Experimental study on thermal wave type adsorption refrigeration system working on a pair of activated carbon and methanol

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The aim of the study was to examine the efficiency of the thermal wave type adsorption refrigerating equipment working on a pair of activated carbon and methanol. Adsorption units can work in trigeneration systems and in applications driven by waste heat. They can be built also as a part of hybrid sorption-compressor systems, and they are very popular in solar refrigeration systems and energy storage units. The device examined in this study operates in a special mode called thermal wave. This mode allows to achieve higher efficiency rates than the normal mode of operation, as a significant contributor to transport heat from one to the other adsorber. To carry out the experiment a test bench was built, consisting of two cylindrical adsorbers filled with activated carbon, condenser, evaporator, oil heater and two oil coolers. Thermal oil circulation was responsible for providing and receiving heat from adsorbers. In order to perform the correct action a special control algorithm device was developed and implemented to keep the temperature in the evaporator at a preset level. The experimental results show the operating parameters changes in both adsorbers. Obtained COP (coefficient of performance) for the cycle was 0.13.

Keywords: refrigeration, adsorption systems, experimental study, AC-methanol pair

1. INTRODUCTION

At the Warsaw University of Technology, the adsorption refrigeration systems have been investigated for over 10 years with the object of using them in district heating systems and solar cooling (Chwieduk, 2012; Grzebielec and Rusowicz, 2004; Grzebielec and Rusowicz, 2013; Grzebielec et al., 2012; Grzebielec et al., 2014; Grzebielec, 2009; Jaworski et al., 2014). In the first phase, the refrigeration systems were modelled and examined with the whole bed considered to be a substance at a uniform temperature (Grzebielec, 2009; Grzebielec and Rusowicz, 2004).

Figure 1 presents an overview of the regular type of adsorption device. Figure 2 shows thermodynamics states of adsorbers during the operation. The device works on a cycle basis (Gwadera and Kupiec, 2011; Wang et al., 2010). During the first half-cycle adsorber 1 is being heated (line A-B-C in Fig. 2), while adsorber 2 is being cooled (line C-D-A in Fig. 2); during the second half-cycle adsorber 1 is being cooled, while adsorber 2 is being heated. It is relatively easy to build such devices, but quite difficult to ensure that they perform efficiently (Grzebielec and Rusowicz, 2004; Gwadera and Kupiec, 2011). The first difficulty is to supply the energy uniformly to the whole bed (Cyklis and Kantor, 2012; Cyklis et al., 2012a; Cyklis et al., 2012b; Cyklis et al., 2013); the second one to recover the heat between the adsorbers, which can improve the efficiency of the whole system by about 30% (Cacciola and Restuccia, 1995; Lu and Wang, 2013). Adsorption units that work in basic cycle have large possibility to recover heat from one adsorber to

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the second one. During the process, the first adsorber has to be cooled, when the second has to be heated. Temperature difference, between point A and C (Figure 2) is large enough to transport heat from one bed to another. Creating such heat recovery system in the beginning phase of the process no external heat source or external cooling systems are necessary.
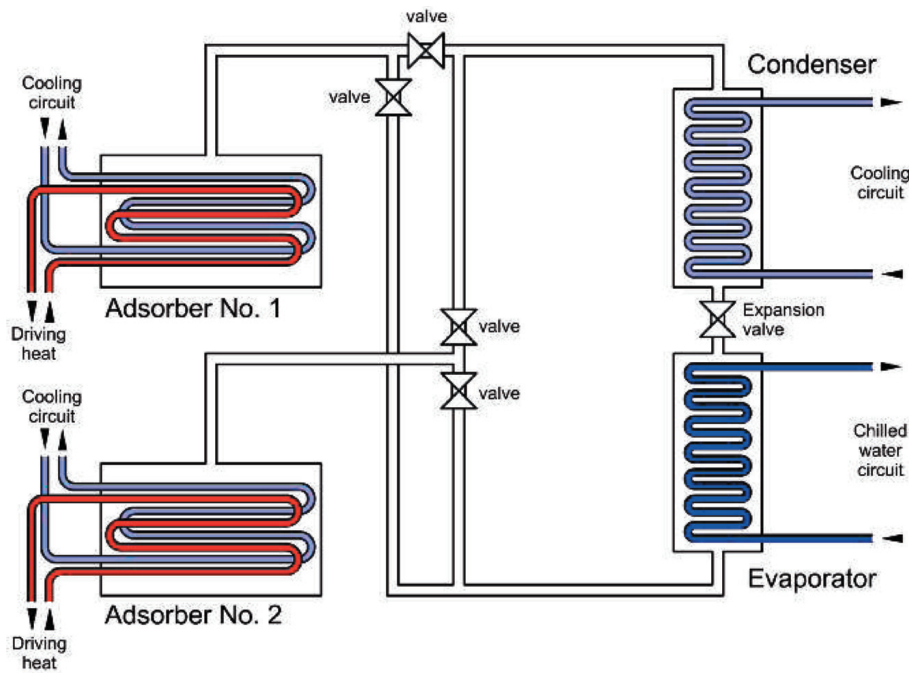

