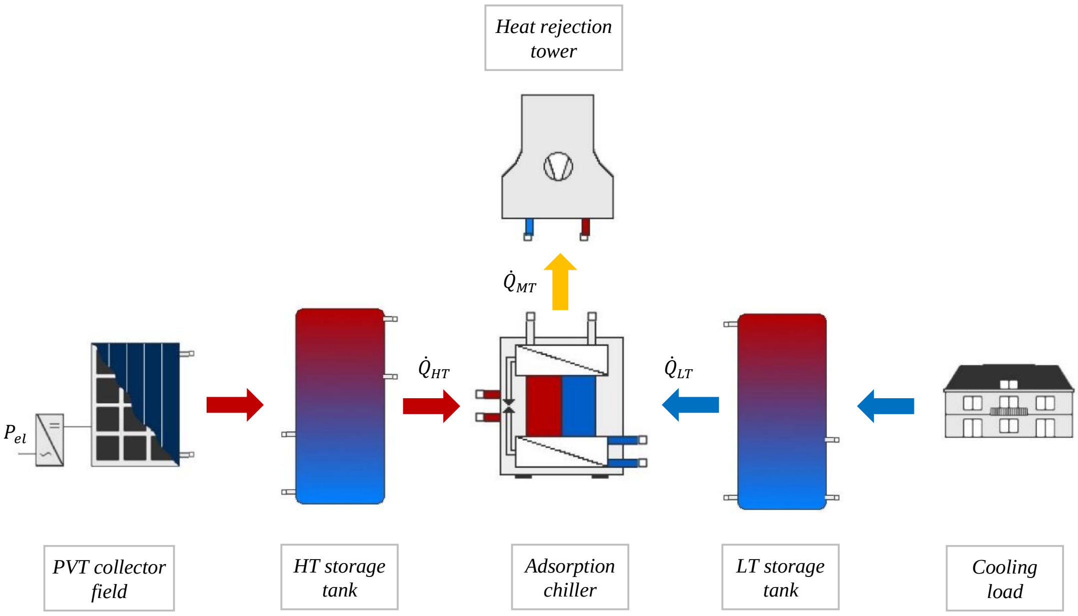

Fig. 1: Schematic overview of the system configuration

The considered PVT collector *Solar One* from the Austrian supplier 3F Solar Technologies GmbH and is a water-driven and covered type of flat plate PVT, see Figure 2. The reason why it was chosen for this described investigation is its double glazing construction with Argon filling that provides improved suitability for applications with higher temperature demand due to reduced heat losses via the front side of the collector. The thermal performance curve of the PVT collector was measured by the Austrian Institute of Technology in 2016. It is displayed in the following Figure 3 (AIT, 2016).

Fig. 2: View of the Solar One PVT collector (3F Solar, 2020)

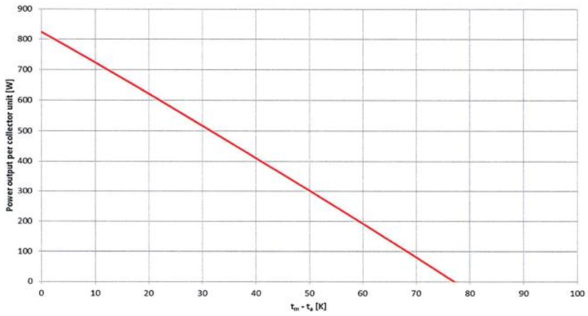

Fig. 3: Thermal performance curve of the Solar One PVT collector; G = 1000 W/m², ambient air velocity = 3 m/s (AIT, 2016)

Other relevant technical information of the PVT collector (3F Solar, 2018):

- Gross area: 1.696 m²
- 60 mono-crystalline Silicon cells
- Nominal electrical power (STC-conditions): 290 Wp
- Maximum thermal power (EN ISO 9806): 825 W

As mentioned above, the double-glazed construction of the PVT collector promises to be more suitable for higher temperature demand that is usually given by sorption chillers. On the other hand, the specific a**d**sorption chiller considered for this analyzed configuration was chosen because it can be operated with relatively low temperature in the HT circuit, compared to a**b**sorption systems. Hence, the combination of these two key components could have the potential to be more efficient in technical and economic issues than other configurations.

