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Energy Recovery Methods in Adsorption Refrigeration Units

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Abstract. Adsorption refrigeration systems, as opposed to absorption type operate in a cyclic manner. The result is that at the beginning of each process must be fed into the adsorber state in which they will adsorb or desorb a refrigerant. In the case of two adsorbers at the start of a cycle, the one of the adsorber must be refrigerated while the second has to be heated. These processes are causing unnecessary energy loss. The aim of the work is to show how these processes can be connected and the heat received from one adsorber is transported to another adsorber. As part of the study, the heat and mass recovery processes will be considered. It turns out that in the thermal wave type systems, it is possible to recover more than 25% of the energy lost to bring the adsorber to the states in which they will operate efficiently to desorb and adsorb refrigerant. That is, it is possible to improve the efficiency of the adsorption refrigeration unit using the proposed improvements.

Keywords: refrigeration, adsorption refrigeration, energy efficiency.

Introduction

Adsorption refrigeration machine is one of the types of sorption devices. Development of sorption unit is associated with synthetic refrigerant phase out (Kuczyński *et al.* 2013; Śmierciew *et al.* 2017). Unlike the more known absorption devices it operates in a cyclical way (Rusowicz, Ruciński 2011). The result of such fact is that its construction is different than construction of the absorption device. In the first halfcycle the refrigerant flows from the desorber into the adsorber. In the second halfcycle absorber and desorber changes its roles and the refrigerant starts to flow in the opposite direction (Xu *et al.* 2016). Figure 1 shows adsorption refrigerating appliance composed of two adsorbers. A set of valves allows that in both cases the refrigerant flows through a condenser, expansion valve and evaporator (Cacciola, Restuccia 1995).

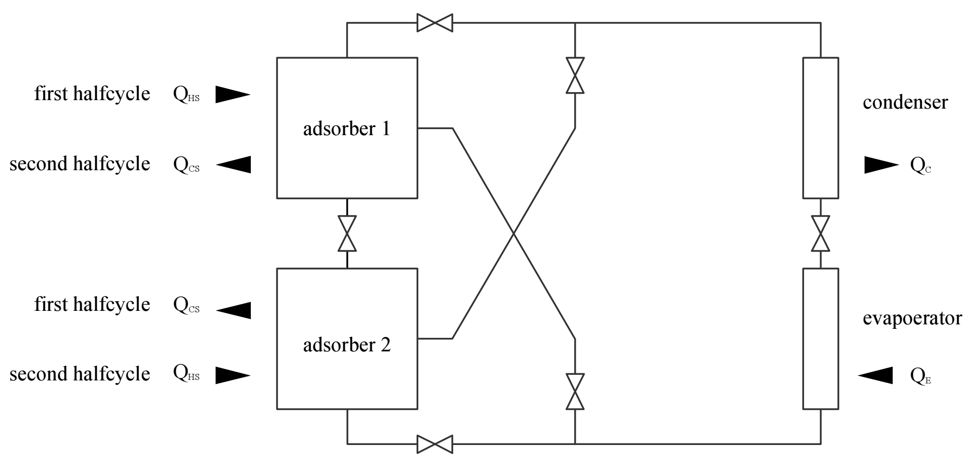

Fig. 1. Two beds adsorption refrigeration unit

Adsorption refrigeration units are characterized by a lower energy efficiency ratio *EER* (energy efficiency ratio) than absorption units, but they have one important advantage – they can operate at lower driven temperature. Absorbers type refrigerator require that the temperature of the heat source is at least 90 °C, the adsorption units are able to operate from temperatures at 50 °C (by suitably chosen working pair) (Freni *et al.* 2016; Wang *et al.* 2014). This advantages make it possible to be useful as a part of direct cooling system connected with direct heating system at the end user (Jędrzejuk, Rucińska 2015).

