Year-round operation the solar powered hybrid adsorption-compression refrigeration cycle

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YEAR-ROUND OPERATION THE SOLAR POWERED HYBRID ADSORPTION-COMPRESSION REFRIGERATION CYCLE

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Abstract: In our earlier papers a hybrid adsorption-compression refrigeration cycle was presented. The hybrid, two stages cycle is based only on the natural refrigerants: water and carbon dioxide. The main advantage of the hybrid cycle is that the carbon dioxide compression cycle is subcritical because during the year-round operation it is possible to maintain the condensing temperature below 20°C. During the hot season, this is achieved by adsorption cooling, during cold seasons the wet cooling tower is sufficient. Already several years of experience, allowed to gather a considerable amount of measurement data. The refrigeration system is working in our laboratory constantly since 2013. In 2015 the adsorption system was upgraded by the manufacturer. In 2017 frequency inverter for wet tower fan controlling was introduced. The refrigeration chamber was used for tests with different content and operation of the refrigeration chamber (loading and unloading). The assumed CO_2 evaporating temperature was -35°C. The averaged for HT (High Temperature) part of the cascade (adsorption cycle only) $COP_{HT}=0.51$ for the whole year 2018. This may be considered a very good performance. Averaged total COP for the cascade system: COP=0.9 compared to COP=0.84 for compression only refrigeration cascade, with much higher TEWI index. For comparison for two-stage compression ($R407C_{HT}+R744_{LT}$) cycle was used. This means that if the cooling tower fan operation is controlled using an inverter, adjusted to the actual heat removal demand, the hybrid cycle is not only ecological but also energetically efficient.

Keywords: hybrid compression adsorption refrigeration cycle

1. INTRODUCTION

The application of carbon dioxide as refrigerant is becoming increasingly popular due to the Montreal Protocol (1987) regulation. Carbon dioxide is introduced in compression systems, but due to the low critical temperature, the cycle requires very high pressure at the discharge side of the compressor and low efficiency is obtained. Therefore carbon dioxide cycles are used for low temperature (LT) stage at the two-stage refrigerating systems. On the other side sorption systems as LiBr/H_2O absorption or zeolite adsorption systems where water is the working fluid has low-temperature limit about 5-8°C. This limits its application for refrigeration. Coupling two systems: sorption at the high-temperature stage and CO_2 at the low-temperature stage, combines the possibility to use

waste heat or solar heat as an energy source for the high-temperature stage, allowing the reduction of discharge pressure in the condenser of CO_2 at the LT stage. In the HT (High Temperature) compression cycles another refrigerant, such as R410A, is frequently used. Several papers on CO_2 applications in different refrigerating cycles has been shown in recent years [1]. Absorption systems are increasingly popular but mostly as one stage air cooling and heat pump systems using LiBr-H_2O [2, 3, 4]. There is also interest in modelling and simulation of adsorption heat pumps, which allows the analysis of the winter cycle of the combined systems [5]. The adsorption technology is also frequently the subject of scientific investigation [6, 7, 8, 9, 10, 11]. The range of produced absorption or adsorption units is from 8 kW up to 21 MW cooling capacity. The choice of

adsorption or absorption technology depends on load, price, and most of all temperature of the heat source for desorber heating [12]. The COP of the absorption cycle, with high-temperature generation (above 120°C), using two-stage, double effect cycle, may be higher than for adsorption. For lower temperature sources such as solar cooling or central heating network, the application of absorption may not be possible at all. The different heat sources for cooling or refrigerating have been also analyzed in several published papers [13, 14, 15, 16]. The adsorption technology makes it possible to apply 65°C heat source for desorber [17, 18]. This is the main difference between the possibilities of contemporary industrial adsorption and absorption technologies. There is also scientific interest in hybrid sorption-compression cycles, however with other assumed aims and refrigerants than presented here [19, 20, 21, 22].