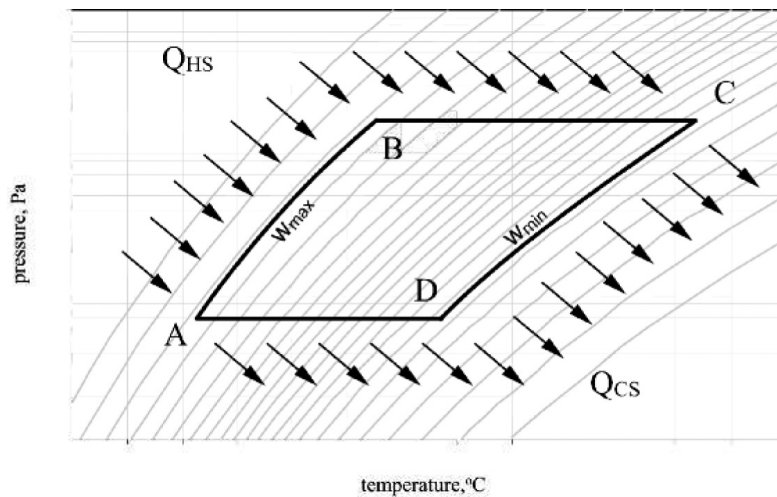Fig. 1. An overview of an adsorption refrigeration device

Fig. 2. Adsorbers uptake changes during the operation

Enhancing the performance of the adsorption refrigeration device consists in changing the adsorber construction. In the new construction, a significant thermal gradient occurs along the adsorption bed. Additionally, an intermediate medium (oil) is introduced to supply the heat to the adsorbers and to receive it back from them. At the same time, it serves as a transfer medium used in the heat recovery processes between the adsorbers.

