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DETERMINATION OF EFFICIENCY LIMITS FOR THE TWO-BED ZEOLITE-WATER ADSORPTION CHILLER

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ABSTRACT

To find a practically reachable efficiency limit an optimization of the internal process has to be performed, which rests on the interaction between two thermodynamic quantities: performance of the heat exchangers and their size that is required to obtain this performance.

In this paper the influence of adsorption system limitation, which results from the periodic operation, i.e. equal construction of all adsorbers, inert mass, effectiveness of heat recovery phase between the adsorbers, etc., on its optimized performance is presented. The study is performed on a zeolite/water adsorption chiller with the heat recovery between the two adsorbers, which are working in a shifted phase. It is shown that theoretically the COP as high as 0.7 could be reached if the system limitations are not considered. The presented optimization method gives us a clearer picture which system efficiencies could be reached for the specific case of external conditions and system limitations.

1. INTRODUCTION

Commercial success of solid-gas heat pumps and chillers is to a large extent a consequence of system dynamics: a discontinuous operation requires a different system realization, which diminishes a system performance and increases a system cost. To answer this question a thermo-economic optimization (Riesch, 1991; Ziegler, 1997; Berlitz *et al*., 1999) can be applied to an adsorption device also (Cerkvenik *et al*., 2001). The goal of the thermo-economic optimisation is to find an optimum relation between a running and investment cost of the device. Lower running cost, can be attained by higher coefficients of performance COP, e.g. by multistaging. Minimizing the required heat exchanger area is another important goal, because the heat exchangers are to a large extent responsible for the investment cost (Berlitz *et al*., 1999). In our case the minimization of the heat exchange area, for the given COP, results from thermodynamic relations between the heat exchangers. This relation, a square-root criterion, can be used to present the optimum plot of the running cost (COP) against the investment cost (heat exchange area).

Adsorption chillers were already optimized with this method (Cerkvenik *et al*., 2001). Due to the complexity of their process dynamics, the work has been limited to the cycles, with a limited heat recovery between adsorbers. To overcome this problem we decided to treat the adsorption system like an absorption one. This implies that the process has to be handled as if it is operating continuously. Of course, this is not realistic, but it helps to understand some important interdependencies. The simplification brought about some new difficulties also, especially with the definition of the internal heat recovery between the adsorbers. The resulting COP values were low due to the limited concentration difference, which was used in calculation.

In this work an adsorption cycle operating with two counter-phase adsorbers and full heat recovery between them is discussed. If compared with previous work (Cerkvenik *et al*., 2001) is the calculation process extended to a larger concentration differences, which results in additional latent heat recovery in the calculation procedure. At this stage we restrict ourselves to the processes with standard heat recovery, without internal mass recovery only.

2. DETERMINATION OF THE PROCESS

To perform the calculation of the device, the internal process has to be determined first. As a boundary condition, the external inlet and outlet temperatures of heat sinks and sources are taken as constant. Furthermore, to determine the quantity of the heat exchanged on the main heat exchangers, the overall heat transfer coefficients are assumed also. The goal of the calculation is to determine the pressure and temperature levels for a specific adsorption device, which would operate within the given external temperature levels. To achieve this in the case of the single-stage sorption devices basically five parameters are required (Cerkvenik, 2001).

As it is known, the single-stage device operates between two pressure levels, e.g. evaporation and condensation pressure level. With the fixation of the two pressure levels the operational range of the specific device is set. They are usually fixed with a mean internal temperature of the evaporation t_{ev} and of a condensation temperature t_{co}. To set the internal process three additional parameters or equations are required. The relation between a lower pressure level (adsorber A1-evaporator heat exchanger pair) and upper pressure level (adsorber A2-condenser heat exchanger pair) is carried through a difference in adsorbed quantity during a single sorption phase, which is called the concentration difference Δx_{ads} also. It is assumed that the concentration difference is equal for the both adsorbers in both sorption phases, adsorption and desorption phase.