2. EXPERIMENTAL METHODOLOGY

In the Laboratory of Thermodynamics and Thermal Machines Measurements (Cracow University of Technology), the set-up with hybrid refrigerating compression/adsorption system was built in 2013

(Figs. 1,2,3,4,5) [23]. At the high temperature (HT) stage an adsorption system (ADS_L1) [24] coupled with tube type solar collectors (SOLAR_L4) and wet cooling tower (TOWER_L5) is applied. The low-temperature stage (CO2_L2) is equipped with two parallel CO2 compressors.

One of the compressors is controlled by a variable frequency drive, both working in a cascade regime. A secondary fluid: ethylene glycol for solar collectors and transportation of heat, from low to high-temperature cycle is applied. The thermal fluxes between subsystems are presented in Fig. 1.
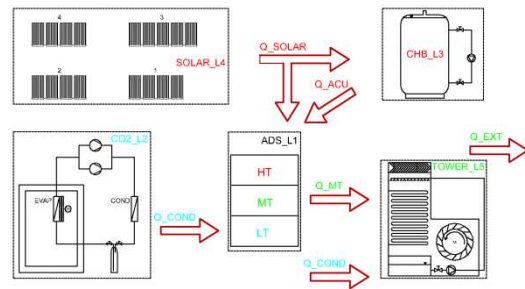

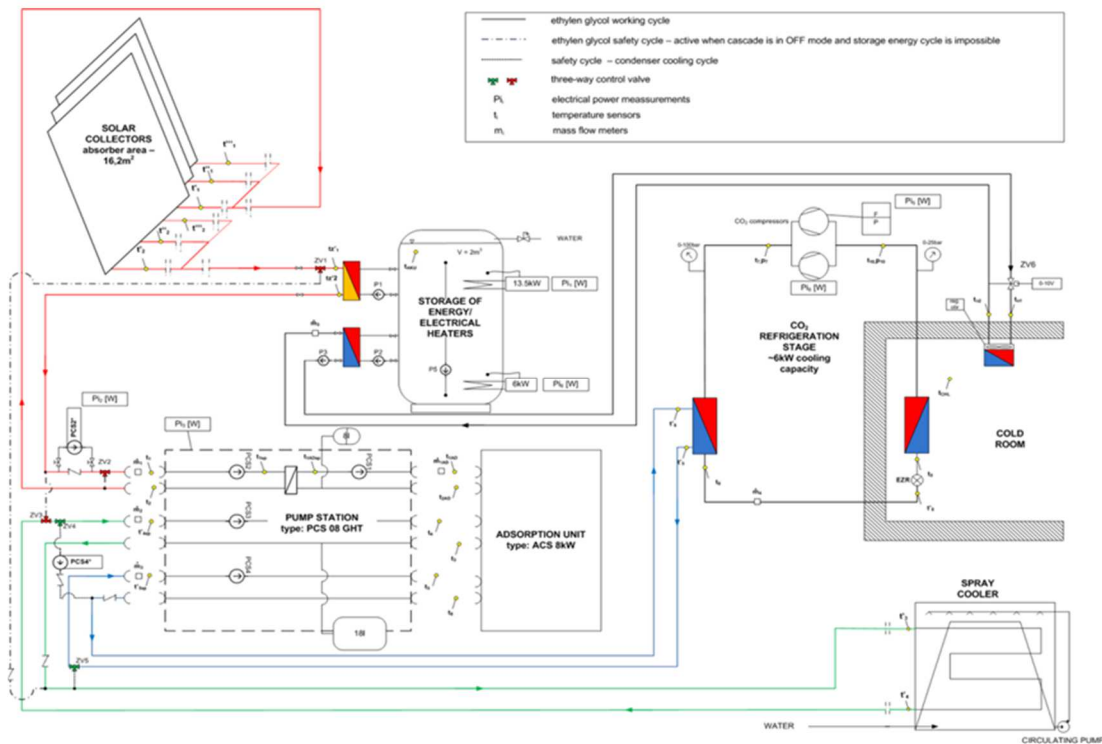Fig. 1.   Schematic diagram of a test setup

Fig. 2.   Logical scheme of the hybrid system. SOLAR_L4 – solar collectors, ADS_L1- adsorption unit, CO2_L2 – LT compression stage, TOWER_L5 – wet cooling tower, CHB_L3 – heat accumulator, LT – low-temperature heat supply, MT – medium temperature heat for desorption system cooling, HT – high-temperature heat

The main advantage of the hybrid cycle is that the carbon dioxide compression cycle is subcritical because during the whole year operation it is possible to maintain the condensing temperature below 20°C. During the hot season, this is achieved by adsorption cooling, during cold seasons the wet cooling tower (Fig. 4) is sufficient.

