TECHNICAL TRANSACTIONS | CZASOPISMO TECHNICZNE
MECHANICS | MECHANIKA
1-M/2015

PIOTR CYKLIS*, ROMAN DUDA*

THE HYBRID SORPTION-COMPRESSION REFRIGERATION CYCLE CONTROL SYSTEM

AUTOMATYKA I STEROWANIE HYBRYDOWEGO SORPCYJNO-SPRĘŻARKOWEGO SYSTEMU ZIĘBNICZEGO

Abstract

The requirements for environmentally friendly refrigerants promote the application of both CO_2 and water as working fluids. Both solutions have disadvantages resulting from the high temperature limit for CO_2 and the low temperature limit for water. This can be avoided by the application of the hybrid adsorption-compression system, where water is the working fluid in the adsorption cycle which is used to cool down the CO_2 compression cycle condenser. The adsorption process is powered with a low-temperature renewable heat source such as solar collectors or waste heat sources. This solution has been developed by the authors of this paper and has not been reported in any other literature source. The different ambient conditions over the course of the year require specially designed control procedures and the automation system. The algorithm has to control positive and negative heat sources operation, valve actions, pumps, fans and compressor operation. In the control algorithm, the ambient temperature and solar conditions or other waste heat sources have to be introduced as control parameters, optimised to achieve maximum efficiency of the whole system. The refrigeration effect as a parameter has to be considered both for the refrigeration capacity as well as the CO_2 evaporation temperature.

Keywords: *hybrid adsorption-compression refrigeration*, *control*

Streszczenie

Wymagania dotyczące użycia przyjaznych dla środowiska czynników chłodniczych promują zastosowanie CO_2 i wody jako czynników roboczych. Oba rozwiązania posiadają wady będące wynikiem ograniczeń maksymalnej temperatury CO_2 i dolnej granicy temperatury wody. Można tego uniknąć przez zastosowanie hybrydowego adsorpcyjno-sprężarkowego systemu chłodniczego, w którym woda jest cieczą roboczą w cyklu adsorpcyjnym, który zaś stosuje się w celu ochłodzenia skraplacza CO_2 w cyklu sprężarkowym. Adsorber jest zasilany energią z niskotemperaturowego odnawialnego źródła ciepła, takiego jak kolektory słoneczne lub źródła ciepła odpadowego. Takie rozwiązanie to nasz własny pomysł i nie odnotowano go w żadnym innym źródle literatury. Natomiast różne warunki otoczenia przez cały rok wymagają specjalnie zaprojektowanych procedur sterowania i rozwiązań automatyki. Algorytm sterujący musi kontrolować działanie dodatnich i ujemnych źródeł ciepła, zawory, pompy, wentylatory i pracę układu sprężarkowego. W tym algorytmie temperatura otoczenia i warunki słoneczne lub z innego źródła ciepła na przykład odpadowego muszą być wprowadzone jako jego parametry, biorąc pod uwagę działanie obiegów w celu osiągnięcia maksymalnej wydajności całego systemu. Zapotrzebowanie na efekt chłodniczy jest parametrem zarówno pod względem mocy chłodniczej, jak i temperatury odparowania CO_2.

Słowa kluczowe: *hybrydowy adsorpcyjno-sprężarkowy system chłodniczy*, *sterowanie*

* Prof. Ph.D. D.Sc. Eng. Piotr Cyklis, M.Sc. Eng. Roman Duda, Faculty of Mechanical Engineering, Cracow University of Technology

1. Introduction

Compression and sorption systems are usually applied alternatively in refrigeration and air conditioning systems for refrigeration and heat pump cycles.

In two stage cascade refrigeration compression cycles, with the same refrigerants on both stages the temperature of about –60°C can be achieved [1]. Cascade compressor applications, with two independent cycles and two different refrigerants, are also frequently used. In this case, two refrigeration compressor cycles are connected by a heat exchanger (evaporator-condenser). The temperature of the LT (low temperature) cycle evaporator may fall below –80°C [2, 3].

The application of carbon dioxide in compression refrigeration system is well known, but due to its low critical temperature, CO_2 requires a high discharge pressure, since the transcritical cycle has to be applied under normal ambient condition. In this case, a gas cooler is applied instead of the condenser. The carbon dioxide cycle is frequently used in the LT stage at the two stage compression refrigerating cycle [4–6].

