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AN INNOVATIVE ECOLOGICAL HYBRID REFRIGERATION CYCLE FOR HIGH POWER REFRIGERATION FACILITY

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Searching for new refrigerants is one of the most significant scientific problems in refrigeration. There are ecological refrigerants commonly known: H_2O and CO_2. H_2O and CO_2 known as natural refrigerants, but they have problems:a high freezing point of H_2O and a low triple point of CO_2. These problems can be solved by the application of a hybrid sorption-compression refrigeration cycle. The cycle combines the application possibility of H_2O in the high temperature sorption stage and the low temperature application of CO_2 in the compression stage. This solution gives significant energy savings in comparison with the two-stage compressor cycle and with the one-stage transcritical CO_2 cycle. Besides, the sorption cycle may be powered by low temperature waste heat or renewable heat. This is an original idea of the authors. In the paper an analysis of the possible extension of this solution for high capacity industrial refrigeration is presented. The estimated energy savings as well as TEWI (Total Equivalent Warming Impact) index for ecological gains are calculated.

Keywords: hybrid ecological refrigeration cycle, adsorption, compression

1. INTRODUCTION

Refrigeration nowadays is searching for new refrigerants, since the Montreal Protocol (1987) regulations strongly affected the refrigerant market as well as scientific research trends. The new findings, for example, R1234yf meet the Montreal Protocol requirements in terms of air pollution but have many disadvantages, which makes it very sensible to look for other opportunities. The application of carbon dioxide as a refrigerant is becoming increasingly popular. However due to the temperature limit and resulting efficiency limitation CO_2 is used mostly for the LT (Low Temperature) stage compression cycle. In the HT (High Temperature) cycle another refrigerant, such as for example R410A, is used. A number of papers on CO_2 applications in different refrigerating cycles has been published in recent years (Suamir et al., 2012; Suamir and Tassou, 2013; Yamaguchi and Zhang, 2009). There is also interest in modelling and simulation of adsorption heat pumps, which allows the analysis of the winter cycle of the combined systems (Evola et al., 2013; Starace et al., 2014). The range of produced absorption or adsorption units is from 8kW up to 21MW 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 (Ullah et al., 2013). The COP of the absorption cycle with high temperature generation (above 120°C) may be higher than that for adsorption using two stage, double effect cycles (Misra et al., 2003; Misra et al., 2005). For lower temperature sources such as solar cooling or central heating network, the application of absorption may not be possible at all. Different heat sources for cooling or refrigerating have been also analysed in

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a number of published papers (Joudi and Dhaidan, 2001; Saha et al., 2003; Syed et al., 2005; Wang et al., 2000). The adsorption technology can work using 65°C as the driving temperature for a desorber (Habib et al., 2011; Saha et al., 2003; Saha, et al., 2006. 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, their application however, has other aims and refrigerants than presented here (Banker et al., 2008; Garimella et al., 2011; Han et al., 2013; Zheng and Meng, 2012).

The problem with H_2O application as a refrigerant is the triple point 0.01 °C and the CO_2 cycle has reduced COP terminology explanation above the critical point 31 °C. A possible solution of this problem is a cascade system combining two cycles: low temperature compression stage (LT) with CO_2 and high temperature sorption stage (HT) with H_2O. There are ecological solutions for HT cycle: adsorption or absorption cycles. Both can be driven with waste heat or solar heat. This reduces the electric energy consumption. The solar driven sorption only cycles have been reported earlier in previous publications (Cyklis and Brak, 2008; Florides, 2003; Grzebielec, 2009; Hassan et al., 2012; Kim and Infante Ferreira, 2003; Kim and Infante Ferreira, 2008; Wang et al., 2000; Zhang et al., 2011).

2. OBJECTIVE, SCOPE AND METHODOLOGY OF WORK

The idea of hybrid cascade system absorption-compression has been analysed by (Anand et al. , 2013; Cimsit and Ozturk, 2012; Fernandez-Serara et al., 2006). The design in Fig.1. consists of an efficient heat exchanger combining the CO_2 condenser with H_2O evaporator. However, this reduces its possibility for direct use of a cooling tower to cool down the condenser in cold seasons, while sorption system itself can be applied for heating as a heat pump (Chen et al., 2010; Grzebielec, 2009; Saha et al., 2003; Starace et al., 2014; Wang et al., 2005; Ward et al., 1979).