An overview of the thermal wave device type (Christy et al., 2001; Shelton, 1990) is shown in Fig. 3, while the temperature variation along the oil circulation is depicted in Fig. 4. As can be seen in Fig. 4, when the direction of oil circulation is reversed, the medium recovers the heat from one adsorber and transfers it to the second one.
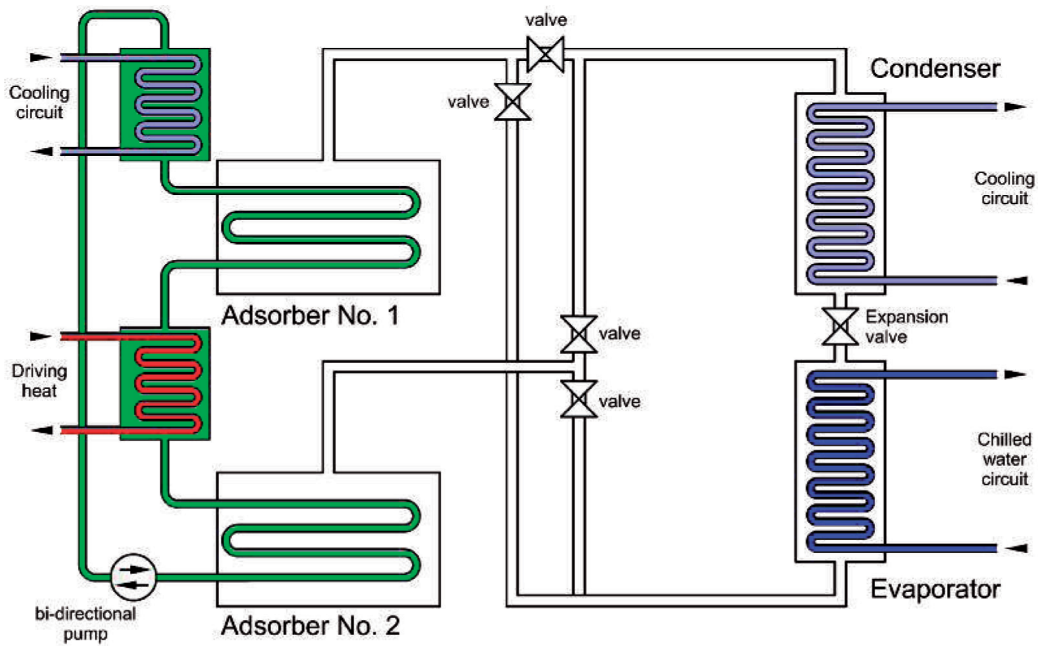
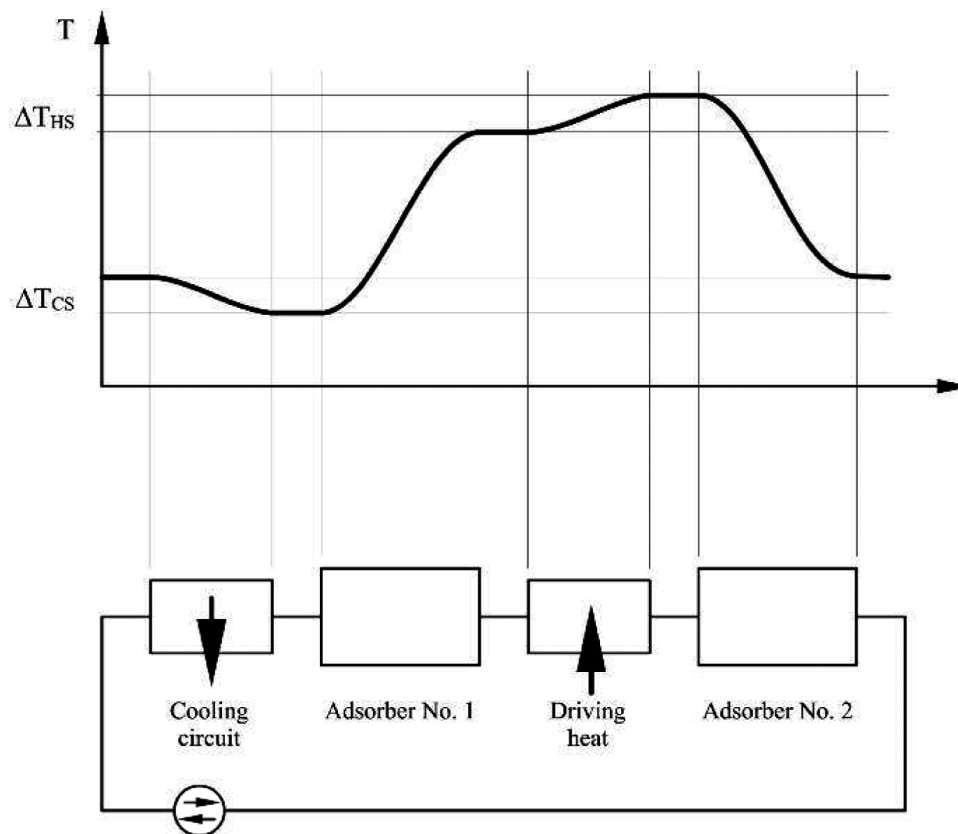Fig. 3. Thermal wave adsorption refrigeration device

Fig. 4. Temperature variation in the oil circulation system

2. CONSTRUCTION OF THE APPARATUS

The thermal wave adsorption refrigeration device was designed and built at the laboratory of the Division of Processes Equipment and Cooling, Faculty of Power and Aeronautical Engineering, Warsaw University of Technology. The aim of the project was to design a device that would be able to work in two types

of installation. One of them will be a trigeneration system. The second system will be a pre-cooler in an oxygen liquefaction used in oxygen-combustion (Job et al., 2013). Activated carbon and methanol were selected as the working pair, as the desired evaporation temperature was less than 0°C (El-Sharkawy et al., 2009; Wand et al., 2009). The installation designed to examine this device comprises three circulation systems: oil, methanol and water. Figure 5 shows an overview of the adsorber. The change in the adsorber construction is the main difference between this adsorption apparatus and the one that was used earlier at the laboratory (Grzebielec, 2009).
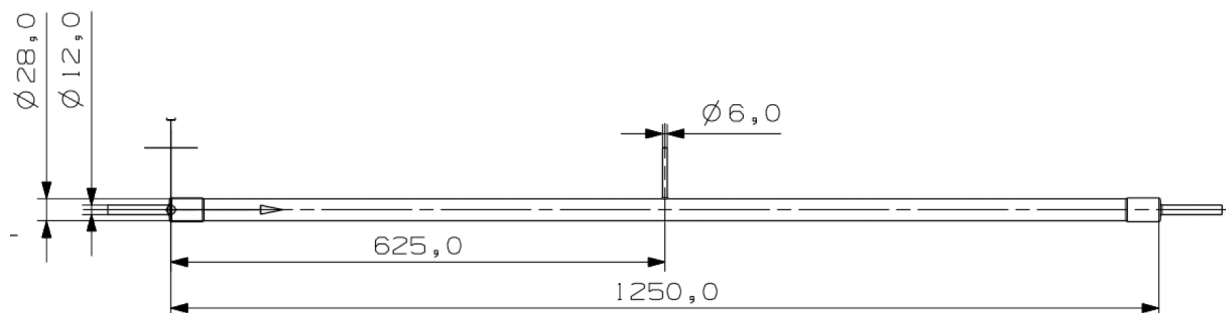