The fourth independent parameter depends on the fact if the internal heat recovery between the adsorbers exits. In conventional design the heat recovery occurs after the finished sorption phase (points 1 and 4, Figure 1) and it can continue until the temperature in both adsorbers reaches the mean temperature level t_m (Figure 1). At this point the maximal effectiveness of heat recovery $\eta_{Hrec}=1.0$ is reached. This state is theoretically possible only. The heat recovery effectiveness is defined as a ratio between the heat, which is transferred and the maximal quantity of heat, which could be transferred during the heat recovery phase

$$\eta_{Hrec} = \frac{Q_{Hrec}}{Q_{max,\,Hrec}}.$$ (1)

The recovered quantity of heat is defined as a sum of the sensible heat and latent heat of adsorption, which is also possible to recover in the case of overlapping temperatures (case B, Figure 1)

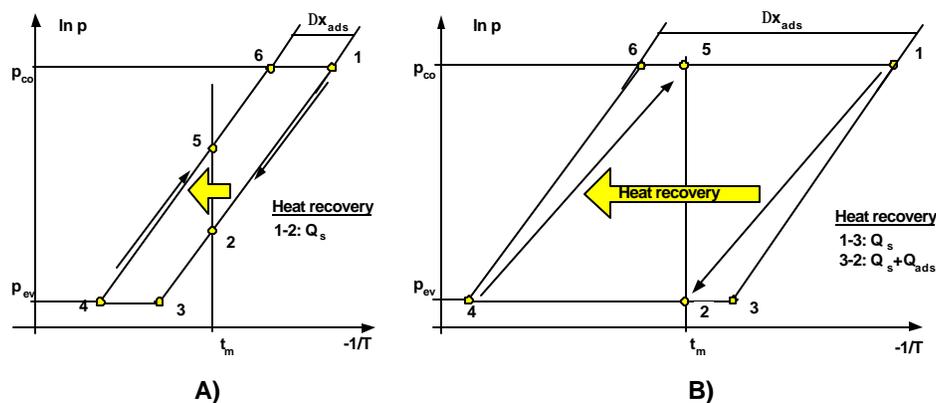$$Q_{Hrec} = Q_s + Q_{ads}.$$ (2)

Figure 1: Process in adsorbers in pressure-temperature diagram. Two distinct cases for the maximal heat recovery between the adsorbers.

The sensible heat is always possible to recover, independently of the concentration difference Δx_{ads}, because the adsorber has always to be cooled down for the beginning of the next adsorption phase (1-2 and 4-5 in both cases, Figure 1). The latent part Q_{ads} depends mostly on the concentration difference. If the concentration difference is low (Cerkvenik *et al.*, 2001) the theoretical mean temperature t_m is not lower than the temperature at which the adsorption process begins (point 3 in case A, Figure 1). Therefore no latent heat could be transferred to the heated

adsorber (4-5, Figure 1). In the case of the higher concentration differences (case B, Figure 1) a part of the heat of adsorption could be transferred also. This represents an additional rise in the device efficiency.

The fifth parameter, which results from the sensible cycling of the adsorbers, is the amount of inactive thermal mass or with other words inert mass, which is not directly participating in the sorption process. It has an important role in the operation of the adsorption device (Cerkvenik, 2001). Due to the constant changing of the sorption phase in the adsorber the whole thermal mass has to be heated up (before the desorption phase) or cooled down (before the adsorption phase) to allow the start of the next sorption phase. Therefore it is crucial to lower the inactive mass, which would bring about an increase in the COP of the device. Usually we present the inactive mass in the device with the inert ratio, which is defined as the relation between the inactive thermal mass of the adsorber to the 'active' adsorbent mass in the adsorber

$$i = \frac{\sum_k m_{inertk}}{m_{ads}} .$$ (3)

As it is known is the inert ratio of 0 practically not possible. There is always an inactive mass, which is required in the construction of the adsorber. Therefore the results for inert ratio of 0, represents the ideal case, which can be used for the comparison purposes only.