The adsorption chiller used for this investigation is the type *eCoo 10* from the German supplier Fahrenheit. It consists of two evacuated process chambers containing Silicagel as the active sorption material. Most relevant technical information from the datasheet (Fahrenheit, 2019) is listed as follows:

- Nominal cooling power: 16.7 kW @ HT = 85°C, MT = 24°C, LT = 19°C
- Maximum COP: 0.65
- Nominal volume flows: $\dot{V}_{HT}$ = 2.5 m³/h, $\dot{V}_{MT}$ = 5.1 m³/h, $\dot{V}_{LT}$ = 2.9 m³/h
- Electrical power demand: 800 W
- Minimum HT temperature to start operation: 55°C

Besides its suitability in terms of temperature requirement, the Fahrenheit chiller was also chosen for this investigation because it is installed in one of the laboratories of the University of Applied Sciences Upper Austria. Therefore, the theoretical work could be supported by experimental tasks, e.g. measurement of the COP under different operating conditions, see also section 3.

2.2 Pre-dimensioning of components

As the size of the adsorption chiller was already given by the available Fahrenheit system, a pre-dimensioning of the PVT collector field and the storages could be done. This first level of system dimensioning did not claim to yield exact numbers for all steps of calculation, but to have basic information of the components´ size in order to be able to start detailed system simulations more efficiently.

PVT collector field

The first dimensioning for the collector field was done basing on the nominal operating point of the chiller, which is characterized by the nominal cooling load of 16.7 kW at 85°C of driving temperature and a COP of 0.65.

The COP is defined as follows:

$$COP = \frac{\dot{Q}_{LT}}{\dot{Q}_{HT}} \quad \text{(eq. 1)}$$

$\dot{Q}_{LT}$ is the cooling power available in the low-temperature (LT) circuit, and $\dot{Q}_{HT}$ is the required driving power that has to be supplied to the high-temperature (HT) circuit of the chiller.

$\dot{Q}_{HT}$ for the given adsorption chiller is:

$$\dot{Q}_{HT} = \frac{\dot{Q}_{LT}}{COP} = \frac{16.7\ kW}{0.65} = 25.7\ kW \quad \text{(eq. 2)}$$

Furthermore, $\dot{Q}_{HT}$ can be used to calculate the temperature difference in the HT-circuit of the chiller:

$$\dot{Q}_{HT} = \dot{m}_{HT} * c_p * \Delta\vartheta_{HT} = \dot{m}_{HT} * c_p * (\vartheta_{HT,in} - \vartheta_{HT,out}) \quad \text{(eq. 3)}$$

$$\Delta\vartheta_{HT} = \frac{\dot{Q}_{HT}}{\dot{V}_{HT} * \rho * c_p} = \frac{25.7\ kW}{2.5 \frac{m^3}{h} * 972\ \frac{kg}{m^3} * 4.196 \frac{kJ}{kg * K} * 3600^{-1} \frac{h}{s}} = 9.07\ K \quad \text{(eq. 4)}$$

$\dot{V}_{HT}$ is the required volume flow in the HT-circuit, specified by the supplier. Density ρ and specific heat capacity c_p of water were taken for an expected mean temperature of 80°C (Böckh and Wetzel, 2009, p. 234).