Fig. 5. Adsorber design overview

The adsorber consists of an inner brazen tube with 12 mm out diameter, through which the working medium (oil) flows, supplying the heat to the bed or taking the heat back from it. The inner tube is mounted inside an outer tube with 28 mm out diameter. Between the tubes there is an activated carbon bed. In the centre of the inner tube a pipe is soldered, through which the methanol flows to and from the bed. The whole assembly is housed in tight foam insulation. The heat transfer should occur between the adsorbent bed and the oil rather than between the bed and the air surrounding the adsorber. The cross-section of the adsorber is presented in Fig. 6.
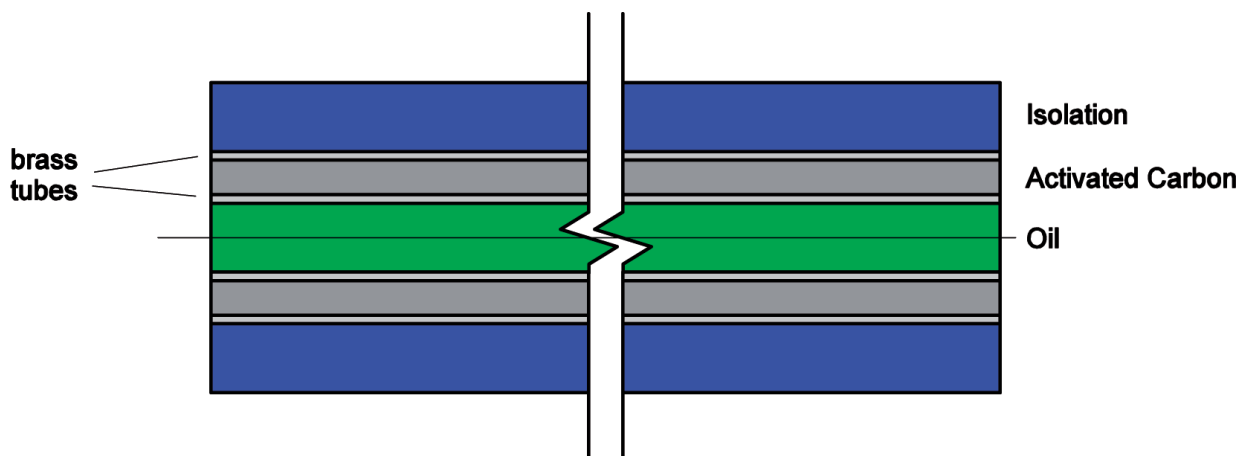