The sorption systems like LiBr/H_2O absorption or silica gel adsorption cycles where H_2O is a working fluid, are limited for refrigeration purposes by H_2O condensing temperature not lower than 4–8°C [7, 8].

There are also some papers covering new idea of hybrid cycle where low temperature cycle (LT) is compression refrigeration and high temperature cycle (HT) is thermal compression. The examples are for such a hybrid cycles are: sorption (CO_2–NH_3 cascade) [9], (N_2O–CO_2 cascade) [10], adsorption [11, 12] or thermoelectric cooling. Adsorption zeolite air conditioning and heat pump have already been developed [13].

Coupling two systems (adsorption at the HT stage and CO_2 compression at the LT stage) is a new idea, combines the possibility of utilising waste heat or solar heat as an energy source for the HT stage [14].

The advantages of the proposed system are: the application of only natural refrigerants and low energy consumption when utilising the solar or waste energy. The TEWI coefficient is significantly lower for the proposed system than for other solutions.

2. The hybrid system design

In the Laboratory of Thermodynamics and Measurements of Thermal Machines at the Cracow University of Technology a test stand with a hybrid refrigeration adsorption--compression system has been designed and constructed [15].

HT stage of the system is the adsorption cycle based on ACS08 adsorber (SorTech AG). This adsorber is coupled with tube solar collectors with heat storage and a sprayed cooling tower for MT (medium temperature) glycol for re-cooling. Solar system is composed of 17 vacuum tube solar collectors HEWALEX KSR-10 and a heat storage tank with a capacity of 2000 litres. An evaporative (sprayed) cooling tower DECSA REF-C-005 with a maximum cooling power about 75 kW is used for cooling the adsorption unit.

The low temperature compression cycle is equipped with two CO_2 compressors Dorin CD300H ph3; one of them is equipped with frequency inverter ABB ACS355-03-08A8-4.