Figure 2 presents unit beds states during operation. First adsorber starts working from the point A (at that time the second adsorber is at the point C). Line A-B presents the pre-heat of the bed – during the heating does not occur refrigerant desorption. This part of operation is called isosteric transformation. After crossing point B refrigerant starts to desorb from the bed. Refrigerant as vapor flows into the condenser. At the same time temperature of the bed all the time increases from T_B to the temperature T_C. The pressure is kept at constant level as a reason of condenser and expansion valve operation, which regulate the outflow of steam.

At the same time the second adsorber starts operation from the point C, where the adsorber is firstly cooled, and beyond the point D, the bed starts to absorb refrigerant incoming from the evaporator. Process requires receipt of heat to the outside.

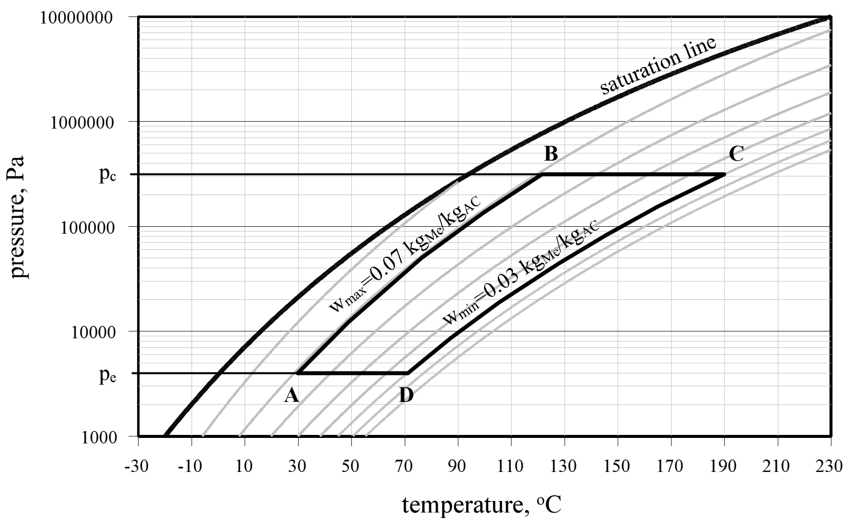

Fig. 2. Adsorber beds states during operation

The cooling energy efficiency ratio *EER* is determined in other way than in the case of other refrigeration systems, in which there is constant heat flux in all parts of the apparatus (Cyklis, Janisz 2015; Fernández *et al.* 2015; Jaworski *et al.* 2016; Kuczyński *et al.* 2013). In the case of the adsorption refrigeration unit there should be used heat instead of the heat capacity (Eq. (1)) because the heat flux in every heat exchangers change during operation.

$$EER = \frac{Q_E}{Q_{HS}} \tag{1}$$

Wherein, the amount of heat taken at the evaporator can be determined from Eq. (2):

$$Q_E = m_{ads} \cdot h_{fg} \cdot (w_{max} - w_{min}) \tag{2}$$

where the amount of refrigerant which flows from one to another bed can be determined based on the bed uptake before w_{max} and after desorption w_{min}, mass of the dry bed m_{ads}. The latent heat of evaporation is represented by h_{fg}. The amount of heat associated with the heat source Q_{HS} contains a number of ingredients (Cacciola, Restuccia 1995).

$$Q_{HS} = Q_{is} + Q_{des} + Q_{b,ads} + Q_{b,ref} \tag{3}$$

where Q_{is} is heat of isosteric transformation, Q_{des} – heat needed to refrigerant desorption from bed, $Q_{b,ads}$ – heat used for warming dry bed from temperature T_B to temperature T_C, $Q_{b,ref}$ – heat used to warming adsorbed refrigerant inside bed from temperature T_B to temperature T_C.

Internal energy recovery

Energy efficiency is the main issue of any industrial and commercial applications (Grzebielec *et al.* 2014; Jędrzejuk, Dybiński 2015; Rusowicz *et al.* 2013). Due to the fact that the first stage of adsorption unit operation requires heating one adsorber and a second adsorber has to be cooled the whole device has a high potential of the internal energy recovery (Chekirou *et al.* 2016; Qu *et al.* 2001).