The input temperature of the HT-circuit $\vartheta_{HT,in}$ is defined with 85°C in the nominal operating point. Therefore, the output temperature of the HT-circuit $\vartheta_{HT,out}$ can be calculated:

$$\vartheta_{HT,out} = \vartheta_{HT,in} - \Delta\vartheta_{HT} = 85°C - 9.07\ K = 75.93°C \approx 76°C \quad \text{(eq. 5)}$$

Considering the simplified approach that the HT-circuit of the chiller is directly connected to the PVT collector field without any losses, the temperatures $\vartheta_{HT,in}$ and $\vartheta_{HT,out}$ also occur as input and output temperatures of the collector field $\vartheta_{C,in}$ and $\vartheta_{C,out}$. The average collector temperature $\vartheta_{C,mean}$ is calculated as follows:

$$\vartheta_{C,mean} = \frac{\vartheta_{C,in} + \vartheta_{C,out}}{2} = \frac{76°C + 85°C}{2} = 80.5°C \quad \text{(eq. 6)}$$

The efficiency of any solar thermal collector is generally described by the following equation (Quaschning, 2011, p. 111):

$$\eta_C = \eta_0 - \frac{c_1}{E} * \left(\vartheta_{C,mean} - \vartheta_a\right) - \frac{c_2}{E} * (\vartheta_{C,mean} - \vartheta_a)^2 \quad \text{(eq. 7)}$$

The optical efficiency η_0, the linear loss coefficient c_1 and the quadratic loss coefficient c_2 for this specific PVT collector are available in the report of its thermal performance test (AIT, 2016). If the irradiance E is chosen with 1000 W/m² and the ambient air temperature ϑ_a with 35°C, the collector efficiency for this operating point of supplying the adsorption chiller can be calculated to:

$$\eta_C = 0.487 - \frac{5.881\ \frac{W}{m^2 * K}}{1000\ \frac{W}{m^2}} * (80.5°C - 35°C) - \frac{0.006\ \frac{W}{m^2 * K^2}}{1000\ \frac{W}{m^2}} * (80.5°C - 35°C)^2 = 0.207 \quad \text{(eq. 8)}$$

Hence, the thermal efficiency of the considered PVT collector at this specific application is 20.7%, corresponding to deliver a thermal power $\dot{Q}_C$ of 207 W_{th} per m² collector area at an irradiance of 1000 W/m². The total area of the required collector field is therefore:

$$A_{C,tot} = \frac{\dot{Q}_{HT}}{\dot{Q}_C} = \frac{25.7\ kW}{0.207\ \frac{kW}{m^2}} = 124.2\ m^2 \approx 124\ m^2 \qquad \text{(eq. 9)}$$

The field of PVT collectors needs a size of 124 m² in order to supply the adsorption chiller with the required thermal power and temperature in the nominal operating point. As the gross area of one collector is specified with 1.696 m², the total number of necessary collectors is 74.

The nominal electrical power output per collector P_{STC} at standard test conditions STC (1000 W/m², AM1.5, 25°C) is 290 W_p (3F Solar, 2018). The PVT collector is equipped with mono-crystalline PV cells that show a typical temperature coefficient c_T in terms of output power of -0.4 to -0.5%/K (Mertens, 2018, p. 104). Assuming that the PV cells are reaching the same temperature of 80°C as the thermal absorber while powering the adsorption chiller, the expected electrical output power $P_{C,nom}$ per collector at this nominal operating condition is:

$$P_{C,nom} = P_{STC} * (1 + c_T * \Delta\vartheta) = 290\ W * (1 - 0.0045 * 55\ K) = 218.2\ W \qquad \text{(eq. 10)}$$

The entire collector field consisting of 74 collectors provides a nominal electrical power $P_{F,nom}$ of:

$$P_{F,nom} = P_{C,nom} * 74 = 16.15\ kW \qquad \text{(eq. 11)}$$

Storages

As illustrated in Figure 1, the cooling system includes two storage tanks, one on the HT side of the chiller and another one on the LT side. The HT storage tank has the purpose to work as a hydraulic compensator, because the heat demand from the chiller is fluctuating due to the internal sorption process and the intermittent operation of the sorption chambers (SOLAIR, 2009, p. 75). On the other hand, it serves as an energy storage for cases of temporal mismatch between solar irradiance (e.g. due to clouds) and cooling demand. For pre-dimensioning the HT storage tank for the considered system, it was defined that the tank should be able to bridge a “dark” time span t_{dark} of 2 hours without solar input. Furthermore, a temperature drop $\Delta\vartheta_{St,HT}$ of 10 K (from 85°C to 75°C) in the tank during this period of discharging was defined to be acceptable. These definitions were used to calculate the required energy $Q_{St,HT}$ to be stored in the tank:

$$Q_{St,HT} = \dot{Q}_{HT} * t_{dark} = 25.7\ kW * 2\ h = 51.4\ kWh \qquad \text{(eq. 12)}$$