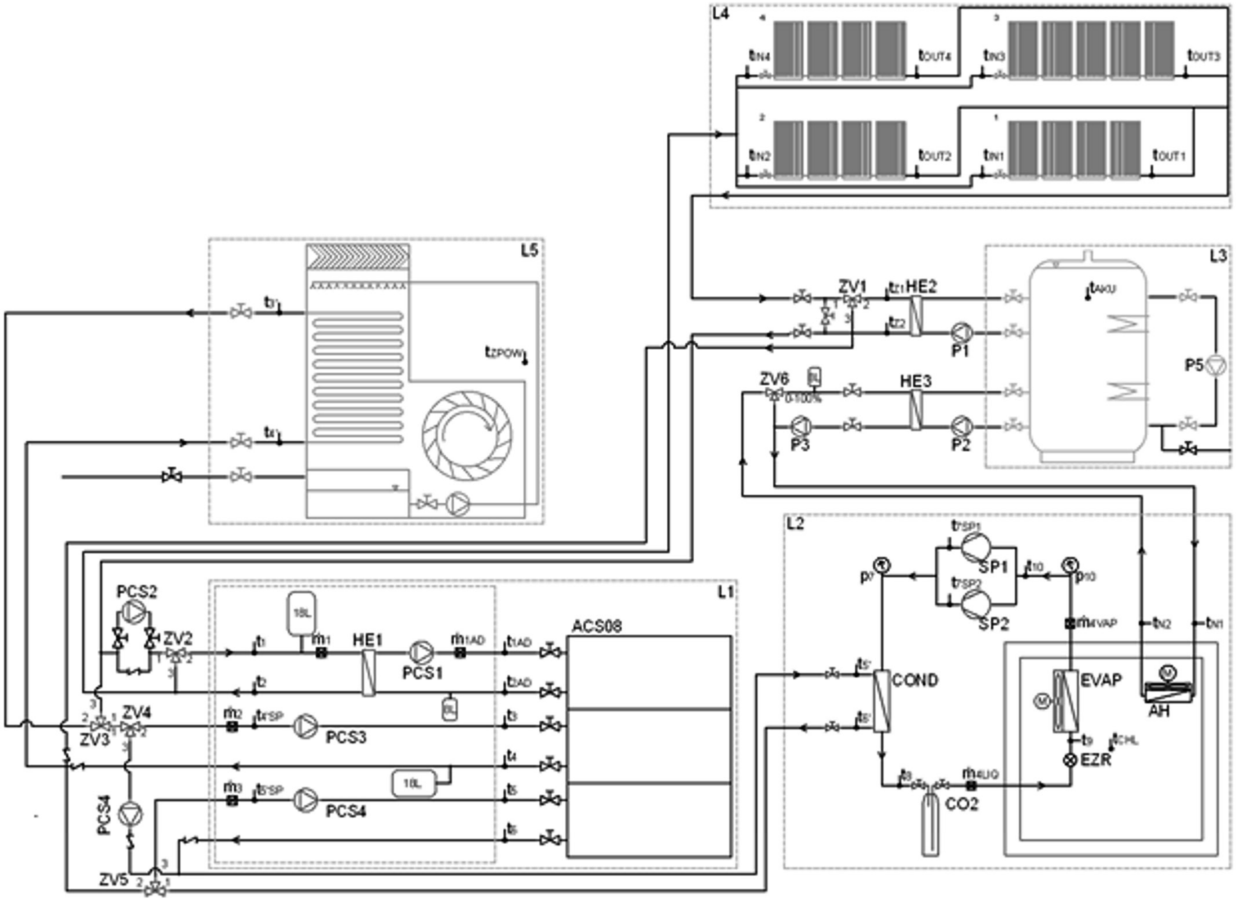

Fig. 1. Schematic diagram of the complete hybrid refrigeration system installed in The Laboratory of Thermodynamics and Thermal Machines Measurements

A refrigeration compartment with internal dimensions 1960 mm × 1920 mm × 2690 mm and with a wall thickness of 200 mm is cooled using evaporator Gunter CXGHF 040.2H/17--ENW50.E with fan VT0398U and high pressure expansion valve CX4 CO2 PCN 801990. The lamellar heat exchanger SWEP B16DWHx64/1P-SC-U is working as a CO_2 condenser. Ethylene glycol is used as secondary liquid for the cooling tower and solar collectors. The air heater Flowair Leo FB 9 has been installed in the cooling chamber to simulate the thermal load.

The complete system is shown in Fig 1. Table 1 presents the measurement devices.

Table 1

Measurement devices mounted in test stand

measurement	count	Sensor	class	used range
t_i	36	Introl IT-CF-1 Pt100	B	–25~200; –50~150; 0~150 [°C]
t_i/curent loop	36	Introl	0.03%	4~20 [mA]
m_{4liq}	1	SIEMENS MASSFLO 2100	0.01%	0~1000 [kg/h]
m_{4liq}	1	SIEMENS MASS 6000	0.01%	0,0002~0,2786 [kg/s]
m_{4vap}	1	Hoffer Flow Controls ACEII	0.05%	10~110 [l/min]
m_1; m_{1AD}; m_2, m_3	4	Hoffer Flow Controls	0.05%	4,73~35,96; 6,62~60.57; 9,46~109.78 [l/min]
m_1; m_{1AD}; m_2, m_3	4	KEP BATRTM2AC	0.05%	0~36; 0~60; 0~110 [l/min]
p_7; p_{10}	2	Vegabar 17	0.05%	0~100 [bar]
p_{AKU}	1	Vegabar 17	0.05%	0~25 [bar]
Pi_i	9	LUMEL	0.01%	0~200; 0~700; 0~3000; 0~8000; 0~10000; 0~15000 [W]
current loop	8	ICP DAS M-7017RC	0.01%	4~20 [mA]

3. Control system design

The main problem of the proposed system, which has to be solved by automatic control, is the continuous: 12 months, 24 hours, working time for refrigeration system.

This is the reason why the cooling tower applied in our laboratory stand has more power than required only for adsorption cooling. The adsorption cooling of the CO_2 condenser is possible only in periods when waste heat or solar heat is available. In case of the the solar heat, during the night, only part of the time the adsorption cycle work may it be powered from the storage tank. Then, the cooling tower has to cool down the condenser directly. During the night, temperature achievable with the wet cooling tower is low enough to cool down the CO_2 condenser to below the critical point. In the case of extremely high air humidity, the electric heater may be used as a backup for adsorption Also, any other kind of waste heat may be used to heat up the desorber. The advantage of the adsorption system is that it may work with 60–65°C driving temperature, depending on the adsorber design.

There are several work regimes for each subsystem.