Heat and mass recovery

The recovery of heat and mass is the most common method used in the adsorption equipment to improve energy efficiency ratio *EER* (Ruciński *et al.* 2016; Rusowicz *et al.* 2014). Until the temperature of the beds are different there is a theoretical possibility of transferring heat from one adsorber to another without heat supply from outside the system (Wang *et al.* 2014; Xu *et al.* 2017). Likewise, pressures – wherein the process is associated with the mass recovery because it causes change in the degree of initial refrigerant uptake inside the beds. Figure 3 presents a change of adsorbers thermodynamic states for heat and mass recovery process. As shown in Figure 3. the first stage of process is mass recovery. Absorbers are connected directly without the condenser and evaporator. This allows the refrigerant to flow from the adsorber 2 into the adsorber 1. This causes the pressure in the adsorber 2 is changed from point C to C', and in the adsorber 1 from A to A'. Changing the amount of refrigerant in the adsorbers causes a slight change in temperature of bed as a result of adsorption and desorption. In the next step connection between adsorbers is closed and the heat recovery process starts. Using secondary fluid, heat is transferred from the second into the first adsorber. Ideally, change of stage of the first adsorber cccures from the point A' to point E, and for the second adsorber from point C' to point F.

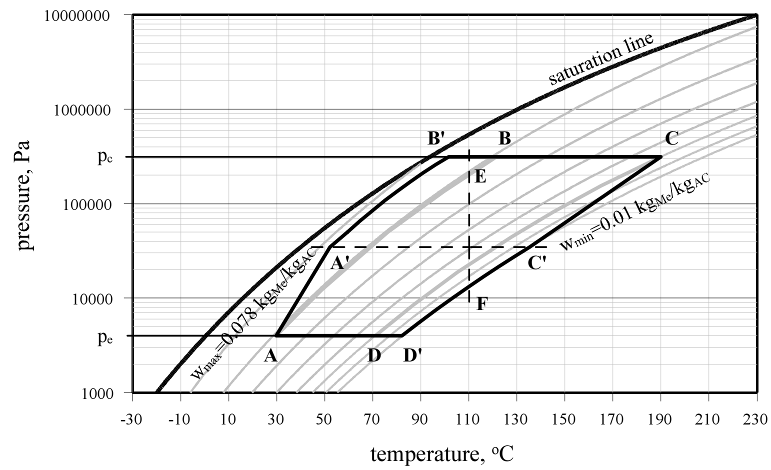

Fig. 3. Heat and mass recovery in two beds adsorption unit

From a technical point of view, there is needed extra energy to move heat from one to another adsorber. On the end of process there is a difference of bed temperature at level of 10 to 30 K. This is a result that beds are porous materials and are characterized by small heat conductivity factor. Besides, heat recovery is usually implemented by secondary fluid as the thermal wave type (Grzebielec *et al.* 2015a). Mass recovery does not cause as many problems as to its use there is enough pipe connecting the two adsorbers with shutoff valves.

Cascade adsorption refrigeration unit

Another solution for internal energy recovery inside the adsorption unit is the use of the third bed. Bed operating at different temperatures and the absorbent material. An example of such solution is the cascade adsorption units presented in Figure 4.

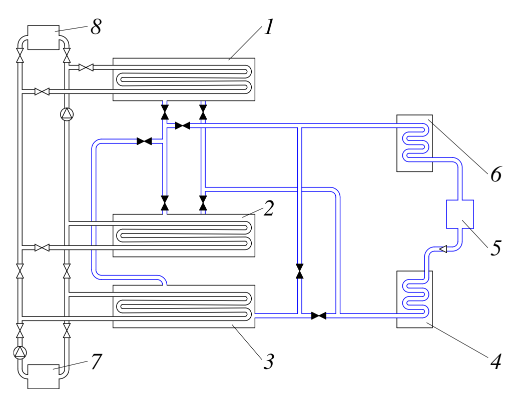

Fig. 4. Cascade adsorption refrigeration unit 1 – adsorber filled with zeolite 2 – adsorber filled with zeolite, 3 – adsorber filled with silica gel, 4 – evaporator, 5 – refrigerant tank, 6 – condenser, 7 – heat source, 8 – heat sink