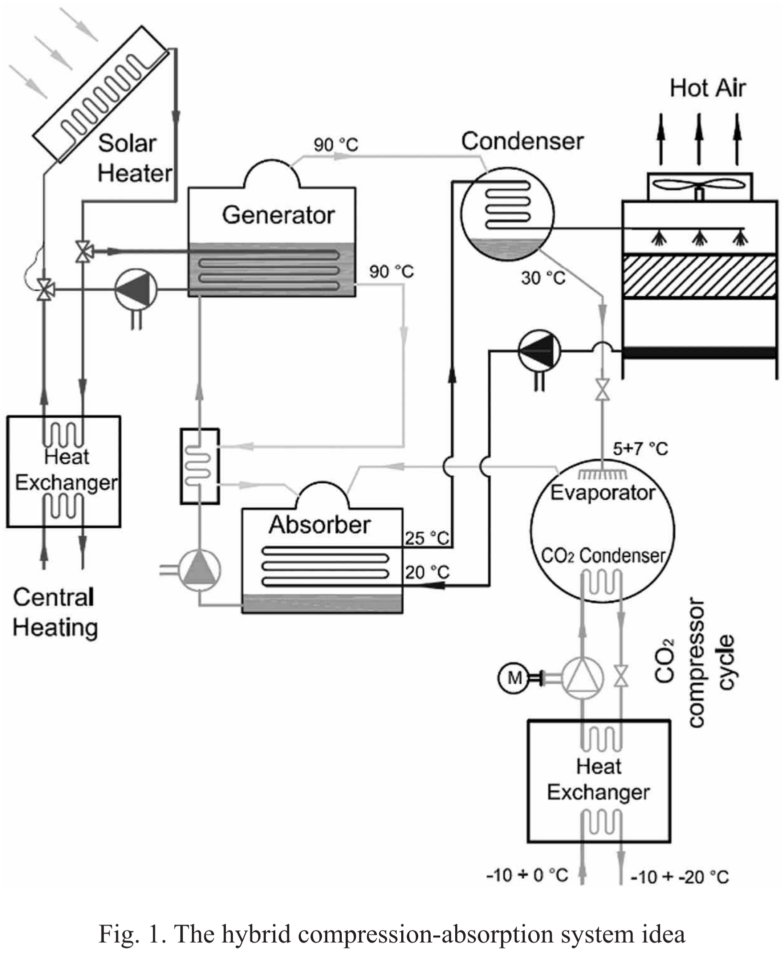

Fig. 1. The hybrid compression-absorption system idea

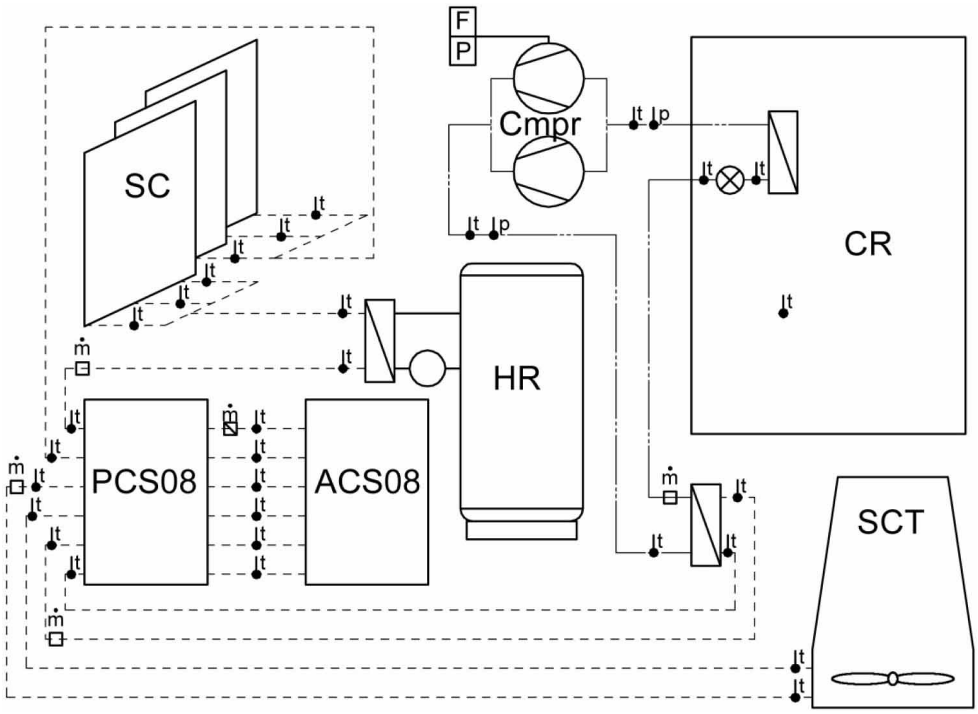

Fig. 2. The hybrid compression-adsorption laboratory stand. SC – solar collectors, PCS08 – pumps, ACS08 – adsorption unit, SCT – sprayed cooling tower, HR – heat container, CR – refrigeration chamber, Cmpr – compressors

The concept of the presented system is the composition of the HT adsorption with LT compression cycle shown in Fig. 2. This original idea has been previously published elsewhere (Cyklis and Kantor, 2011a; 2011b). This idea has been a basis for the test system constructed in the Laboratory of Thermodynamics and Thermal Machines Measurements at Cracow University of Technology. The core of the cycle is the ACS08 adsorption system (SorTech, 2009), with about 8 kW nominal cooling power. The ACS08 is connected to the system using a pumping station (PCS08). The compression CO_2 cycle is composed of two compressors Dorin CD300H (Cmpr) working in a parallel cascade mode. The solar heat source (SC) comprises 17 vacuum tube solar collectors HEWALEX KSR-10 with a net area of about 17.2 m^2. The system has already been operated for two years. During system operation many tests have been carried out with different temperatures of heat source, cooling tower (SCT) and resulting cooling temperature for the CO_2 condenser. There is also a heat container (HR) used for solar heat storage. An example of one complete test cycle is shown in Fig. 3.

Testing equipment used:

- glycol flow: turbine flow meters HOFFER HO1/2x1/2 class of accuracy 0.25% with impulse meters KEP BATRTM2AC class 0.01%,
- CO_2 flow: SIEMENS SITRANS F C MASSFLO 2000 (Coriolis type) class 0.1% on liquid side,
- Pressure: Vegabar 17 transducers class 0.5%,
- temperature: Pt100, current loop class 0.3%,
- electric power: LUMEL M30P-LCTM74 meters class 0.5%.
- Data acquisition system operates with eight 16-bit ICP DAS measuring cards with the range of ±20 mA, 0~20 mA, 4~20 mA class 0.1%.
- For data acquisition PC software have been prepared with visualization possibilities. The system has been connected via the RS485 port using DCON protocol.

All calculated enthalpy, density and other liquid properties are related to (NIST, 2014).

Estimated measurement uncertainty for enthalpy of all liquids is better than 4.3%, calculated uncertainty for electric power reading including averaging is about 1%.