For subsystem L1, the adsorber work shall have four main regimes:

1. A summer day working (SDW) regime is when the input temperature from heat source exceeds 65°C, and the ambient air temperature is higher than 13°C. Under such conditions the adsorption subsystem works in the cooling mode. Since the outlet cooling temperature from the adsorber is a function of cooling load, it is sufficient to leave the system at lowest possible cooling temperature as possible. This self-adjustment function of the adsorption unit allows achieving the lowest possible condensing temperature, reducing total energy consumption. This regime occurs until two above mentioned temperatures used as control functions will not be crossed;
2. Summer night work (SNW). The adsorber work is no longer possible when heat source temperature decreases below 65°C, then the adsorption system has to be stopped, and then, only the wet tower is used to cool down the CO_2 condenser;
3. Heat pump work (HPW). This option is used when the ambient air temperature goes below 13°C. Then, the adsorber may be used separately as a heat pump collecting all waste heat and ambient heat and using the heat collector as HT source, while the MT (medium temperature heat) is used for domestic/company heating. In this case, the CO_2 cycle condenser is cooled down directly from the cooling tower;
4. Additional Heater Work (AHW). The temperature of the heat source is below 65°C and the requirements for condenser cooling are higher than the cooling tower can provide. This may be the case only in special ambient conditions with a very high relative air humidity and high temperature when no waste or solar heat source is available.

Subsystem L2 – compression cycle CO_2

Commonly known CO_2 compression refrigerating cycle control system will not be discussed here in details. However, there are two important differences:

1. The cooling requirements for CO_2 condenser may in some cases be limited, and additional cooling power may be required. In this case the control signal is released to run AHW program in the L1 subsystem, reducing the compressor power at the same time;
2. One of the compressors is equipped with the frequency inverter. This makes it possible to change refrigeration capacity according to the current chamber load, instead of conventional on/off system.

Subsystem L3, L4, L5 – heat storage, solar collectors, wet cooling tower

The heat storage subsystem is simple in operation. It has an electric heater with an on/off system only for L1 AHW mode. Not mentioned earlier ZV valves and pumps have to work accordingly to other subsystem modes, opening flow path accordingly to the system needs:

1. Mode SAC – the solar heat accumulation is controlled using temperature readings. Once the temperature reading is higher than required, the PCS2 pump starts working and continues until the outlet temperature from the solar collectors exceeds the temperature in the heat storage container for 15 K. Then the P1 pump starts and the heat storage container load starts. This accumulation goes on until the glycol temperature in the solar circuit falls below the container temperature by 2–3 K. In case of fast solar collectors temperature decrease the PCS2 pump is switched off. When heat container temperature limit is reached (95°C achieved), the mode SAC is switched to mode SWS;
2. Mode SW solar work– the heat storage container is fully loaded to 95°C, P1 pump then switches off, if the L1 subsystem is on SDW mode, the glycol directly heats the adsorber. In case of to high solar temperature or subsystem L1 not operating, the mode SW switches into SWS mode;
3. SWS mode – solar waste mode. This is the case when no heat source is needed (L1 is not operating, accumulator is full) and there is considerable amount of solar radiation and the temperature readings in solar subsystem exceeds the set point (about 100°C). Then pump PCS2 then has to be put into operation and all heat is removed in the cooling tower.

In Table 2, the control system setup for each mode is shown.

Table 2

Regimes Modes and working Systems

	COMMON EQUIPMENT						
MODE	**ZV1**	**ZV2**	**ZV3**	**ZV4**	**ZV5**	**PCS2**	**PCS4’**
SDW/SAC	POS-1-2	POS-1-3	POS-1-2	POS-1-2	POS-1-3	T-CTL	OFF
SDW/SW	POS-1-2	POS-1-2	POS-1-2	POS-1-2	POS-1-3	T-CTL	OFF
SDW/SWS	POS-1-3	POS-1-3	POS-2-3	POS-1-2	POS-1-3	T-CTL	OFF
SNW	POS-1-2	POS-1-3	POS-1-2	POS-1-3	POS-1-2	OFF	ON
HPW	POS-1-2	POS-1-3	POS-1-2	POS-1-3	POS-1-2	ON	ON
AHW	POS-1-2	POS-1-2	POS-1-2	POS-1-2	POS-1-3	ON	OFF

	L1			
MODE	**ACS**	**PCS1**	**PCS3**	**PCS4**
SDW/SAC	OFF	ACS-CTL	ACS-CTL	ACS-CTL
SDW/SW	ON	ACS-CTL	ACS-CTL	ACS-CTL
SDW/SWS	ON	OFF	OFF	OFF
SNW	OFF	ACS-CTL	ACS-CTL	ACS-CTL
HPW	ON	ACS-CTL	ACS-CTL	ACS-CTL
AHW	ON	ACS-CTL	ACS-CTL	ACS-CTL