The necessary volume of the HT storage tank $V_{St,HT}$ is the following:

$$V_{St,HT} = \frac{Q_{St,HT}}{\rho * c_p * \Delta\vartheta_{St,HT}} = \frac{51.4\ kWh}{972\ \frac{kg}{m^3} * 4.196\ \frac{kJ}{kg * K} * 3600^{-1}\ \frac{h}{s} * 10\ K} = 4.54\ m^3 \qquad \text{(eq. 13)}$$

The storage tank on the LT side of the adsorption chiller was not intended to fulfil any energy storage purpose as this is already covered by the HT storage tank. The LT tank should only serve as a hydraulic compensator to buffer the fluctuating generation of cooling power by the chiller. The typical cycle duration for switching the operation of the two adsorption process chambers was assumed to be between 10 and 15 min. Therefore, the LT storage tank was dimensioned to buffer a cycle time t_{cycle} of 15 min. Within this time span, the temperature in the tank should not rise beyond 24°C, leading to a temperature difference $\Delta\vartheta_{St,LT}$ of 5 K in reference to the nominal temperature of 19°C. Using these assumptions, the energy to be stored in the LT storage tank can be calculated:

$$Q_{St,LT} = \dot{Q}_{LT} * t_{cycle} = 16.7\ kW * 0.25\ h = 4.18\ kWh \qquad \text{(eq. 14)}$$

The necessary volume of the LT storage tank $V_{St,LT}$ is:

$$V_{St,LT} = \frac{Q_{St,LT}}{\rho * c_p * \Delta\vartheta_{St,LT}} = \frac{4.18\ kWh}{998\ \frac{kg}{m^3} * 4.183\ \frac{kJ}{kg * K} * 3600^{-1}\ \frac{h}{s} * 5\ K} = 0.721\ m^3 \qquad \text{(eq. 15)}$$

Density ρ and specific heat capacity c_p for equation 15 were taken from Böckh and Wetzel (2009, p. 234) for an average water temperature of 22°C.

Heat rejection tower

The extracted heat from the cooling load $\dot{Q}_{LT}$ and the driving heat of the chiller $\dot{Q}_{HT}$ has to be released into ambient air by the mid-temperature (MT) circuit of the chiller. The corresponding rejection heat $\dot{Q}_{MT}$ is calculated for the nominal operating:

$$\dot{Q}_{MT} = \dot{Q}_{HT} + \dot{Q}_{LT} = 25.7\ kW + 16.7\ kW = 42.4\ kW \qquad \text{(eq. 16)}$$

The supplier Fahrenheit also provides heat rejection systems for their chillers. For this case, the hybrid heat rejection tower *eRec 20 | 58 WV* was chosen, because it has a nominal rejection power of 58 kW. The electrical power demand is specified with 1.08 kW (Fahrenheit, 2020).

2.3 Summary of the system configuration

The pre-dimensioned system for realizing the concept of Zero-Emission Cooling can be summarized as follows:

The PVT collector field needs a size of 124 m² in order to generate the required HT-power of 25.7 kW_{th} at 85°C. Corresponding to the specified operation point for a COP of 0.65 according to the chiller´s datasheet, the system can provide a cooling power of 16.7 kW.

An electrical power of 16.2 kW_{el} will be generated by the collector field, if the PV cells are operated at a temperature of 80°C. The heat rejection tower and the electric components within the chiller require a total electrical power of around 2 kW_{el}, leading to an excess power of 14 kW_{el} that can be delivered to the grid.