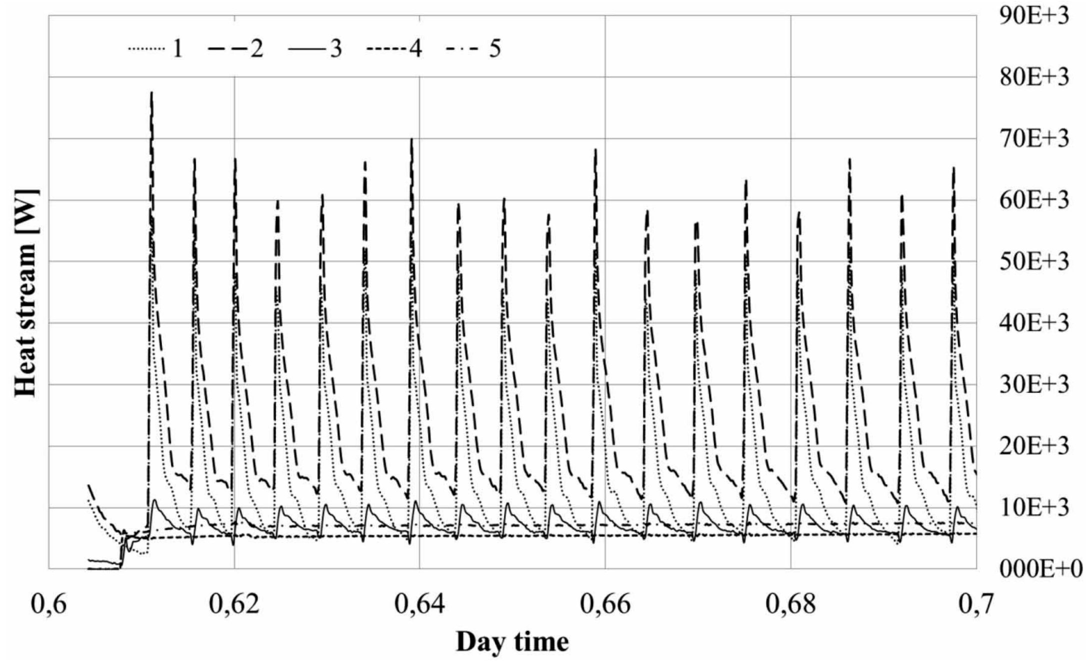

Fig. 3. The heat streams during the steady system operation: 1 – heat source for adsorption, 2 – cooling tower, 3 – adsorption cooling power,4 – CO_2 evaporating heat, 5 – CO_2 condensing heat

It has been found that within the range of solar temperature of 65-95°C, no significant influence of the temperature on the adsorption cycle performance has been detected. Also a periodic adsorption system action has no influence on the compression LT part of the cascade work. In Fig. 4 a summary of the results of the tests is presented. Two ranges of CO_2 condensing temperature are depicted; the higher for condenser cooling directly forms cooling tower in cold seasons. There is also a comparison between the pure compression cycle and two stage cycles. The developed system efficiency in terms of EER coefficient is higher than compression only cycles.

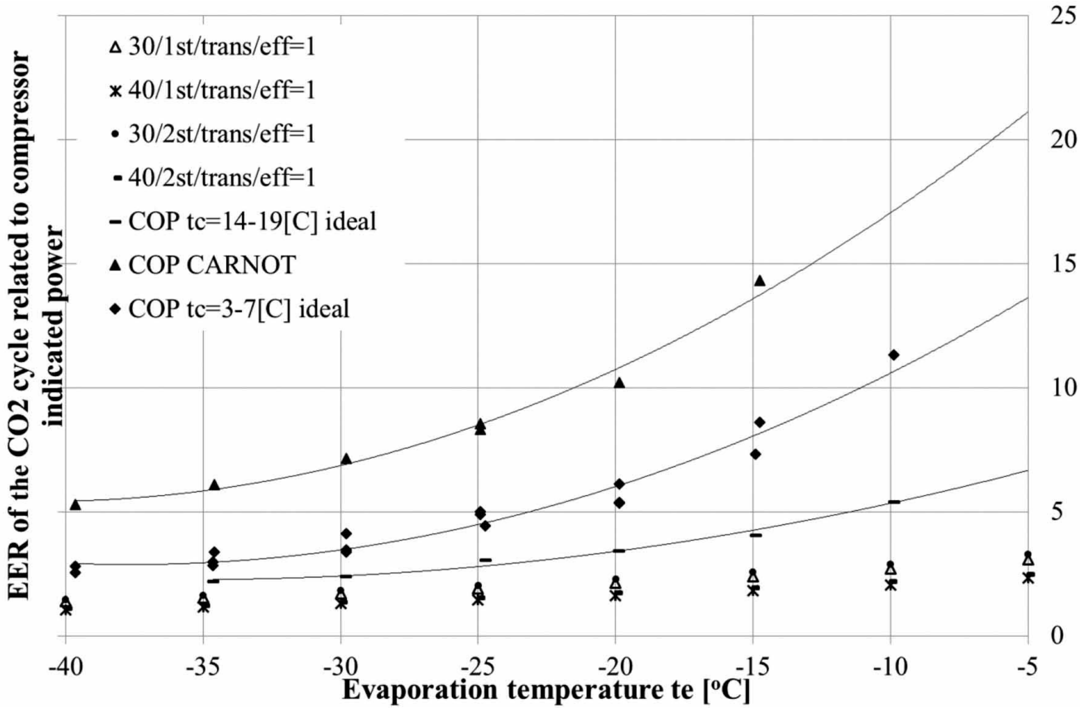

Fig. 4. EER efficiency of the hybrid cycle related to the CO_2 compressor indicated power for two condensing temperatures 14-19°C and 3-7°C. Also pure compression CO_2 one and two stage transcritical cycles are shown for comparison, with Carnot cycle as reference