3. OPTIMISATION CRITERION

Still nothing is known about the cost of the device, which would operate for the chosen parameters. It is known that to reach a high COP an increase in the heat exchange area is required, if the chosen parameters are fixed. It is the fact that the heat exchangers and their vessels, particularly the adsorbers, represent the major cost for the adsorption cooling device. Thus the cost of the system can be expressed as the sum of the products of the specific cost s_i for the main heat exchangers, evaporator, both adsorbers and condenser and their heat exchanger transfer areas A_i

$$S_{main} = \sum_i s_i \cdot A_i .$$ (4)

To include the specific costs s_i into the calculation of the COP the square-root criterion will be used.

$$\frac{A_i}{A_j} = \frac{Q_i \cdot k_j \cdot \Delta T_{ln,j}}{Q_j \cdot k_i \cdot \Delta T_{ln,i}} = \frac{\left[\dfrac{R_i \cdot z_i}{k_i \cdot z_i \cdot s_i}\right]^{\frac{1}{2}}}{\left[\dfrac{R_j \cdot z_j}{k_j \cdot z_j \cdot s_j}\right]^{\frac{1}{2}}}$$ (5)

It rests on a known working-pair property data and implements the cost relations between the main heat exchangers. The square-root criterion can be derived by minimization of the cost function for the sorption machine, with the introduction of the features like pressure – temperature - concentration relationship as a supplementary boundary condition (Ziegler, 1997). The cost function contains the costs for all main components, because they present the main part of the device investment cost. The cost for pumps, cooling tower, auxiliaries etc. are not included in this optimization process. In case of an economic analysis of the total system (Berlitz *et al.*, 1999), they could be added to the total heat exchanger cost later.

In the square-root method the optimal machine is determined with an iterative calculation of the systems internal parameters. Exceptions are the concentration difference Δx_{ads}, effectiveness of the heat recovery η_{HRec} between the two adsorbers and the inert ratio i. These parameters are fixed to reasonable values and are changed to study the sensitivity of the optimization results. First, reasonable internal temperatures are assumed and the heat transfer areas

A_i are determined. Afterwards the given total heat exchange area is optimally distributed to the main components in such a way that the minimal heat transfer area A is achieved for the given conditions.

Due to the fact that the intention of this paper is to show the basics, the specific cost for all main components, s_i, have been set equal. With this assumption only the cycle thermodynamics influence have an impact on the heat exchange area distribution between the heat exchangers. Consequently cost relations were excluded from the square-root criterion (Equation 5). With different heat exchanger costs the heat exchange area would be distributed differently according to the cost relations.

4. ZEOLITE/WATER CYCLE OPTIMIZATION

To make the optimization of a simplified adsorption chiller possible the following assumptions are made.

The adsorption cycle is remodeled into a quasi-continuously working cycle. To achieve this, average temperatures for both adsorption and desorption phase have to be calculated. The average internal temperature is the mean entropic temperature of the adsorption / desorption process. On the external side of the heat exchangers mean temperature is equal to arithmetic mean temperature, due to the constant conditions. The entropic mean temperatures are in good approximation equal to the arithmetic mean temperatures, which, however, are larger than the logarithmic mean temperatures when these are small as compared to difference in temperature glide of the two heat exchanging fluids (Ziegler, 1998). Consequently, the demand on heat exchange area will always be under-estimated in our comparison.

The heat exchange between the adsorbers normally follows after the finished adsorption and desorption phase in the adsorbers. For the optimization process it is assumed that the machine is a single-effect adsorption machine with two adsorbers. The two adsorbers work in counter-phase, with continuous heat exchange between them, when shifting the phase. We can assume this heat recovery as a quasi-continuous ´solution´ heat exchanger.

Because water is used as a refrigerant, the temperature in the evaporator has to be above 0°C.

Pressure drops in the system and heat losses were assumed to be small and neglected in the calculations.

For the adsorption system optimization the property data for zeolite 13X is used as the adsorbent. It may be not the most efficient working pair for the given external driving temperature but it was found reliable for the use in the adsorption heat pumps (Rothmeyer, 1985). In case of using other adsorbents, like other zeolites or silicagel, the COP could be higher. Still, this does not change the qualitative arguments presented in the paper.

