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Experimental investigation of the ecological hybrid refrigeration cycle

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Abstract The requirements for environmentally friendly refrigerants promote application of CO_2 and water as working fluids. However there are two problems related to that, namely high temperature limit for CO_2 in condenser due to the low critical temperature, and low temperature limit for water being the result of high triple point temperature. This can be avoided by application of the hybrid adsorption-compression system, where water is the working fluid in the adsorption high temperature cycle used to cool down the CO_2 compression cycle condenser. The adsorption process is powered with a low temperature renewable heat source as solar collectors or other waste heat source. The refrigeration system integrating adsorption and compression system has been designed and constructed in the Laboratory of Thermodynamics and Thermal Machine Measurements of Cracow University of Technology. The heat source for adsorption system consists of 16 tube tulbular collectors. The CO_2 compression low temperature cycle is based on two parallel compressors with frequency inverter. Energy efficiency and TEWI of this hybrid system is quite promising in comparison with the compression only systems.

Keywords: Hybrid refrigerating cycle; Adsorption; Two stage refrigerating

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Nomenclature

GWP	–	global warming potential CO_2 equivalent
E	–	energy use of the cycle per year, kWh
f	–	refrigerant recovery
L	–	emission to the atmosphere, kg/yr
m	–	amount of refrigerant in installation, kg
n	–	cycle life, yr
N	–	supplied electric power of the cycle, kW
tr	–	yearly number of work hours, h
z	–	CO_2 emission for the electric energy; in Poland $z = 0,94$ kgCO_2/kWh

1 Introduction

In refrigeration and thermal energy transformation cycles compressor or sorption systems are widely used for heat pumps, refrigeration and air conditioning applications. Since Montreal Protocol (1987) [11,12] there is a need to introduce ecological working fluids instead of chlorofluorocarbons (CFC) or hydrochlorofluorocarbons (HCFC) refrigerants. Carbon dioxide (CO_2) is introduced in compression systems, but due to the low critical temperature the cycle requires high pressure at the discharge side of the compressor. In one-stage refrigerating compression systems with CO_2 the gas cooler instead of condenser is needed. Then the coefficient of performance (COP) is low and discharge pressure for the compressor rises above 7 MPa. This results in high compression temperature and then the two stage compression is required. This is why CO_2 is used for low temperature stage (LT) at the two stage refrigerating systems. On the other side sorption systems as LiBr/H_2O absorption [3,6] or zeolite adsorption systems [4,5,7,10] where water is the working fluid have low temperature limit of about 5-8 °C. Coupling of two systems: sorption at the high temperature (HT) stage and CO_2 at the LT stage, combines the possibility to utilise waste heat or solar heat as energy source for HP stage, allowing the reduction of discharge pressure in the condenser of CO_2 at the LT stage. Besides only natural ecological fluids are used and whats more the whole year operation work as a refrigeration cycle and/or heat pump is possible. The combination of absorption and compression cycles have been presented in [8,9]. The adsorption compression hybrid cycle is authors invention as well as absorption-compression with CO_2 [1,2].

2 The system design

In the Laboratory of Thermodynamics and Thermal Machine Measurements the stand with hybrid refrigerating compression/adsorption system has been designed and built. At the HT stage an adsorption system made by SORTECH (ACS08) [5] is coupled with the tube type solar collector and wet cooling tower. The ACS08 characteristics given by the producer for 75 °C desorption temperature has been shown in Fig. 1. The LT stage is equipped with two Dorin CO_2 compressors with frequency inverter. The ethylene glycol for solar collectors and heat transport from LT to HT cycle has been introduced. This reduces the efficiency of the system , but for the laboratory purpose gives more convenient design, construction and operation. Besides the secondary liquid introduction makes the work as a heat pump in winter season possible. To reduce the losses of the temperature level the condenser has been chosen with 50% higher heat transfer area than designed.