One of the ecological coefficients commonly used for comparison of refrigerating systems is TEWI (CO_2 kg equivalent). It has a formula:

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

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

Five cycles have been selected for comparison:

- compression two stage cycle with CO_2 and R410 as the base line result for comparison in Figs. 5 and 6 (zero horizontal axis)
- transcritical CO_2 one stage
- transcritical CO_2 two stages
- hybrid adsorption-compression with cooling directly from sprayed 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).

Additionally in Fig. 5 a comparison with idealised hybrid adsorption-compression cycle calculated with no energy loss assumption has been presented.

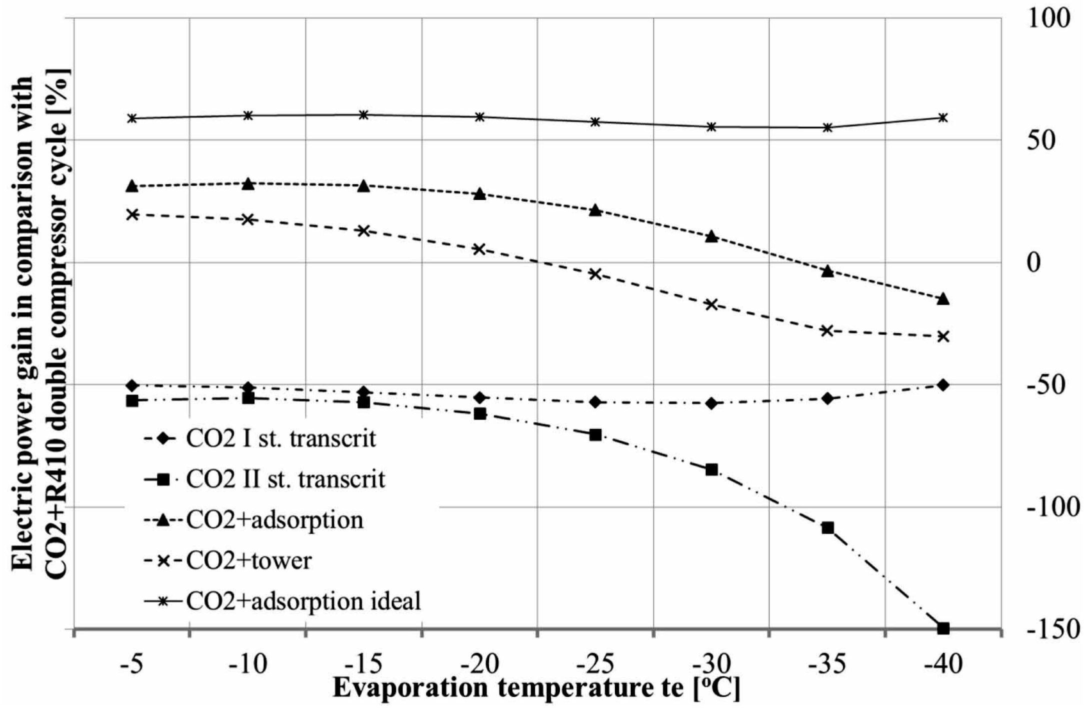

Fig. 5. Total electric power including auxiliary power consumption for cooling tower, pumps etc. for five cycles

The analysis has been provided for the evaporation temperature of CO_2 ranging from -40 °C up to -5°C (Figs. 5 and 6). In Figs. 5 and 6 the new hybrid adsorption-compression cycle for refrigeration both energy consumption and TEWI coefficient are significantly lower than those for the conventional compression only cycles. In case of energy efficiency up to 30% of energy could be reduced, while for the TEWI coefficient improvement higher than 60% could be expected.