The thermal storages are estimated to have a required volume of 4.5 m³ for the HT side and 0.7 m³ for the LT circuit. The cooling load is not specified, but it is assumed to be a small office building or a family house with a cooling demand suitable for the capability of the considered adsorption chiller.

3. Laboratory measurements

The University of Applied Sciences Upper Austria operates a modular heat engineering laboratory that was developed to investigate a wide range of thermal processes with a temperature range of up to 200°C (Resch and Kraft, 2016). Thermal cooling is one of the operating modes of this laboratory. Therefore, a Fahrenheit adsorption chiller *eCoo 10* is installed that can be driven by various heat sources like solar thermal collectors, a biomass kettle or a tempering device. A buffer storage tank with a volume of 1000 liters emulates the cooling load for the chiller. Figure 4 provides a view of this lab arrangement. Heat rejection is either done via a wet cooling tower on the roof-top (see Figure 5) or via an internal waste heat cooling circuit that is connected to a water basin with 80 m³ of volume and a constant temperature of 12°C.

Fig. 4: Adsorption chiller Fahrenheit *eCoo 10* and the emulated cooling load at the heat engineering laboratory

Fig. 5: Wet cooling tower on the roof-top of the University of Applied Sciences Upper Austria

In reference to the described concept of Zero-Emission Cooling, this laboratory configuration was used to obtain experimental data of the adsorption chiller. The chiller was driven in different operation conditions in order to measure the thermal power in its three hydraulic circuits (HT, MT and LT) and to determine the corresponding COP. The mass flows are measured by electromagnetic flow sensors *KROHNE OPTIFLUX 6300* with an accuracy of +/- 0.5% of measured value (MV). The sensors for measuring the inlet and outlet temperatures are PT100 1/10 DIN class B with an accuracy of +/- 0.065 K of MV (@ 70°C). The HT-circuit of the chiller was supplied by a tempering device *Huber Unistat 530 W* in combination with a 1000 liters buffer storage tank in order to ensure constant inlet temperature for the chiller. The heat rejection was done by the internal waste heat cooling circuit, but combined with a bypass valve for controlling the MT inlet temperature. Similarly, the LT inlet temperature is controlled by bypassing the cooling load partly.

18 different operating conditions were investigated during this laboratory measurement with HT-temperatures between 55°C and 85°C, MT-temperatures between 20°C and 40°C and LT-temperatures between 15°C and 30°C. The volume flows were constantly set to $\dot{V}_{HT}$ = 2.5 m³/h, $\dot{V}_{MT}$ = 5.1 m³/h, $\dot{V}_{LT}$ = 2.9 m³/h according to the specified nominal operating point. The following Figure 6 illustrates an extract of the measurement sequence at the operating point with HT/MT/LT = 80°C/30°C/25°C. Inlet and outlet temperatures of the three circuits HT, MT and LT are given. The obvious fluctuations of all temperatures is caused by the cyclic operation of the two internal adsorption chambers and are typical for this kind of chiller. Remarkable is the cycle time of 7 min, which is below the assumption that was used to do the pre-dimensioning of the LT storage (see sub-section 2.2).