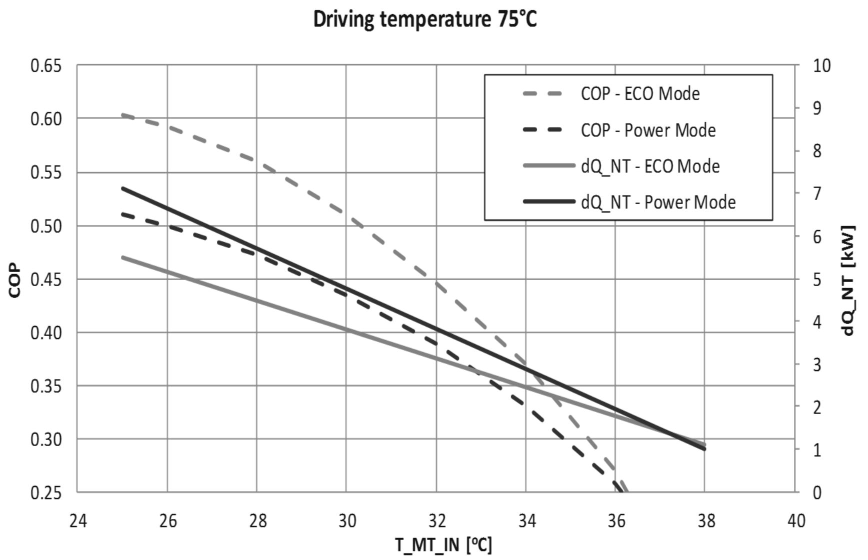

Figure 1: The COP of the adsorption ACS 08 cycle for 75 °C driving temperature and various recooling temp (T_MT_IN) also output capacity is shown in kW; dQ_NT cooling capacity of the ACS08. ECO mode: higher COP, less capacity, Power mode: lower COP, higher capacity [5].

In case of Central Europe weather conditions, it is not very often to get the temperature level of 90–95 °C directly from solar collectors. For adsorption systems the driving temperature may be as low as 65 °C. That was the reason to use adsorption instead of adsorption at the HT stage (Fig. 1).

For the reason of safety there are independent safety control devices for overheating or over-pressuring the units. Besides the main control system has also safety setups.

The control and automation is designed on the basis of programmable logic controler (PLC) Siemens system. There are also additional heaters for the heat tank to make it possible to proceed with the measurements also in bad weather conditions.

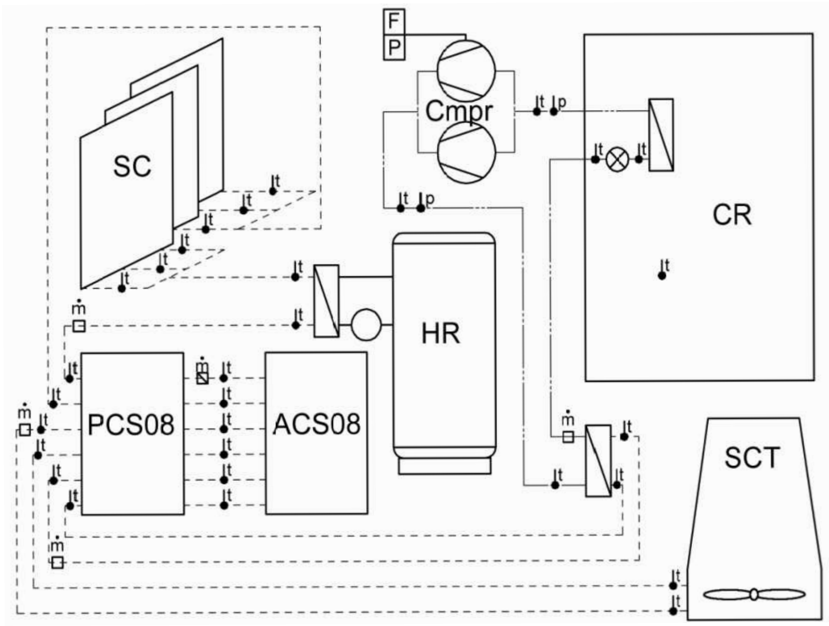

Figure 2: Schematic diagram of the laboratory stand with hybrid adsorption-compression refrigeration two stage cycle: SC – solar collectors; HR – heat reservoir; CR – refrigeration chamber; SCT – sprayed cooling tower; PCS08 – pump station fro adsorber; ACS08 – adsorber; F – frequency converter; P – power meter; Cmpr – compressors; t,p, $\dot{m}$ – temperature, pressure and flow meters respectively.

Figure 3 shows the realisation of adsorber connections and compressor stands. The mass flow rate of CO_2 after the condenser is measured using the mass flow meter. Resistance thermometer (Pt100) for temperature measurements and turbine flow meters for glycol have been applied.