This type of hybrid system requires a considerable amount of power for cooling tower fans. Therefore it is very important to control the fans of the wet cooling tower using frequency inverter. Already several years of experience, allowed to gather a considerable amount of measurement data. In this paper summarized results for heat transfer between system elements are shown. In Fig. 2 the logical schematic of the system is presented. Heat transfer between elements is denoted with subscribed arrows. The names of heat streams are denoted as subscripts in Figs 9, 11.

During our tests, all necessary temperatures and pressures were measured and then refrigerant and liquid enthalpy were calculated using NIST REFPROP. The mass flow rate or volumetric flow rate were also measured, as well as the power consumption of all devices including fans, compressors, pumps, and all control equipment. Ambient air parameters were also registered.

Fig. 4.   Wet cooling tower

Fig. 5. CO_2 compressors with controls

Fig. 6.   Solar collectors

The refrigeration system (Fig. 1, 2, 3, 4, 5, 6) is operating in our laboratory constantly since 2013. In 2015 the adsorption system was upgraded by the manufacturer (SORTECH eCoo Fig. 3). Since 2017 fan in the cooling tower is controlled by the frequency inverter. The refrigeration chamber was used for tests with different content and operation (loading and unloading). The CO_2 evaporating temperature was mostly -35°C. In Fig. 9 solar heat flux recovery by solar collectors for averaged day-in-month in 2018 is presented.

Fig. 3.   Adsorption cycle main unit

Highest values of acquired solar heat flux are for May and August, lowest for December, September, and February in 2018. This, however, does not mean that solar heat gain, in case of the hybrid system, can be transformed directly into the cooling power of the adsorption system.

The COP of the adsorption system depends significantly on the temperature and humidity of the ambient air and the amount of heat removed by the cooling tower. It is presented in Figs 9, 11.

In Fig. 10 an example characteristics of a wet cooling tower is presented. These functions were averaged from the results of the experimental tests. Usually, this power is neglected in the literature, while analyzing cycle COP. However, in the real working conditions total COP of a system shall include as energy loss also a power supply for cooling fans and pumps. Therefore frequency inverters for the tower fan and pump were introduced and function shown in Fig. 10 were used for system control.

The measurement system used in the facility is described in table 1.

Tab. 1.   Measuring equipment installed in the refrigeration adsorption-compression hybrid system

| Sensor	Class	Usefull range
Introl IT-CF-1 Pt100	B	-25~200; -50~150; 0~150°C
Introl	0.03%	4~20 mA
SIEMENS MASSFLO 2100	0.01%	0~1000 kg/h
SIEMENS MASS 6000	0.01%	0.0002~0.2786 kg/s
Hoffer Flow Controls ACEII	0.05%	10~110 l/min
Hoffer Flow Controls	0.05%	4.73~35.96; 6.62~60.57; 9.46~109.78 l/min
KEP BATRTM2AC	0.05%	0~36; 0~60; 0~110 l/min
Vegabar 17	0.05%	0~100 bar
Vegabar 17	0.05%	0~25 bar
LUMEL	0.01%	0~200; 0~700; 0~3000; 0~8000; 0~10000; 0~15000 W
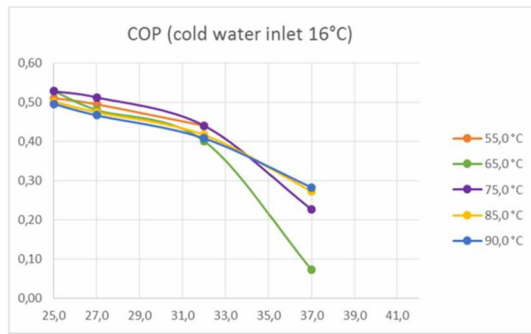
Fig. 7.   The adsorption cycle COP for 16°C water inlet
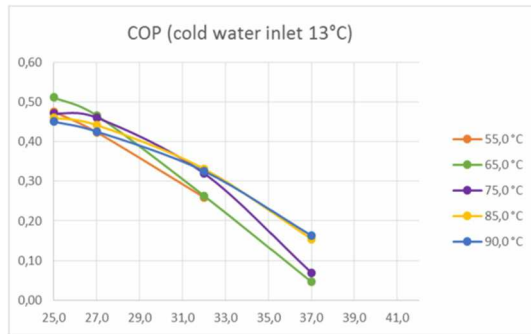