	L2						
MODE	**AKC**	**ECX**	**SP1**	**SP2**	**EZR**	**MEVAP**	**MAH**
SDW/SAC	ON	ON	AKC-CTL	AKC-CTL	ECX-CTL	AKC-CTL	MAN-CTL
SDW/SW	ON	ON	AKC-CTL	AKC-CTL	ECX-CTL	AKC-CTL	MAN-CTL
SDW/SWS	OFF	OFF	OFF	OFF	OFF	OFF	MAN-CTL
SNW	ON	ON	AKC-CTL	AKC-CTL	ECX-CTL	AKC-CTL	MAN-CTL
HPW	ON	ON	AKC-CTL	AKC-CTL	ECX-CTL	AKC-CTL	MAN-CTL
AHW	ON	ON	AKC-CTL	AKC-CTL	ECX-CTL	AKC-CTL	MAN-CTL

	L3						
MODE	**P1**	**P2**	**P3**	**P5**	**ZV6**	**EH1**	**EH2**
SDW/SAC	T-CTL	MAN-CTL	MAN-CTL	ON	MAN-CTL	OFF	OFF
SDW/SW	OFF	MAN-CTL	MAN-CTL	OFF	MAN-CTL	OFF	OFF
SDW/SWS	OFF	MAN-CTL	MAN-CTL	OFF	MAN-CTL	OFF	OFF
SNW	ON	MAN-CTL	MAN-CTL	ON	MAN-CTL	OFF	OFF
HPW	ON	MAN-CTL	MAN-CTL	ON	MAN-CTL	OFF	OFF
AHW	ON	MAN-CTL	MAN-CTL	ON	MAN-CTL	ON	ON

	L5	
MODE	**PTWR**	**MTWR**
SDW/SAC	ACS-CTL	ACS-CTL
SDW/SW	ACS-CTL	ACS-CTL
SDW/SWS	T-CTL	T-CTL
SNW	T-CTL	T-CTL
HPW	ON	ON
AHW	ACS-CTL	ACS-CTL

4. Hybrid system advantages

The hybrid system presented in the paper has been put into operation in the Laboratory of Thermodynamics and Thermal Machines Measurements at Cracow University of Technology (Politechnika Krakowska). Several tests have been done with a different system setup. This allowed for the calculation of real values for energy consumption shown in Fig. 2.

The results of investigation of the new hybrid system (CO_2 + adsorption) have been compared to the calculated and experimental results of four other systems: CO_2 only one and two stages transcritical cycles, CO_2 + cooling tower only, double stage compression cycle with R410 as HT stage and CO_2 as LT stage. In most cases, the results of the new hybrid cycle have been better than others in terms of energy. The TEWI coefficient of a new cycle has been significantly better than other investigated cases.

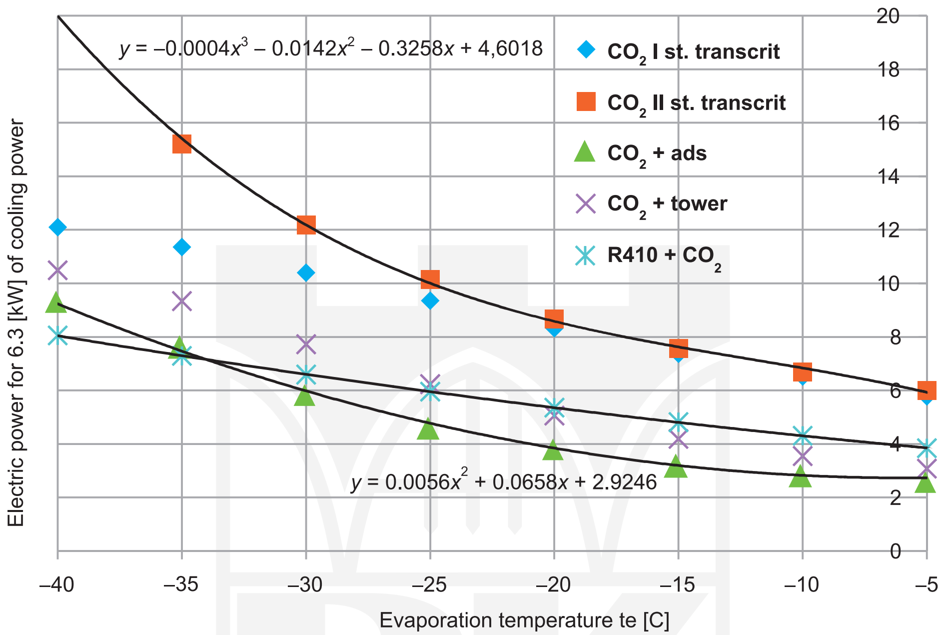

Fig. 2. Results of the experimental investigations of the cycle shown in Fig. 1

The results of this investigation and the control system set up for the determined working modes are the basis for system work optimization during the whole year, 24 hours a day cycle.