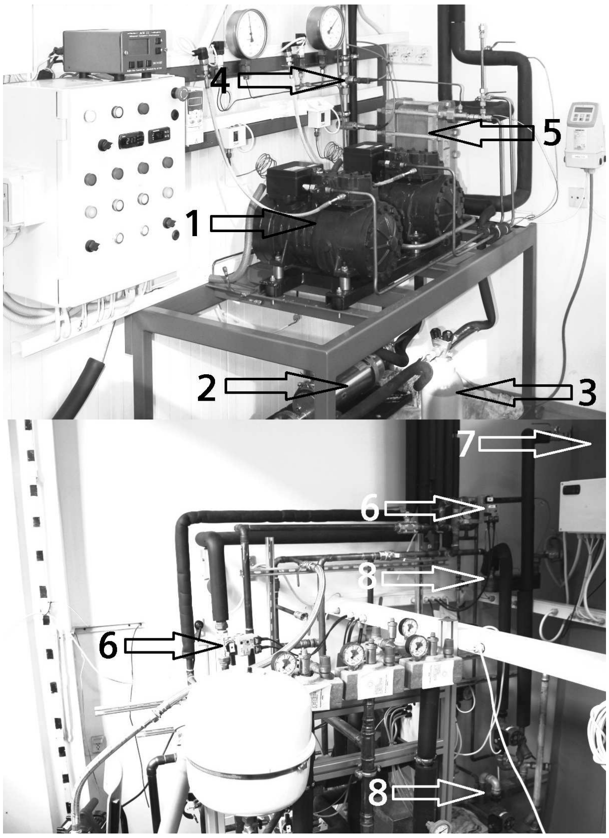

Figure 3: The adsorption system connection and CO_2 compressors on stand with measuring equipment: 1 – compressors, 2 – mass flow meter, 3 – CO_2 bottle, 4 – pressure transducer, 5 – CO_2 condenser, 6 – control valves, 7 – heat storage, 8 – heat exchanger.

3 System control

System control has been designed to assure operational working states of the hybrid adsorption-compression cycle:

1. Full load (summer day): solar collectors are operating, heat from solar collectors is accumulated in the 2 m^3 tank, adsorption unit is in operation producing cooled glycol at temperatures of 6–15 °C, cooled glycol is used to cool down CO_2 condenser, the LT compression refrigeration system is operating. The LT cycle has a control possibility with two compressors working as a cascade, one of them is coupled with the

frequency inverter. The LT cycle load is a function of refrigeration chamber load and adsorption cycle actual capacity.

2. Work with low ambient temperature (summer late night, late autumn, winter): The condenser cooling is realized directly from the cooling tower. Achievable condensing temperature is below 17 °C. The adsorption unit can be then used as a heat pump for heating if necessary.
3. Solar heat removal: the refrigeration LT system is not operating due to the maintenance or failure, the heat container temperature exceeds 95 °C, all solar heat is dumped through the wet tower.
4. Loading of the heat accumulator: the wet tower and refrigeration LT cycle are not operating, only pumps and circuit connecting solar collectors and accumulator are in operation until temperature of 95 °C is reached.
5. Electric heating of the heat accumulator (only for laboratory tests).

4 Results of experimental investigations

The system has been launched in late July 2012. First tests have been made during very hot summer days with the full load of solar collectors assuring constant, high supply temperature for the ACS unit. An example of the one full cycle is shown in Fig. 4.

Within the range of supply temperature, namely 65–95 °C for the adsorption no significant influence on the cycle performance has been detected. Also periodic adsorption system action has no influence on the compression LT part of the cascade work. In Fig. 5 summary of the results of the tests are shown.

For comparison the following cycles have been chosen:

- Carnot cycle,
- two stage compression cycle with CO_2 and R410,
- one stage transcritical CO_2 cycle,
- two stages transcritical CO_2 cycle,
- hybrid adsorption-compression with cooling directly from wet cooling tower without adsorption (14–19 °C of CO_2 condensing),
- hybrid adsorption-compression with cooling from adsorption (3–7 °C of CO_2 condensing).