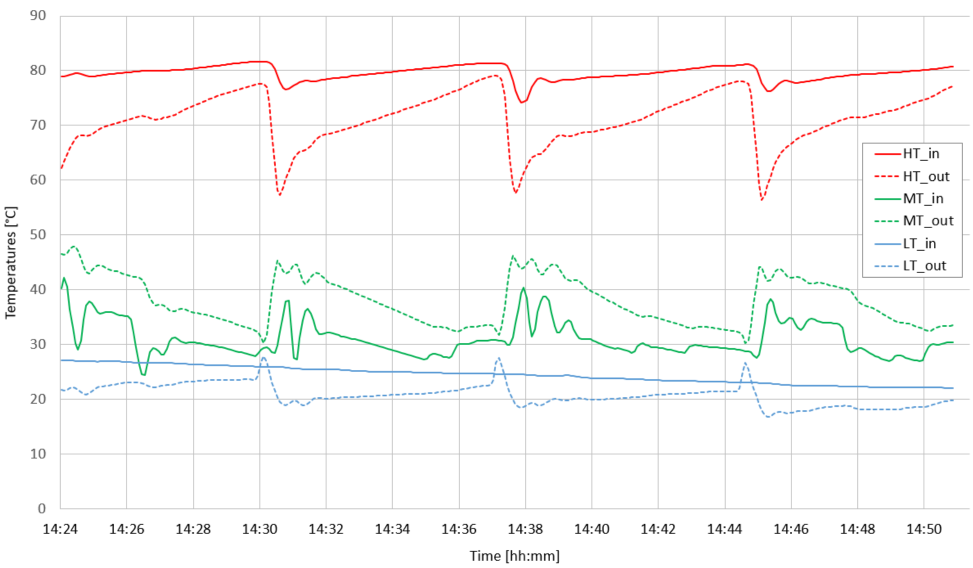

Fig. 6: Measured temperatures of the Fahrenheit adsorption chiller eCoo 10 at HT/MT/LT = 80°C/30°C/25°C

The results of the calculation of thermal powers averaged for the displayed time span are the following:

$\dot{Q}_{HT}$ = 24.15 kW, $\dot{Q}_{MT}$ = 41.34 kW, $\dot{Q}_{LT}$ = 12.19 kW

The COP for this specific operating point can be calculated according to Equation 1:

$$COP = \frac{\dot{Q}_{LT}}{\dot{Q}_{HT}} = \frac{12.19\ kW}{24.15\ kW} = 0.505$$

This COP at HT/MT/LT = 80°C/30°C/25°C was the maximum performance that could be achieved during the conduction of laboratory measurements. The averaged value of COP over these considered 18 operating points covering a wide temperature range was calculated with 0.41.

4. Simulation of the Zero-Emission Cooling concept

Basing on the results of the pre-dimensioning, the Zero-Emission Cooling system concept was realised in the simulation software POLYSUN, according to Figure 1. The available model for the PVT collector was parameterized with the conversion efficiency coefficients taken from the report of its thermal performance test (AIT, 2016). The Fahrenheit chiller was represented by the general model of a sorption chiller available in POLYSUN. The parameters for specifying the performance of the chiller were taken from the results of the laboratory measurements. The cooling load was defined to be an office building with a total floor space of 300 m² and a specific cooling power demand of 25 W/m². The total cooling power demand results to 7.5 kW, which is less than 50% of the chiller´s cooling capacity of 16.7 kW. The location of this installation was chosen with the city of Wels in Austria.

Figure 7 depicts the annual simulation of room temperature in the considered building as well as the resulting deficit of cooling power. The top chart describes the situation without cooling in order to obtain the maximum expected room temperature, which would be 32.5°C in this case. The bottom chart includes the proposed cooling system with 124 m² of PVT collectors and the adsorption chiller *eCoo 10*. The room temperature setpoint was 22°C, and the operation of the chiller was limited to the time span between beginning of April and end of August.