In case of CO_2 one or two stage compression transcritical cycles, the TEWI values are by 10-20% lower than CO_2 + R410 but the electric power is significantly higher, so this solution is not realistic for practical usage. Besides the pressures are about 10 MPa, which requires a special system design.

The CO_2+tower cycle has been used for low ambient temperature. In this case CO_2 condenser has been cooled directly from the sprayed cooling tower. The adsorption for low ambient temperature may be reconfigured for heat pump action. The TEWI results in this case are close to adsorption-compression

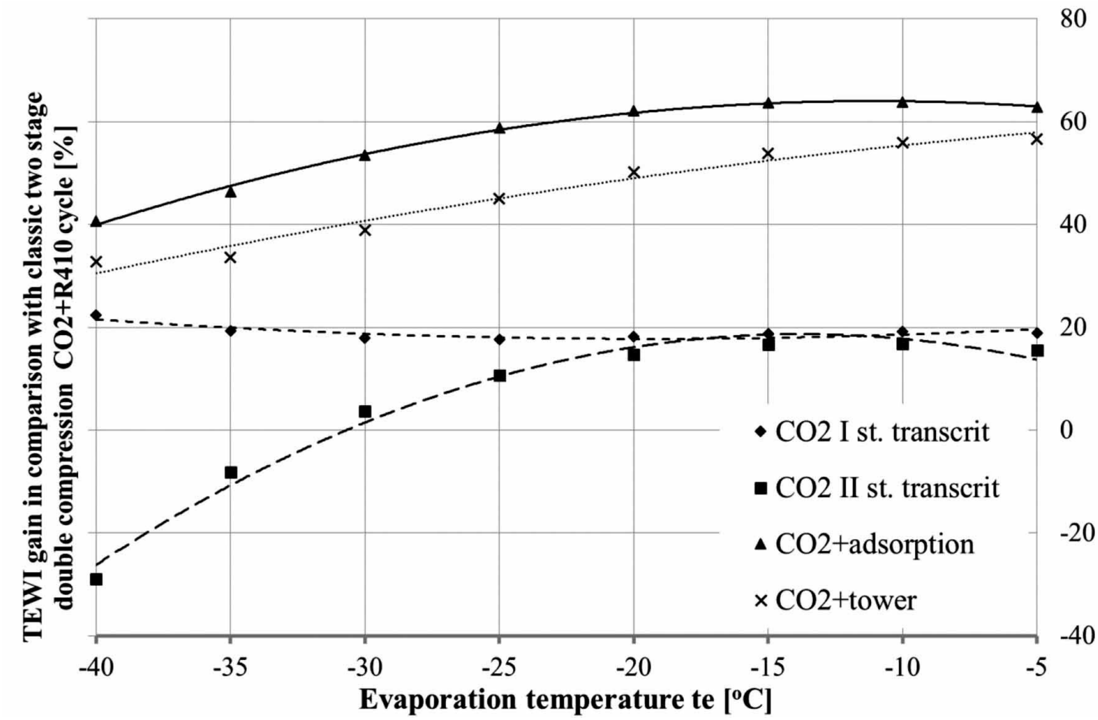

Fig. 6. TEWI index including auxiliary power consumption for cooling tower, pumps etc. for five cycles

cycle, but the energetic values are by about 10% lower. Based on the above experimental results, for a small system the idea of hybrid refrigeration has been implemented for a design of an industrial high power cold storage. The waste heat of the industrial process (combustion gases cooling) was considered as a source for heat supply. The schematic drawing of the plant is shown in Fig. 7, and the technical data for refrigeration storage is given in Table 1.

Table 1. Cold storage requirements

	Value	Unit
Cold storage capacity	2000	t/24h
Refrigerating tunnel (t/24h)	-35	°C
Cold room storage	-25	°C
Cold room depository	-25	°C
Dispense chamber	4	°C
Refrigerating power requested	115	kW
Requirements for CO_2 cycle		
t_e	-45	°C
t_c	7	°C
Cooling capacity	115	kW

The working parameters for the LT compression cycle have been calculated using Coolpack software (Skovrup et al., 2012). The calculated condenser power for CO_2 is 188 kW, with condensing temperature of 7 °C. On this basis the adsorption unit SCAD 090 with a nominal cooling power of 252.2 kW has been chosen. A Grasso HP45 compressor was chosen for the CO_2 cycle. Wet cooling tower has to remove 521 kW of the thermal power at 29/34 °C, so a CDW600 has been chosen. The efficiencies for each subsystem have been introduced on the basis of laboratory stand small scale tests results.