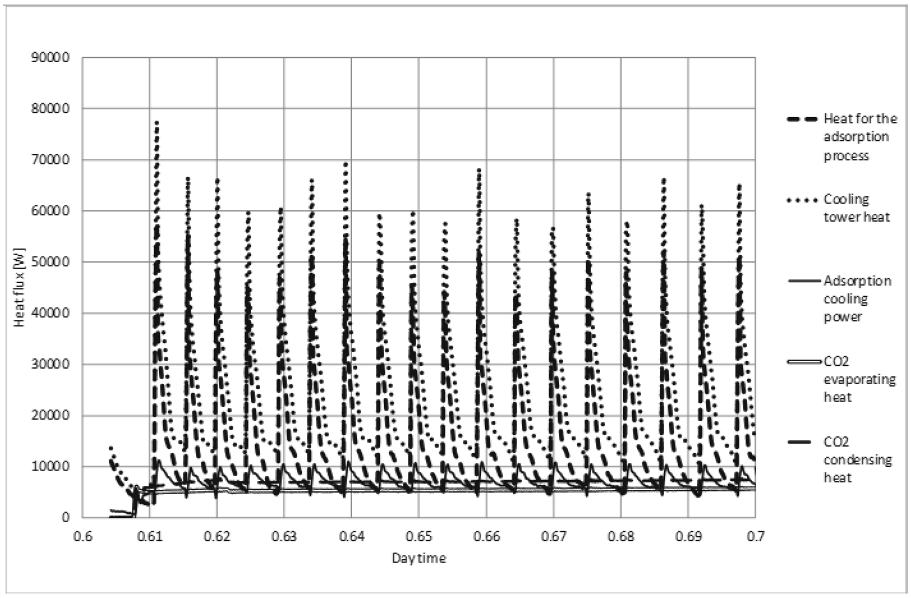

Figure 4: Heat flux distribution during the steady operation of the system.

Energy efficiency ratio (EER) has been used here instead of COP, since the formula dominator for COP usually consists of thermal energy and for EER electric or mechanical power. Therefore for adsorption evaluation earlier in the paper, COP has been deemed as more adequate.

The total equivalent warming impact (TEWI) ecological coefficient has been calculated on the basis of the following formula:

$$TEWI = GWP \cdot L \cdot n + GWP \cdot m \cdot (1 - f) + n \cdot E \cdot z \,, \tag{1}$$

$$E = N \cdot tr \,. \tag{2}$$

The analysis has been provided for the CO_2 evaporation temperature ranging from -5 up to -40 °C (Figs. 5,6,7). It has been shown that for adsorber cooling both energy consumption and TEWI coefficient are much better than for conventional compression only cycles. In case of energy efficiency we may expect up to 30% of energy reduction while for TEWI even by up to 60%.

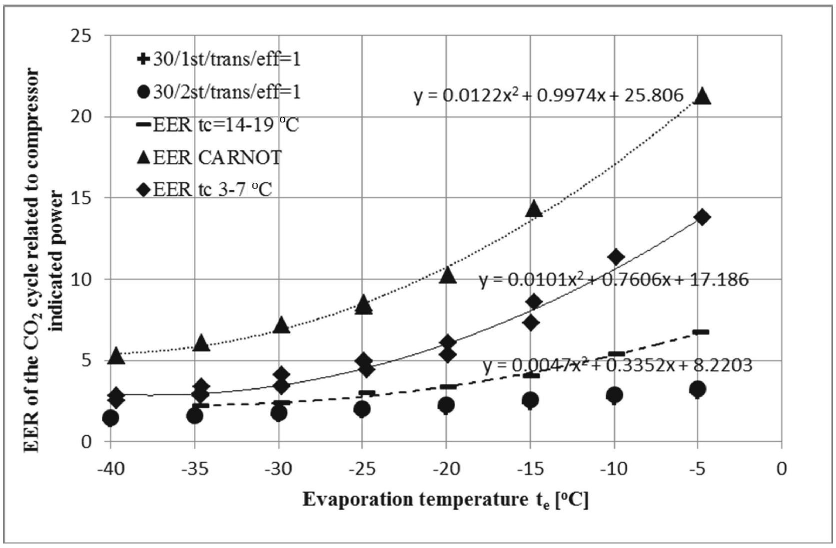

Figure 5: Energy efficiency ratio (EER) of the hybrid cycle related to the CO_2 compressor indicated power for two condensing temperatures 14–19 °C and 3–7 °C. Also pure compression one and two stage CO_2 transcritical cycles are shown for comparison, with the Carnot cycle as reference.