Fig. 6. Adsorber cross-section

2.1. Oil circulation

The oil circulation system (Fig. 7) comprising a pump, an oil surge tank, and five heat exchangers consisting of two coolers, two adsorbers and one oil heater core. An assembly of four solenoid valves was mounted to control the direction of oil flow; switching the valves makes the oil flow to the right or to the left. The open surge tank protects the system against an uncontrolled pressure rise, and compensates for thermal expansion of the heat carrier.
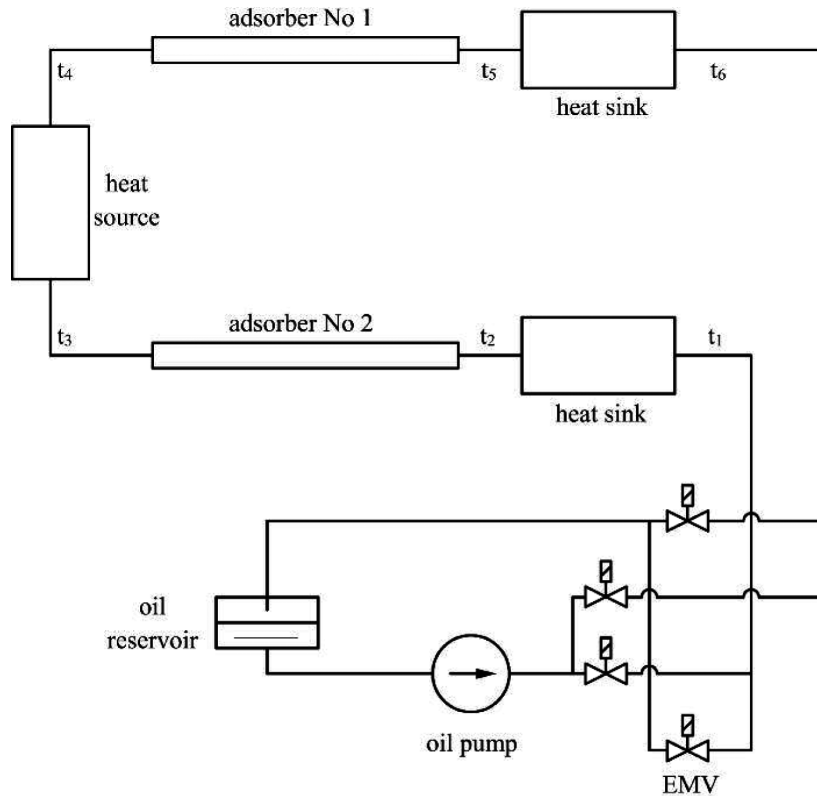
Fig. 7. Oil circulation overview, t_1 to t_6 indicate oil temperature recording points

2.2. Methanol circulation

The methanol circulation system is presented in Figure 8, the methanol being the main working medium here. The methanol circulation system comprises a set of solenoid valves and non-return valves which provide a connection between the adsorbers on one side and the condenser and evaporator on the other. This set makes the stream of methanol from the desorbing bed always flow to the condenser, and then, after flowing through the electronic expansion valve, to the evaporator. Finally the working medium is adsorbed by the second adsorber. In Fig. 7, temperature and pressure measurement points are also indicated.
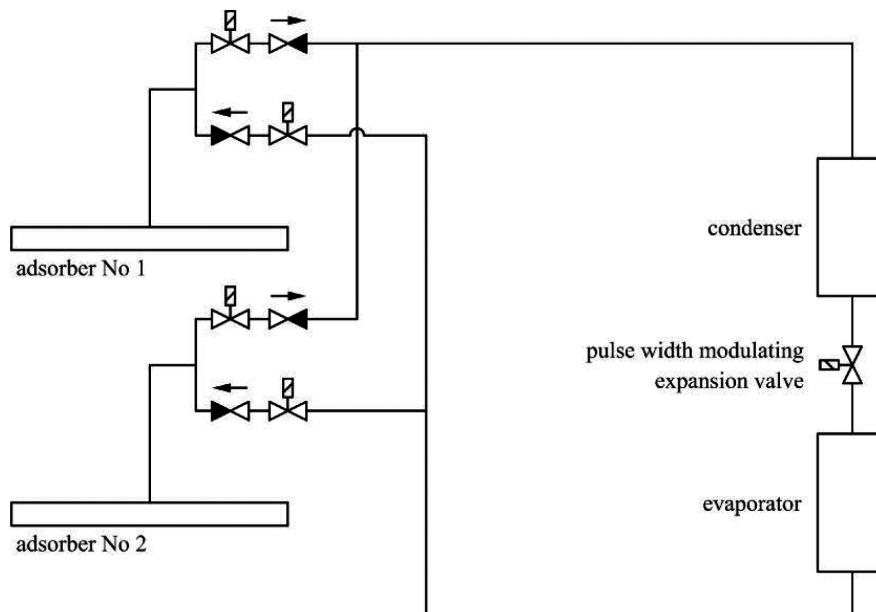

Fig. 8. Methanol circulation

2.3. Water circulation

In order to facilitate determination the power of each heat exchangers, a water circulation system was introduced. The water flows through condenser, evaporator and both heat sink exchangers. The temperature were measured before and after all of these heat exchangers, together the water volumetric flux. The data obtained was used to calculate heat flux in every heat exchanger.