A comparison between energy efficiency and TEWI has been calculated for five cycles – both hybrid and/or compression only. A comparison between energy and TEWI has been given for five cycle designs in Fig. 8. The reduction in yearly energy consumption for this particular system exceeds 340 MWh for

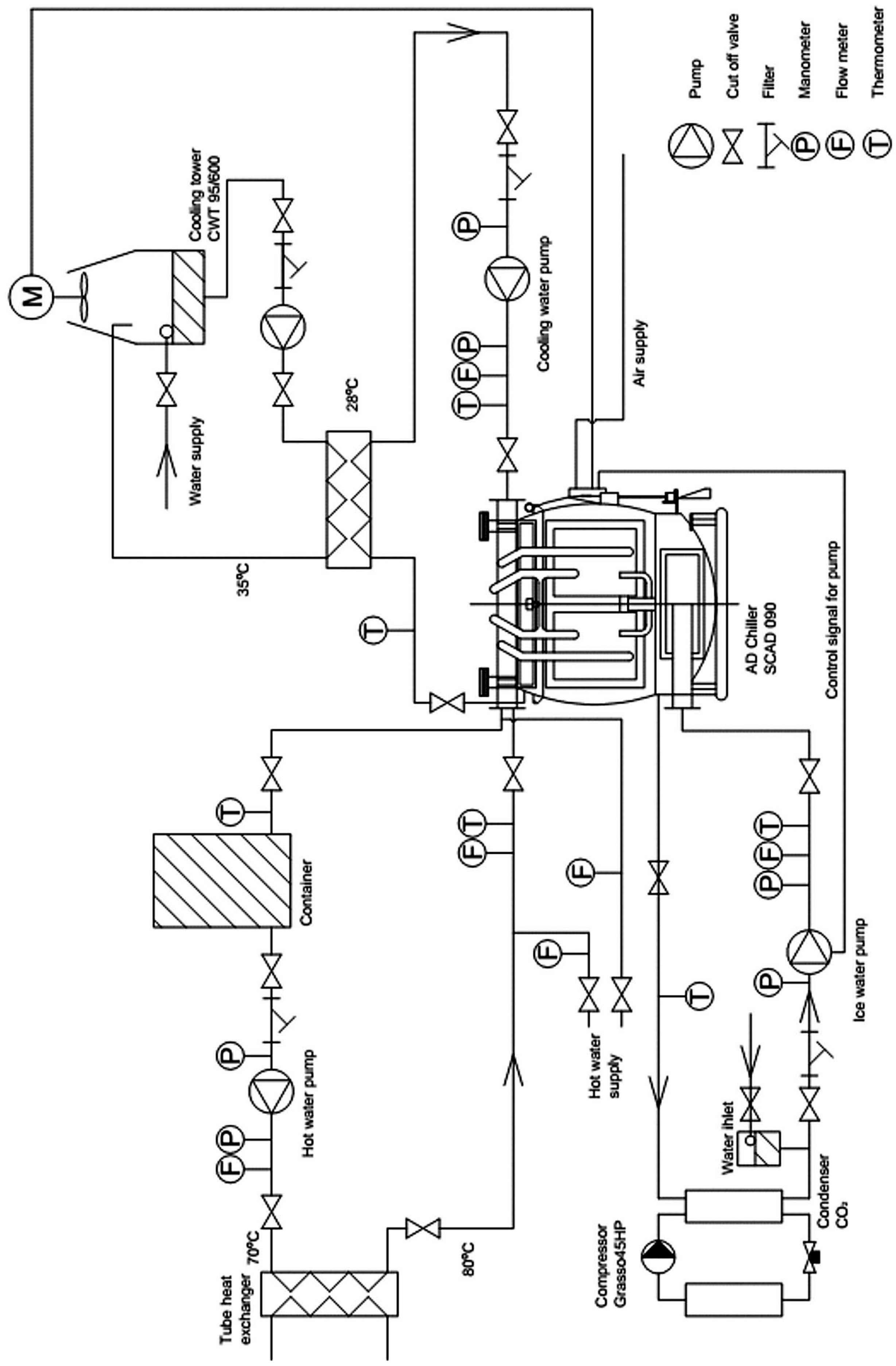

Fig. 7. Schematic design of the prototype industrial hybrid refrigeration system (115 kW cooling power)

the hybrid cycle, which is equivalent to 29,000 tons of CO_2 (TEWI), in comparison with the R410+CO_2 compression two stage cycle. Usually the results for high power adsorption cycles are better than those for smaller cycles, so the results shown in Fig. 8 may be considered as conservative.