5. SENSITIVITY STUDY OF ADSORPTION CYCLE LIMITATIONS

The internal temperatures are calculated iteratively and can vary in a range given by the external temperature conditions (Table 1). The temperature level of the driving heat is chosen in a way that a gas burner could be used as a heat source.

Table 1: Parameters for the optimisation of the single-effect zeolite/water cooling device

Main component	T_{in} [°C]	T_{out} [°C]	k [W $m^{-2}K^{-1}$]
Evaporator	12	6	1500
Condenser	27	35	2500
Adsorber – adsorption	27	35	200
Adsorber – desorption	250	250	250

To define the limits for the COP of the adsorption cycles, the influence of some specific adsorption cycle limitations have to be considered. Because the adsorbers are of the same geometry we will not discuss the limitation of equal

heat exchangers (Cerkvenik *et al*., 2001). Our intention is in the first place to show the influence of the inert ratio i, heat recovery effectiveness η_{HRec} and concentration difference Δx_{ads} the adsorption device performance.

5.1 Influence of inert ratio on maximal efficiency

To discuss the effect of the inert ratio, we will restrict ourselves on the presentation of the maximal efficiency, which could be reached with the specific device. The device would reach the maximal efficiency, if the maximal concentration difference for given external conditions, in this case Δx_{ads}=0.2, and internal heat recovery effectiveness of η_{HRec}=1.0 could be achieved.

The influence of the inert ratio i on the characteristic plot has been to a certain extend already presented before (Cerkvenik, 2001). Still to round the presentation, we will present the calculation results for the variation of the inert ratio between 0 to 10 (Figure 2). The i=0 is practically not possible and will serve for the presentation only.
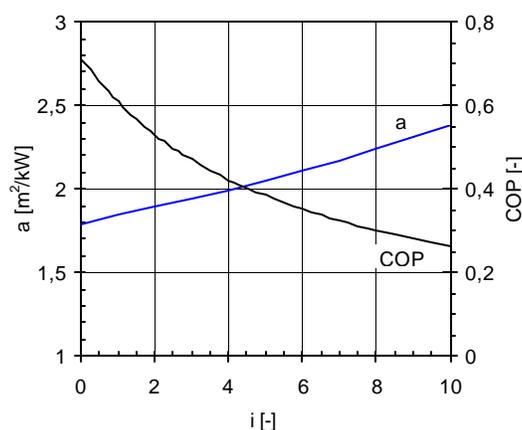

Figure 2: Calculation results for the variation of the inert ratio. The heat recovery effectiveness is set to maximum, η_{HRec}=1.0, and the concentration difference to the maximal possible, Δx_{ads}=0.2.

As it can be seen the inert ratio greatly influences on the efficiency of the adsorption device. If the inactive thermal mass is considered in the calculations, the COP decreases from the theoretical COP over 0.7 down to 0.25, in the case of inert ratios over 10. With an increase in the inert ratio, more sensible heat has to be thermally cycled during the operation of the adsorbers. This has a direct effect on the heat consumption on the desorption side and furthermore, on the cooling COP also. On the other side, the fact that more mass has to be thermally cycled results in larger heat exchange areas, which are required to transfer larger quantities of heat.

Thus it is very important to build the adsorbers in such a way that the inert ratio is as low as possible. For the further calculations, the inert ratio i=1 will be used. It can be expected that this ratio is possible to achieve.

5.2 influence of internal heat recovery effectiveness

The influence of the heat recovery effectiveness on the system characteristics is presented in Figure 3 as a relation of the COP versus the specific heat exchange area a. The plot is a result of the variation of the heat recovery effectiveness between η_{HRec}=0.0 (in Figure 3: point at the lowest COP and the highest a) and η_{HRec}=1.0 (point at the highest COP value). The variation is performed for the constant concentration difference of Δx_{ads}=0.2. For an easier presentation of the optimisation results some of the results are marked with their heat recovery effectiveness.