3. METHODOLOGY

In the context of experimental studies a continuous oil temperature were measured at the points shown in Fig. 7. There was also measured temperature of the water before and after all heat exchangers through which water flows. These parameters were measured in order to determine the instantaneous heat flux of heat exchangers according to Eq. (1):

$$\dot{Q} = \dot{m}\, c_p \left(T_{out} - T_{in} \right) \tag{1}$$

where c_p – specific heat of water and oil was dependent on a logarithmic average temperature in the exchanger. Mass flow was determined on the basis of the volumetric flow rate q according to Eq. (2).

$$\dot{m} = q \cdot \rho \tag{2}$$

where ρ – density is determined based on the fluid temperature at the measurement point. Water flow was determined using rotameters (Fig. 9). In contrast, the oil flow rate was determined by measuring the known volume filling time. Volume flow rate was measured during flow in both directions. In both cases, the measured value equals 1.7 l/min. For the temperature measuring oil density was 880 kg/m^3 and that of the water 999.1 kg/m^3.
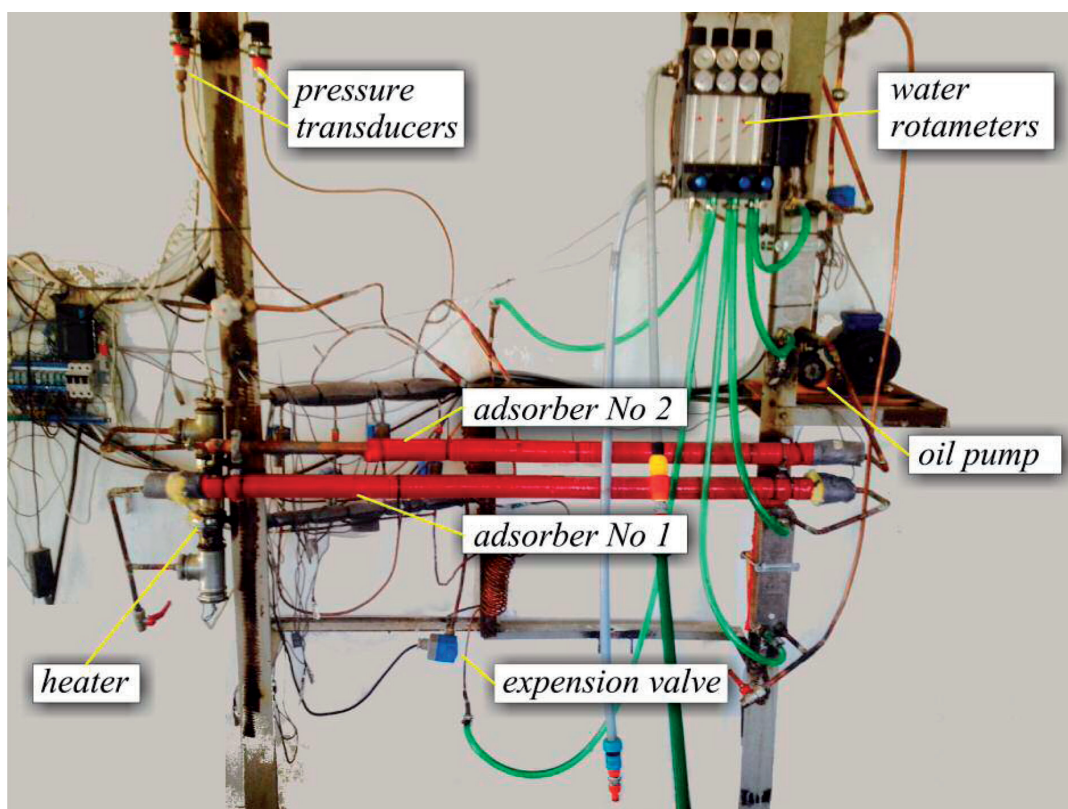

Fig. 9. Laboratory stand

For temperature measurements NTC5 temperature sensors were used with measurement uncertainty of 1%. Filling time was measured with accuracy of ±1s and the tank volume was 2 liters. During experiment the pressure of methanol in the adsorbers was measured with piezoelectric quartz pressure transducer having an accuracy of measurement of ±0.3%. On the basis of the pressure was determined saturation temperature to determine the temperature of evaporation and condensation in accordance with equation (Cacciola and Restuccia, 1995):

$$\ln P = a + \frac{b}{T} \qquad (3)$$

where for methanol the coefficients were $a = 20.84$ and $b = -4694$ respectively. In Eq. (3), temperature is given in Kelvin degrees and pressure is calculated in mbar. The temperature determined from the measured pressure enables estimation of the heat source requirements the adsorption device can co-operate.

4. RESEARCH RESULTS

From the experiments performance curves of the adsorption refrigeration device could be recorded. The pressure in each adsorber was measured in order to determine the working temperatures of the evaporator and the condenser. The experimental data are reported in Fig. 10. Figures 10 and 11 show four full half-cycles, during the further course of the experiment the results are reproducible and characteristics are similar to those presented.