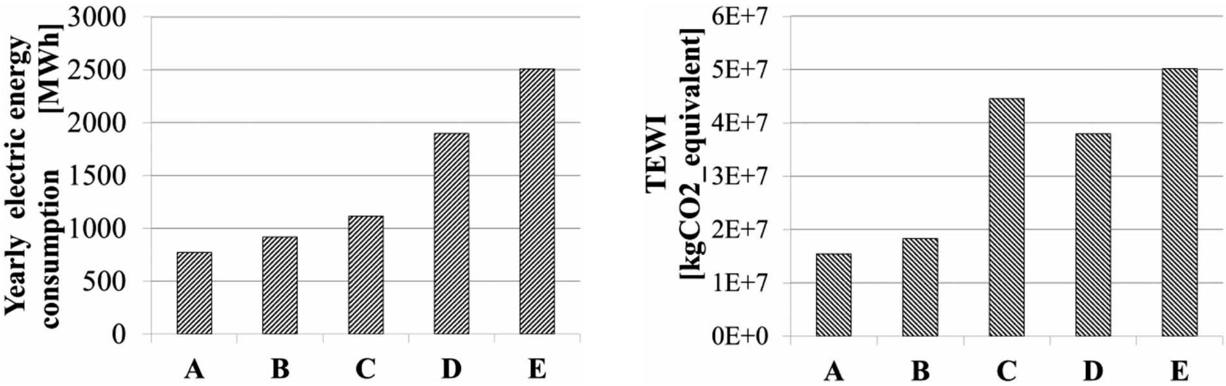

Fig. 8. Comparison of energy consumption and TEWI for five cycle designs
A- CO_2+adsorption, B- CO_2+tower, C- CO_2+R410, D- one stage CO_2, E- double stage CO_2

3. CONCLUSIONS

The application of hybrid adsorption/compression cycle for high capacity industrial refrigeration, using waste or a renewable heat source for adsorption has been analysed in the paper. The investment costs increase for high power adsorber, so the compression refrigeration system seems to be less expensive. However, when considering energy consumption reduction influencing the yearly operating costs, the combined economy of the new solution is promising. The analysis shows that for the evaporation temperature of CO_2 ranging from -40 °C up to -5 °C the new hybrid adsorption-compression cycle for refrigeration both energy consumption and TEWI coefficient are significantly lower than those for the conventional two stages compression cycles. In case of energy efficiency up to 30% of energy could be reduced, while for the TEWI coefficient improvement higher than 60% could be expected. The results for higher capacity refrigeration systems will be even better, since the electric power consumption for secondary equipment (measurement, controls, pumps etc.) is comparatively lower.

Anyhow, in the countries where adsorption systems play important roles in industry pure adsorption systems are used only for cooling or air conditioning. The above presented innovative hybrid cycle provides another possibility for cold effect production utilisation, which expands options of waste energy utilisation. Besides, the TEWI factors are for a hybrid cycle much lower than those for a compression cycle, so the system is purely ecological considering that only natural refrigerants are used. Additionally, no environmental pollution occurs when the cycle is opened to ambient air during maintenance or system failure.

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SYMBOLS

E	energy use of the cycle per year, kWh
EER	Energy Efficiency Rating
f	refrigerant recovery coefficient, -
GWP	Global Warming Potential kg equivalent, with the relationship to CO_2
L	emission to the atmosphere, kg/yr

m	amount of refrigerant in installation, kg
N	supplied electric power of the cycle, kW
n	life of the cycle, yr
tr	yearly number of working hours, h
TEWI	Total Equivalent Warming Potential
z	CO_2 emission for the electric energy; in Poland $z = 0.94$ kgCO_2/kWh

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