Cascade system like conventional adsorption refrigeration unit also operates in a periodic cycle. The entire cycle consists of four stages. Stages of operation is plotted on diagram (Fig. 5). This solution is only possible for some working pair. Looking at the Figure 2 and 3 is easy to see that for a methanol-AC pair is impossible. However, for solutions working on a water-zeolite or water-silicagel pair it is much as possible.

Stage 1

The first stage begins when the absorbers are in the following states:

adsorber 1 corresponds to the state of point I (Fig. 5);
adsorber 2 corresponds to the state of point E (Fig. 5);
adsorber 3 corresponds to the state of point C (Fig. 5).

The first process which takes place during operation is the pressure equalization process. High pressure gas flows from the adsorber 1 to the adsorber 2. Figure 5 corresponds to the warped I-J and E-F. In the meantime, the adsorber 3 is cooled (curve C-D-A). When the pressure drops due to the adsorption of the vapor pressure of full adsorber is connected to the evaporator (point D). After leveling the pressure in the adsorbers 1 and 2 pipe connecting the two adsorbers is closed. The next part of this stage is to cool the adsorber 1 and heating absorber No. 2. As the temperature of the adsorber 1 is higher than the absorber 2 can use the heat received from the adsorber 1 to heat absorber No. 2. This process represents the curves of J-K-M, and F-G-H. When the pressure in the adsorber 2 rises to the condensation pressure p_C adsorber is connected to a condenser.

Stage 2

In the second stage, the adsorber 1 still needs to be cooled, while adsorber 2 heated. Adsorber 3 has to be heated from point A to point B via C. The temperature of the adsorber 1 is significantly higher than the temperature of the adsorber 3, heat received from the adsorber 1 to the heat absorber No. 3. This process is illustrated as curve A-B for adsorber 3 and the curve M-E for adsorber 1. In the adsorber 2 as a result of desorption the refrigerant is flowing into the condenser. Temperature of refrigerant is getting higher. Since it is much higher than the temperature in the adsorber 3 may be used to heat them. The refrigerant, therefore, before reaching the condenser flows through the adsorber No. 3. In the Figure 5 this process is corresponding to the I-H curve for the adsorber 2 and B-C for the adsorber 3.

Stage 3 and 4

The other two stages are analogous to the first two except that the adsorber 1 acts as an absorber 2 while the adsorber 2 has adsorber 1 role.