A pulse type electronic expansion valve was used in the device, so that the pressure and evaporation temperature could be controlled using researchers' software. Since water was used as the cooled medium in the experiment, the boiling point of methanol was set to be 10°C. The pressure level was used to control the signal for opening or closing the valves.
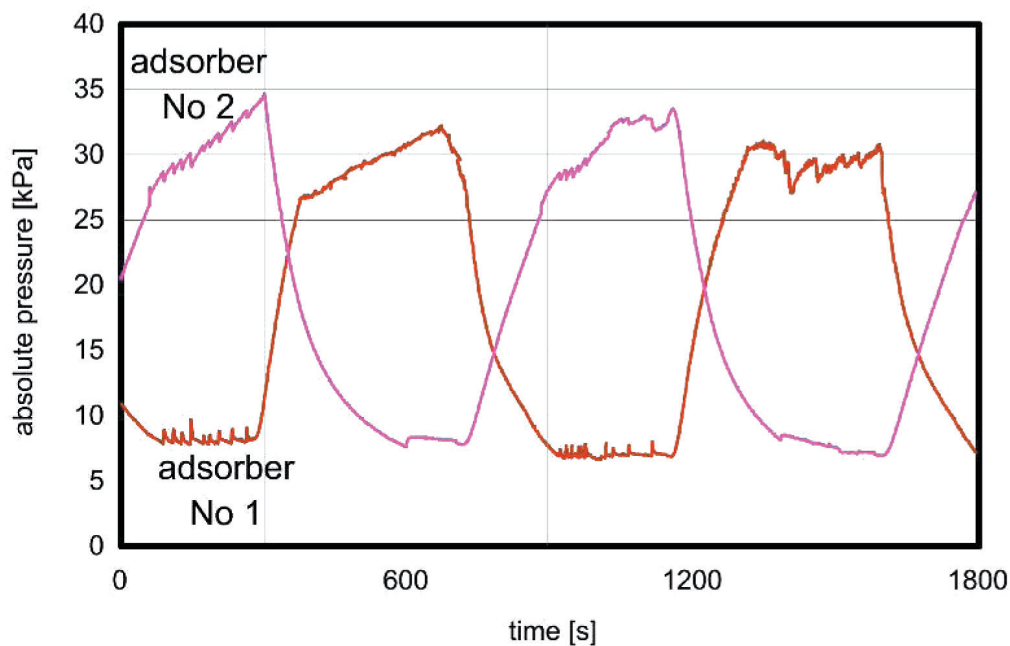

Fig. 10. Pressure variations in the adsorbers during the device operation

Oil temperature measurements at four points are presented in Fig. 11. In the first half-cycle the temperature difference between t_4 and t_5 represents heat of desorption while the temperature difference between t_3 and t_2 corresponds to heat of adsorption in the second adsorber.
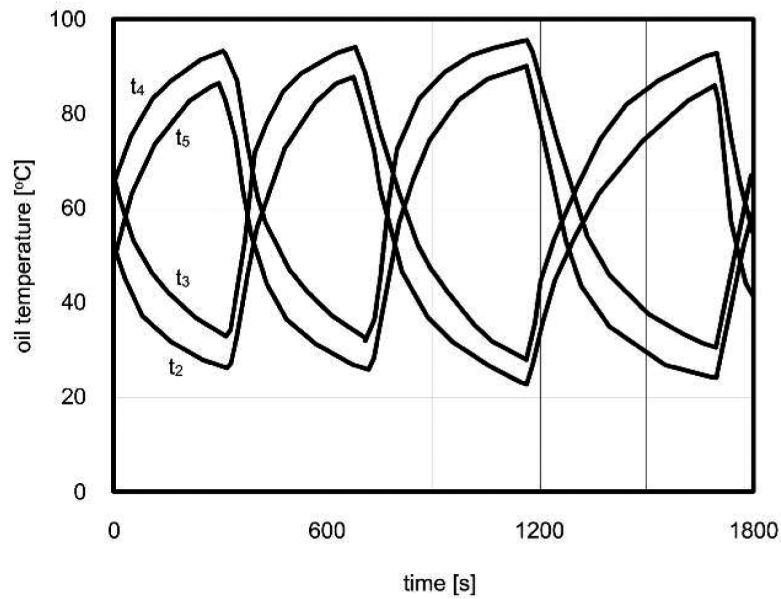
Fig. 11. Temperatures in the oil circulation system