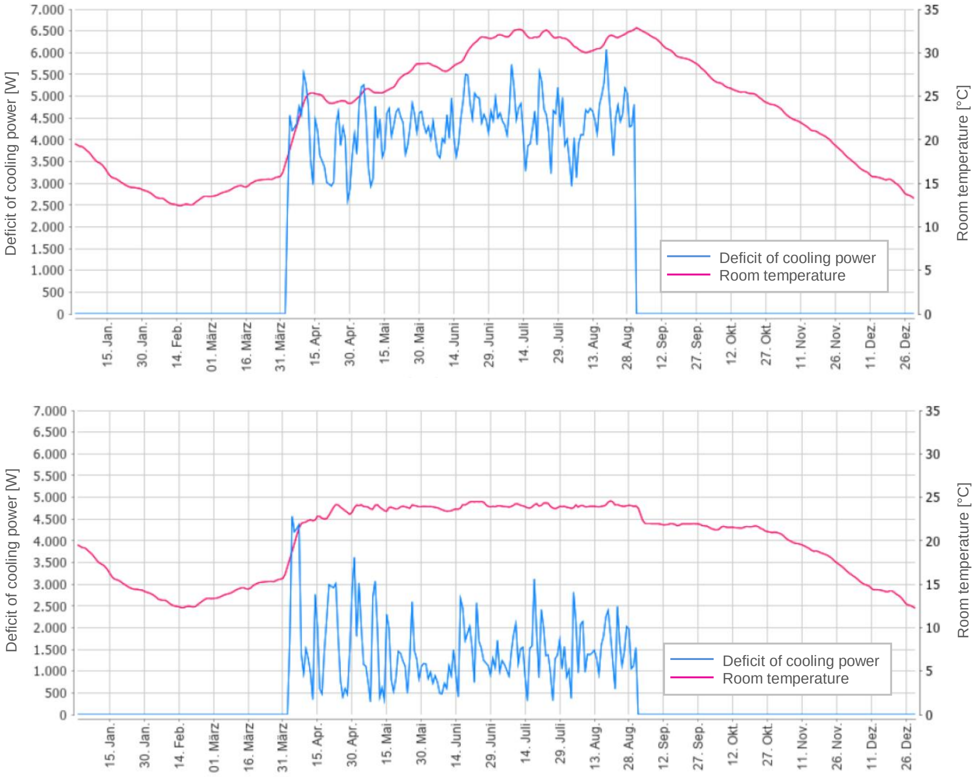

Fig. 7: Simulation of room temperature without cooling (top) and with proposed cooling system (bottom)

The resulting room temperature during summer with activated cooling system was around 24°C, meaning that the setpoint could not be reached. In terms of cooling power it can be observed that the maximum demand is simulated to 6 kW in case of deactivated cooling. On the same day, the deficit of cooling power in case of activated cooling is still 2.5 kW, resulting in an effective cooling power of the chiller of 3.5 kW. This performance result is not satisfying compared to the nominal chiller power of 16.7 kW. First analysis of the simulation details shows that the PVT collector field hardly reaches the required output temperature of 85°C and therefore the chiller cannot run on optimal COPs. Deeper investigation of these results and an extension of the simulation has to be done in order to improve the thermal performance of this proposed Zero-Emission Cooling concept.

5. Summary of results

The results obtained so far during the investigation of the described concept of Zero-Emission Cooling can be summarized as follows:

- The pre-dimensioning of the entire system was done basing on a COP of the chiller of 0.65. The laboratory measurements of the chiller performance revealed that this assumption was too optimistic, as the average measured COP over the entire temperature range was 0.41. The COP of 0.65 given by the supplier´s datasheet is the maximum possible one under optimum conditions, which should not be used for considering system configurations with PVT collectors.
- Experimental work with the chiller during the laboratory measurements confirmed its robustness against changing hydraulic and thermal conditions. As promised by the datasheet, the chiller starts to work at driving temperatures above 55°C, which makes it attractive to be combined with low-temperature heat sources. Although, a low COP has to be accepted at such a low driving temperature.
- The considered PVT collector is constructed with double-glazing in order to reduce heat losses via the front side and therefore to be capable of providing higher temperatures. Nevertheless, the efficiency of the collector at a temperature difference of 45 K to ambient air is reduced to 20.7%. This leads to the high demand of 124 m² collector area in order to be able to generate the required 25.7 kW_{th} at 80°C mean temperature.
- First simulations of the system for the location of Wels point out that the defined room temperature in the considered office building cannot be maintained completely. A deficit of cooling power occurs, although the cooling load of the building is less than 50% of the chiller´s cooling capacity. An explanation for this issue can be that the chiller does not run in the range of high COP due to the limited driving temperature delivered by the PVT collector field.
- The electrical energy output of the PVT collector field of 16 kW_{el} can only be used partly by the cooling system itself. The electric components of the chiller and the heat rejection tower have a combined power demand of 2 kW, which corresponds to 13% of the power produced by the collectors.