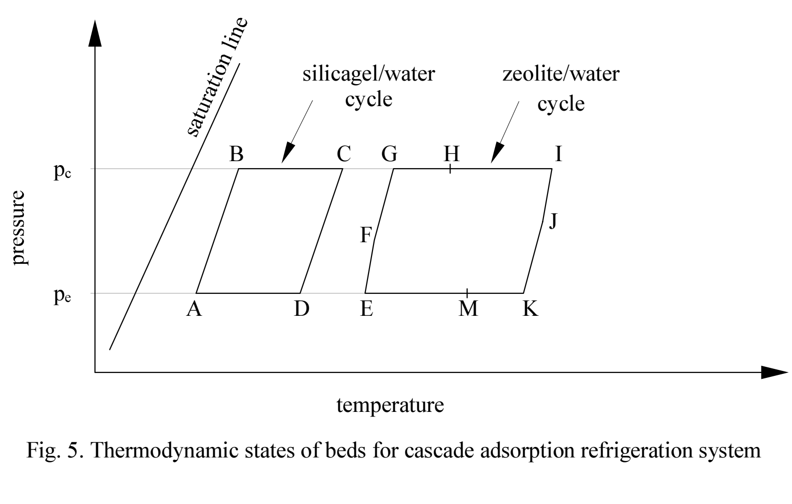

Fig. 5. Thermodynamic states of beds for cascade adsorption refrigeration system

Calculation results for internal recovery system

Cascade adsorption refrigeration units are able to achieve EER above 1, what for adsorption devices is a very large value. It should be noted that this value is obtained for the high temperature heat source. Nevertheless, the EER much larger than in the previously mentioned examples. Unfortunately, the main drawback of this solution is the low value of the SCP specific cooling power (W/kg_{ads}). It is several times lower than for the absorption unit. And this means in practice that the device must be precisely those few times larger and heavier to get exactly the same cooling capacity.

In Figure 6 there is shown the heat and mass recovery for unit driven by lower temperature than that of the layout pattern 3. It is clear that the potential for heat recovery is much lower (Grzebielec *et al.* 2015b).

Analyzing the refrigeration unit operating on a working pair AC-methanol with beds of 1 kg it was found that it is possible to improve the EER by 25% (from 0.183 to 0,229) when the driving temperature exceeds 250 °C. At a driving temperature of 140°C EER increases by 5% (from 0.151 to 0.158). Calculation was made for thermal wave type adsorption unit using finite difference method. The unit was detailed described in Grzebielec *et al.* work (Grzebielec *et al.* 2015a). In both cases, there was not included the energy required for transport heat from one bed to another.

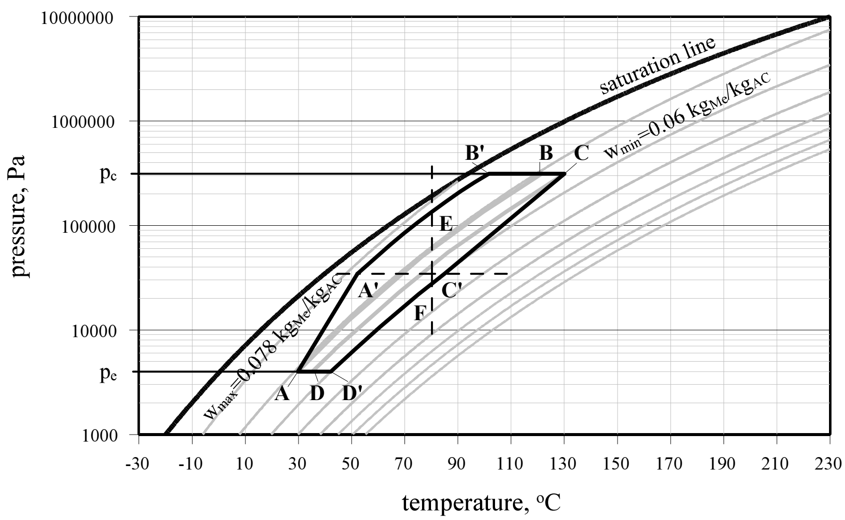

Fig. 6. The potential of heat and mass recovery for lower driven temperatures

Results

The analysis shows that heat recovery processes make sense only in the systems in which it is available high temperature of heat source. Calculations made for 1 kg Activated Carbon beds shows that for driving temperatures at 140 °C causes heat recovery below 5%, which is less than additional costs for transport heat from one adsorber to another. With driving temperatures at level of 250 °C there can be achieved improving the efficiency of 25%.

The cascade adsorption refrigeration system for regular driving needs high temperature heat source, which also prevents the use of such systems in the low driven temperature units.

The results show that meaningful improvement in efficiency is only for a high temperature heat source. However, when there is a source of heat at a high temperature exceeding 100 °C absorption device has larger EER, even if the adsorption device includes mass and heat recovery. The result is that the use of adsorption refrigeration equipment is very limited, and a commercial sense only in case of low temperature heat sources, and, in this case the method of improving the efficiency often do not produce the desired effect.

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