Fig. 8.   The adsorption cycle COP for 13°C water inlet
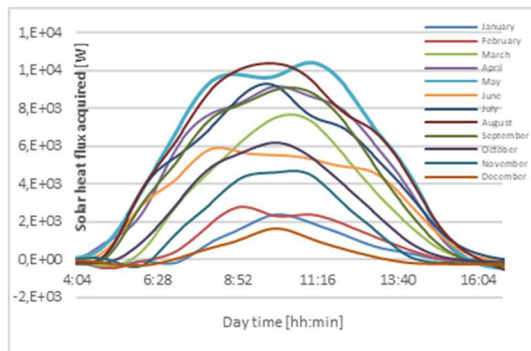

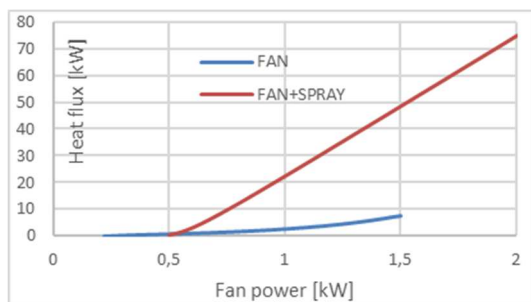Fig. 9.   Solar heat recovery in 2018 for an averaged day in a month

Fig. 10.   Heat flux in the cooling tower related to the fan revolution speed/power
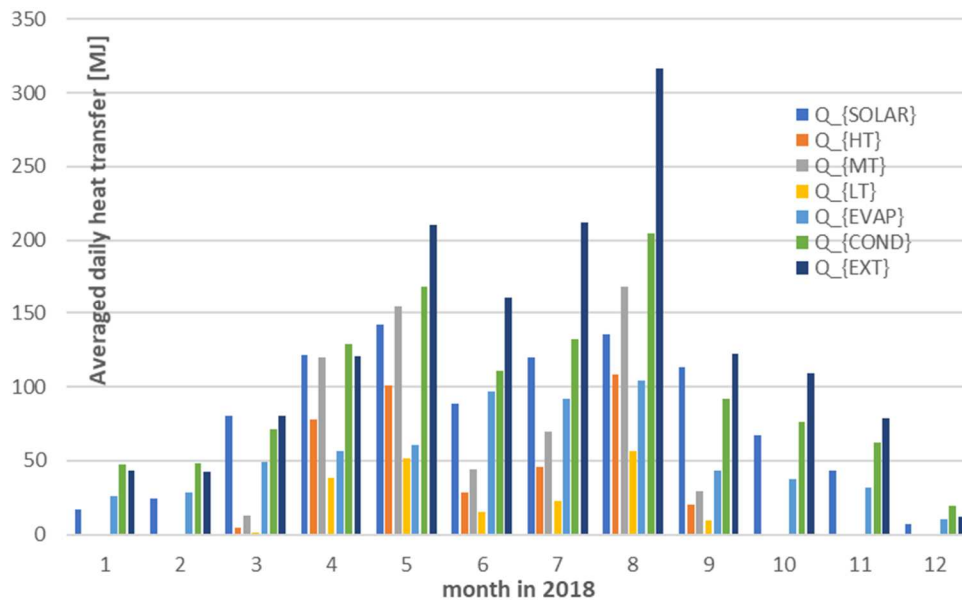
Fig. 11. Daily heat transfer in the heat exchangers