6. Conclusions and outlook

The concept of Zero-Emission Cooling as part of the solar combined cooling, heating and power systems (S-CCHP) provides an interesting approach for directing the worldwide cooling sector towards an emission-free and renewable future. The technology of adsorption chillers is a robust and mature alternative to the conventional cooling systems using compression chillers. The combination with double-glazed PVT collectors is possible, although it requires substantial collector areas in order to be capable of generating enough thermal power at reasonable temperatures. Coincidently, large areas of PVT collectors produce significantly more electrical power than needed by the cooling system.

Deeper investigation in terms of the following issues could reveal potential for improving the considered cooling concept:

- Enlargement of the simulation: optimization of control strategies, location-dependent aspects, variation of cooling loads
- Comparison with separated solar systems: Solar thermal collector field for supplying the chiller thermally and optimized number of PV modules to supply all electrical consumers
- Ecologic and economic assessment in comparison to conventional cooling systems
- Enlargement of the system in terms of utilizing the solar heat of the PVT collectors also for supporting hot water generation and space heating
- Implementation of hydraulic solutions to use the rejected heat for soil regeneration, swimming pool heating or pre-heating for hot water generation and space heating

7. Acknowledgments

This project is financed by research subsidies granted by the government of Upper Austria. Further acknowledgments are dedicated to the following students of the University of Applied Sciences Upper Austria for contributing to this project: Theresa Laister, Manuel Raschhofer, Daniel Schnauer, Alija Spahic, Marcel Urich and Christian Wagner.

8. References

3F Solar Technologies GmbH, 2018. Solar One Hybridkollektor Produktdatenblatt. Vienna

3F Solar Technologies GmbH, 2020. Solar One Hybridkollektor. Available at: https://www.3f-solar.at/3f-hybridkollektor/; accessed: 24 July 2020

AIT – Austrian Institute of Technology, 2016. Report of thermal performance testing | PVT collector Solar One from manufacturer 3F Solar Technologies GmbH. AIT, Vienna

Böckh, P. v., Wetzel, T., 2009. Wärmeübertragung | Grundlagen und Praxis, third ed. Springer, Berlin

Fahrenheit GmbH, 2019. Technische Daten und Montageanleitung (TDI) für eCoo 10. München

Fahrenheit GmbH, 2020. Rückkühler: Effizient, hygienisch, freikühlfähig. Available at: https://download.fahrenheit.cool/Deutsch/Datenbl%C3%A4tter/Zubeh%C3%B6r/FAHRENHEIT_Technische_Daten_R%C3%BCckk%C3%BChler_2018.pdf; accessed: 27 August 2020

Herrando, M., Pantaleo, A. M., Wang, K., Markides, C. N., 2019. Solar combined cooling, heating and power systems based on hybrid PVT, PV or solar-thermal collectors for building applications. Renewable Energy, Vol. 143, pp. 637-647

Mertens, K., 2018. Photovoltaik | Lehrbuch zu Grundlagen, Technologie und Praxis, 4th ed. Hanser, München

OECD/IEA, 2018. The Future of Cooling - Opportunities for energy efficient air conditioning, edited by IEA Publications, International Energy Agency.

Quaschning, V., 2011. Regenerative Energiesysteme | Technologie – Berechnung – Simulation, 7th ed. Hanser, München

Resch, A., Kraft, R., 2016. Industrial Integration of Mid-Temperature Solar Heat – First Experiences and Measurement Results. Conference Proceedings Eurosun 2016, Palma de Mallorca. doi:10.18086/eurosun.2016.02.11

SOLAIR, 2009. Requirements on the design and configuration of small and medium sized solar air-conditioning applications. Available at: www.solair-project.eu; accessed: 28 July 2020

Weiss, W., Spörk-Dür, M., 2019. Solar Heat Worldwide – Global Market Development and Trends in 2018 | Detailed Market Figures 2017.

Zenhäusern, D., Bamberger, E., Baggenstos, A., 2017. PVT Wrap-Up | Energiesysteme mit Photovoltaisch-Thermischen Solarkollektoren