The resulting plot is similar to the plot, which is given for the absorption cooling devices (Ziegler, 1997; Cerkvenik *et al*., 1999; Cerkvenik, 2001). As it can be seen, the use of internal heat recovery increases the COP of the device. In the case of the higher effectiveness η_{HRec}, more sensible heat is recovered to the adsorber in the desorption half-cycle, which results in a lower energy consumption of the device. Beside this, due to the lower quantity of driving heat, which has to be transferred during the desorption half-cycle, a less heat exchange area is required.
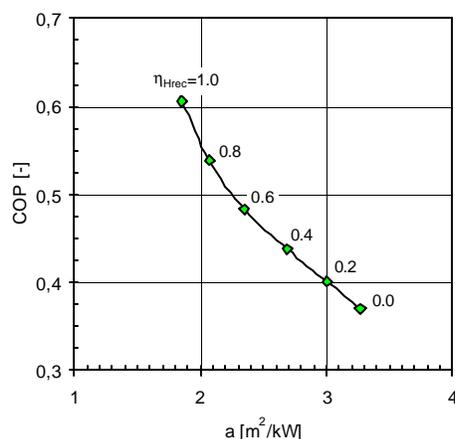
Figure 3: Influence of the internal heat recovery effectiveness η_{HRec} on the COP-a relation for the constant concentration difference of $\Delta x_{ads}=0.2$. Inert ratio is i=1.

As it is written before, the latent heat could be recovered between the adsorbers also. The impact of the latent heat recovery can be noticed in Figure 3. It can be seen that at the effectiveness of about 0.5 the inclination of the plot slightly increases. This is due to the fact that beside the sensible heat also a part of latent heat is recovered to the colder adsorber. In the later case is the gradient of the quantity of specific heat over the temperature higher as in the case of sensible heat only. This results in the additional COP increase.

5.3 Influence of concentration difference

The concentration difference Δx_{ads} is the next independent parameter, which can be varied in the calculation procedure. As a result of the variation of the Δx_{ads} a set of plots, similar to the plot in Figure 3, is given. With the simultaneous variation of the both parameters, η_{Hrec} and Δx_{ads}, the field of optimum points is given, which could be reached with the specific adsorption device. The resulting optimal operational field, for the adsorption devices with the heat recovery and for the conditions in the Table 1, is presented in Figure 4. The results are presented as a mesh of the constant concentration differences and heat recovery effectiveness. For the further discussion, the plot of the constant effectiveness $\eta_{HRec}=0.9$ is marked with a thick line. On the plot, the reference concentration differences in the range between 0.01 to 0.2, are presented.
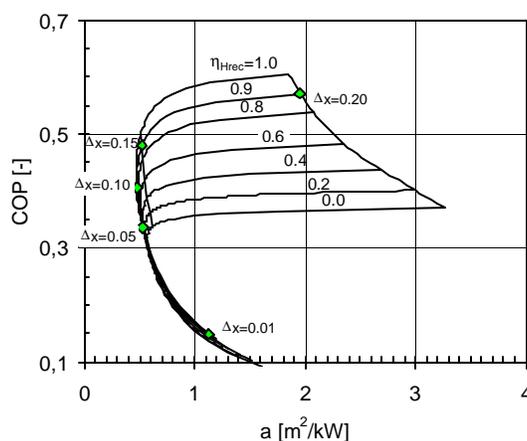

Figure 4: Influence of the internal heat recovery effectiveness and concentration difference on the relation between the COP and the specific heat exchange area. The inert ratio is i=1.

The value of $\Delta x_{ads}=0.01$ represents the device, which can in the given time period operate with only 1% concentration difference. Due to the fact that such a device mainly thermally cycles the inactive mass, it has the

lowest COP values in the Figure 4. The corresponding specific heat exchange area, which is required at this point, is high due to the fact that the area of the adsorbers per kW cooling energy increases if the concentration differences Δx_{ads} is limiting to zero.

If the device would reach a higher Δx_{ads} in the equal cycle time (from $\Delta x_{ads}=0.01$ towards 0.2 in Figure 4) the COP would increase rapidly. The major influence on the increase has the change in the heat ratio between the heat of adsorption to the sensible heat. Beside this, at the higher Δx_{ads} the latent part can be partly internally recovered, which increases the COP additionally.