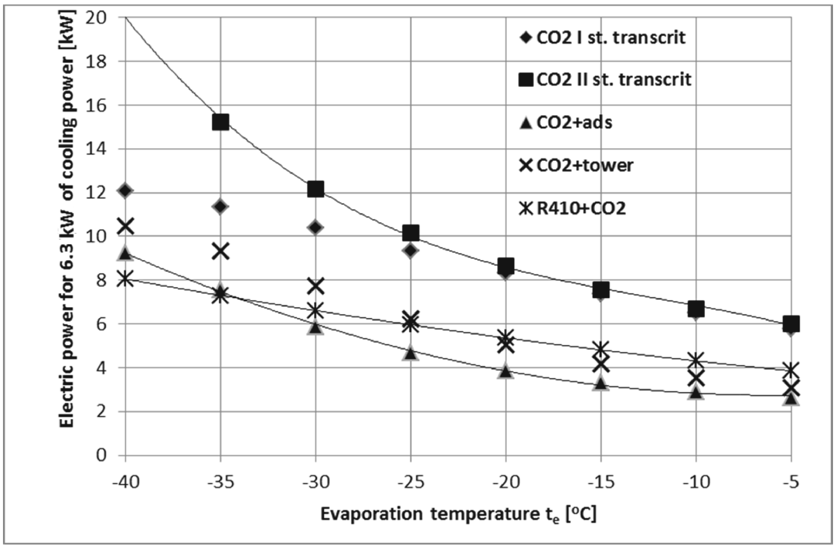

Figure 6: Total electric power including auxiliary power consumption for cooling tower, pumps etc. for five cycles.

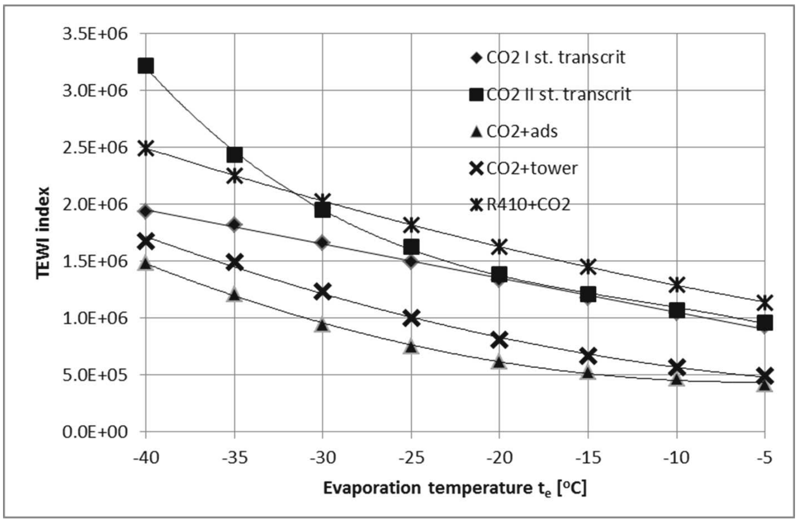

Figure 7: Comparison of TEWI index including auxiliary power consumption for cooling tower, pumps, etc. for five cycles.

5 Conclusions

The idea of a hybrid two stage adsorption-compression system is new. The system has been designed and constructed in the Laboratory of Thermodynamics and Thermal Machine Measurements at the Cracow University of Technology.

The reduction of the compressor work, comparing to the conventional one-stage or two-stage compression refrigeration system using CO_2 as a working fluid is significant. There is also significant reduction of the discharge pressure in the system. The hybrid system shows its advantages also in comparison with frequently used compression only R410+CO_2 combination.

The idea of coupling hybrid two systems has also the development possibilities. The source heat used here, namely the solar collectors, may be substituted by the engine and/or compressor cooling heat, when using engine driven compressor. Also other waste heat source may be used with relatively low temperature starting with 65 °C.

Wet cooling towers are at this stage proposed for recooling. In systems ‘ready for market’ this shall not be used for many reasons. There are two possibilities depending on local conditions. First is to use ground heat exchanger which will be the recooling source in summer and heat source for heat pump cycle in winter. Another possibility is to use swimming pool heating for recooling. In both cases during cold days or nights the CO_2 condenser may be cooled using water/glycol mixture directly from the re-cooler, and the sorption system may be reversed and used as heat pump. This solution gives flexibility while applying good control system.

The system shown here is expensive at the laboratory stage, but not all measuring equipment is needed for thew end user. The possibilities of integration: refrigeration, air conditioning, heat pump in one system will reduce unit costs and increase the system usage time and payback period.

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