Based on the measurements, real instantaneous powers of each component of the system could be determined. Thermal power of heat source and cooling capacity during the experiment are shown in Fig. 12.
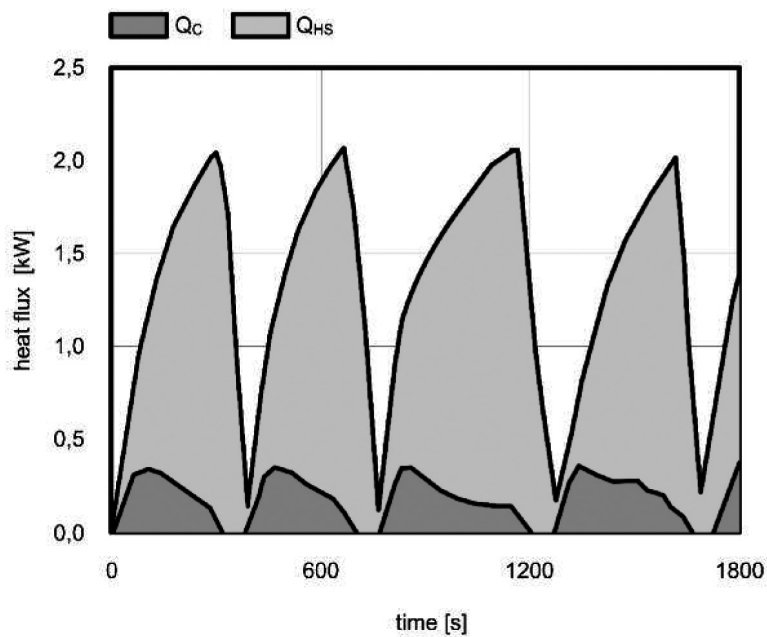

Fig. 12. Thermal power of heat source and cooling capacity

The coefficient of performance *COP* of adsorption devices is determined in a different manner than for other refrigeration cycles. It has to be calculated using Eq. (4)

$$COP = \frac{Q_C}{Q_{HS}} = \frac{\int \dot{Q}_C dt}{\int \dot{Q}_{HS} dt} \qquad (4)$$

where Q_C is the amount of heat received in form of cooling for a certain period of time, and Q_{HS} is the amount of heat supplied to the system at the same time by a heat source. With measurements of instantaneous thermal power, the amount of heat can be determined by integration of the power over time

using a trapezoidal method. For the investigated case the average value of *COP* amounted to the level of 0.13, while in the previous research (Grzebielec, 2009) on a regular type adsorption device in the same conditions *COP* was 0.04.

5. SUMMARY AND CONCLUSIONS

In this article the results of the experimental research concerning a state-of-the-art thermal wave adsorption refrigeration device are presented. Due to different working temperatures of the adsorbers, the change in the thermal power of each system component could be determined. The measurement results are presented in Figs. 10–12 showing four half-cycles of the adsorption device operating under steady state conditions. In the following experiment, the cycle was repeated, so that these results can be regarded as representative for the calculation of the coefficient of performance of the adsorption refrigeration apparatus.

The coefficient of performance COP of 0.13 which makes this solution does not seem to compete with other cooling cycles. Such a low coefficient of performance due to the excessive duration of the half cycles represents approximately 6–7 minutes. According to Figure 11 it can be concluded that the coefficient of performance will be much higher for a shorter time of a half-cycle, because in the first minutes the thermal power of the heat source is low and the cooling capacity is the highest. In the next part of the cycle cooling capacity decreases as a result of decreasing of desorption. Mass flow of refrigerant in the condenser and the evaporator is low. At the same time heating power is increasing till the end of half cycle. On the basis of these observations, it is believed that the cycle time must be shorter.

SYMBOLS

a,b	coefficients, [–]
c	specific heat, [J·kg^{-1}·K^{-1}]
COP	coefficient of performance, [-]
EMV	electromagnetic valve,
$\dot{m}$	mass flow, [kg·s^{-1}]
P	pressure, [Pa]
q	volumetric flow rate, [m^3·s^{-1}]
Q	heat, [J]
$\dot{Q}$	heat flux, [J·s^{-1}]
t	time, [s]
T	temperature, [°C]
w	uptake, [kg$_{methanol}$·kg$^{-1}_{AC}$]

Greek symbols

ρ	density, [kg·m^{-3}]

Subscripts

AC	activated carbon,
HS	heat source,
C	cooling,
CS	cooling system,
in	inlet,
min	min value,
max	max value,
out	outlet,
p	constant pressure.

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