5. Conclusions

The new hybrid system shown in this paper has been designed, constructed and investigated in the Laboratory of Thermodynamics and Thermal Machines Measurements at the Cracow University of Technology.

The system assumptions, as a new ecological idea with lower energy consumption and a low TEWI coefficient have been checked and validated. The achieved experimental efficiency is significantly better than conventional systems.

The system control design allowing for optimisation of the hybrid system operation for different ambient conditions and required refrigeration temperatures has been shown.

This publication has been written as a part of the project financed from the funds of the Polish National Centre of Research and Development (agreement no. N R06 0002 10 0936/R/T02/2010/10)

References

[1] Cecchinato L., Corradi M., *Transcritical carbon dioxide small commercial cooling applications analysis*, Elsevier International Journal of Refrigeration, No. 34, 2012, pp. 50-62.

[2] da Silva A., Pedone Bandarra Filho E., Heleno Pontes Antunes A., *Comparison of a R744 cascade refrigeration system with R404A and R22 conventional systems for supermarkets*, Elsevier Applied Thermal Engineering, No. 41, 2012, pp. 30-35.

[3] Getu H.M., Bansal P.K., *Thermodynamic analysis of an R744-R717 cascade refrigeration system*, Elsevier International Journal of Refrigeration, No. 31, 2008, pp. 45-54.

[4] Pearson A., *Carbon dioxide-new uses for an old refrigerant*, Elsevier International Journal of Refrigeration, No. 28, 2005, pp. 1140-1148.

[5] Ge Y.T., Tassou S.A., *Control optimisation of CO_2 cycles for medium temperature retail food refrigeration systems*, Elsevier International Journal of Refrigeration, No. 32, 2009, pp. 1376-1388.

[6] Girottoa S., Minettoa S., Neksa P., *Commercial refrigeration system using CO2 as the refrigerant*, Elsevier International Journal of Refrigeration, No. 27, 2004, pp. 717-723.

[7] Desideri U., Proietti S., Sdringola P., *Solar-powered cooling systems: Technical and economic analysis on industrial refrigeration and air-conditioning applications*, Elsevier Applied Energy, No. 86, 2009, pp. 1376-1386.

[8] Cimsit C., Ozturk I.T., *Analysis of compressioneabsorption cascade refrigeration cycles*, Elsevier Applied Thermal Engineering, No. 40, 2012, pp. 311-317.

[9] Fernandez-Seara J., Sieres J., Vazquez M., *Compression-absorption cascade refrigeration system*, Elsevier Applied Thermal Engineering, No. 26, 2006, pp. 502-512.

[10] Bhattacharyya S., Garai A., Sarkar J., *Thermodynamic analysis and optimization of a novel N_2O–CO_2 cascade system for refrigeration and heating*, Elsevier International Journal of Refrigeration, No. 32, 2009, pp. 1077-1084.

[11] Wang L., Ma A., Tan Y., Cui X., Cui H., *Study on Solar-Assisted Cascade Refrigeration System*, Elsevier Energy Procedia, No.16, pp. 1503-1509.

[12] Labus J., Bruno J.C., Coronas A., *Performance analysis of small capacity absorption chillers by using different modeling methods*, Elsevier Applied Thermal Engineering, No. 58, 2013, pp. 305-313.

[13] Sekret R., Turski M., *Research on an adsorption cooling system supplied by solar energy*, Elsevier Energy and Buildings, No. 51, 2012, pp. 15-20.

[14] Cyklis P., Kantor R., *Concept of hybrid adsorption-compression refrigeration system*, Zeszyty Naukowe Politechniki Poznanskiej, 2011.

[15] Cyklis P., Kantor R., Górski B., Ryncarz T., *Hybrydowe sorpcyjno-sprężarkowe systemy ziębnicze. Część III – Wyniki badań systemu*, Technika Chłodnicza i Klimatyzacyjna, No. 1, 2013, p. 203.