The minimum of the heat exchange area is reached at the point of $\Delta x_{ads}=0.10$. Despite to the minimal value the optimal operational point can not be concluded from the minimum of the heat exchange area. The position of the optimal operational point can be determined with the further economic analysis (Summerer, 1996; Ziegler, 1997; Cerkvenik *et al*., 1999). The specific heat exchange area a has to be converted into the first cost of the device and on the other side, the COP into the operational cost, which relates with the energy consumption and energy rejection. In this work we will restrict ourselves to the determination of the optimum plot, as it is presented in Figure 4.

At the higher concentration differences, over $\Delta x_{ads}=0.10$, the specific heat exchange area increases again. At the same time the COP increases also. It can be seen that for the higher COP more has to be invested into the heat exchange areas. It can be noted also, that the heat recovery effectiveness gains in importance with the higher concentration difference. Because more heat is transferred at the adsorbers, due to the large Δx_{ads}, any additional increase in the effectiveness will represent an improvement in the COP and a decrease in the specific heat exchange area also. It can be said, that it is very important to reach the high concentration differences Δx_{ads} parallel to the effective internal heat recovery η_{HRec}.

Similar it could be performed for systems, where beside the heat transfer also the mass is transferred between the adsorbers (Szarzynski, 1997; Pons *et al*., 1999). The same can be said for the cycles, where thermal wave heat regeneration is used to internally recover the available heat. Due to the additional complexity of the calculation we will leave out the discussion of these cases.

6. CONCLUSIONS

The intention of this paper was the introduction of the square-root method optimization to adsorption cycles with two adsorbers and conventional internal heat recovery between them. This optimization method rests on the first and second law of thermodynamics. To make it possible to introduce this method to the adsorption system, a simplification of the adsorption system dynamic is performed. The quasi-continuous modification of the adsorption process dynamics allowed us to optimize the process in a similar way as the absorption one. Because the adsorption system does not operate continuously some limitations and differences of the process arise in comparison with the absorption one. Therefore the process loses some degrees of freedom in determination of internal process parameters. With the adsorption process limitations, i.e. lower heat exchange effectiveness η_{HRec} and higher inert mass ratio i, the system performance drops drastically.

The optimisation results are presented in the COP to specific heat exchanger area plot, which could be used for the presentation of the running to investment cost relation also. The limitations are included gradually to present their influence on the optimal performance. First, the influence of inert mass is presented. It can be seen that it has a crucial influence on the device performance. In the unrealistic case, with the inert ratio i=0, a COP over 0.7 can be achieved. On the other side, at inert ratios over 10, the COP over 0.25 can not be reached.

The variation of heat recovery effectiveness is together with the variation of the concentration difference used for the construction of the characteristic plot of the device. The variation of the both parameters, has given us the field of the optimal operational points, which can be reached with the chosen adsorption device for the given external conditions.

The same optimization method can be used also for other adsorption pairs and chemical reactions, which could be used for heat pumps. This would be very useful for more accurate prediction of the sorption cycle performance and for the comparison of performance, specific capacity and economics of the different systems.

NOMENCLATURE

a	specific heat exchange area	($m^2/W_{cooling}$)
A	heat exchange area	(m^2)
COP	coefficient of performance	(-)
Δx	concentration difference	(-)
i	inert ratio	(-)
k	heat transfer coefficient	(W/m^2K)
p	pressure	(Pa)
Q	heat	(W)
R	slope of the isostere in the Dühring plot	(-)
s	specific cost of main component	(ECU/m^2)
S	cost of main component (ECU)	
z	ratio of the logarithmic temperature difference to the arithmetic mean temperature difference	(-)
x	adsorbed mass ratio	(kg/kg)
T	temperature	(K)
ΔT	temperature difference	(K)
η	internal heat exchange effectiveness	(-)
ζ	ratio of the heat flow at main component to the cooling power	(-)

Subscripts
A1, A2	adsorbers
ads	adsorbent
co	condensation
ev	evaporation
i	index
j	index
inert	inert
k	index
ln	logarithmic
max	maximal
min	minimal
SHX	solution heat exchanger
we	weak

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