3. PERFORMANCE RESULTS

In Fig. 11 heat transfer energy between subsystems denoted in Fig. 2 during the average day (24 hours) in 12 months is presented. Useable heat transfer QLT values shown in Fig. 11 are lower in hot days than expected because of higher MT ambient temperature, which is a significant factor for adsorption cycle COP (Figs. 7.8). The adsorption system was not used for CO_2 condenser cooling in the period of 1.01-31.03.2018 and 1.10.2018-31.12.2018. During this time the cooling tower was sufficient for the direct CO_2 condenser cooling. The thermodynamic efficiency of the system may be estimated using the COP (Coefficient of Performance). Thermodynamic analysis always denotes efficiency as the achieved energy result divided by the energy cost. This seems obvious but in case of hybrid systems powered partially by renewables, this definition does not reflect the real thermodynamical efficiency. The COP for adsorption system used for cooling is defined traditionally as:

$$COP_{HT} = \frac{Q_{cond}}{Q_{HT}}, \qquad (1)$$

where: Q_{cond} – heat energy removed from the low-temperature source (in this case evaporator CO_2, Q_{HT} – heat for adsorption generator

The COP for all year according to formula (1) is 0.51. This number is consistent with the producer's data [24], higher than expected for long-time operation.

For the compression, refrigeration cycle COP is defined as:

$$COP = \frac{\dot{Q}_{evap}}{N_{compr}}, \qquad (1)$$

where: Q_{evap} – CO_2 evaporation heat, N_{compr} – compressors power.

In the case of two stages, compression-only cycle equation (2) is also valid.

Total COP=0.9 for this system was calculated using whole year values of heat and power. For similar conditions, the compression-only cascade COP=0.84. Those results, however, neglect in both cases power supply for auxiliary systems (pumps, fans and control devices), which in the case of a hybrid cascade is higher. For the compression cascade, TEWI index is 60% higher than hybrid cascade [23].

4. CONCLUSIONS

The averaged for HT part of the cascade (adsorption cycle only) COP_{HT}=0.51 for the whole year 2018. This may be considered very good performance for adsorption system powered by waste/renewable heat. This means that about half of the total solar energy acquired by solar collectors was used. Calculated from yearly averaged energy transfers total COP for the cascade system was COP=0.9. For double stage compression-only refrigeration cascade for similar conditions calculated COP=0.84. For comparison for two-stage compression (R407C_{HT}+R744_{LT}) cycle with higher TEWI index was used.

The cooling tower fan operation is controlled using inverter adjusted to the actual heat removal demand. This allows for significant electric power requirement reduction for the system.

During the cold season, the adsorption cycle may work as a heat pump because CO_2 condenser was cooled directly by the cooling tower. This means also that the solar system is not utilized as an energy source for the CO_2 compression system and become a heat source for the heat pump. In this case, three heat

sources for a heat pump is used: solar collectors, condenser and compressor cooling, ambient air as a low-temperature heat source for a heat pump. This solution increases total Renewable Energy Source (RES) usage for the whole year.

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Biographical notes

Roman Duda received his MSc in Power Engineering (specialisation: power engineering systems and facilities) in 2012 from Institute of Thermal Power Engineering at the Faculty of Mechanical Engineering of Cracow University of Technology, after the work in iBros technic, has been a Researcher for the Institute of Thermal and Process Engineering at the Cracow University of Technology, where currently he works as assistant. His scientific interest is focused on issues related to the utilisation of renewable energy for cold production.

Piotr Cyklis received his MSc in Mechanical Engineering in 1984 at the Faculty of Mechanical Engineering of the Cracow University of Technology, and Professor title in 2010. Since 1984 has been a researcher at the CUT, Laboratory of Thermodynamics and Thermal Machines Measurements. Specialising in innovative anticlockwise cycles, thermal processes and volumetric compressors.