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Increase of the efficiency of the heat transfer phase in solid sorption or reaction systems

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Abstract

An important drawback of solid sorption systems which are operated in batch mode against liquid sorption systems is the imperfect heat exchange between loaded and unloaded adsorbent, as compared to the almost perfect counter-flow solution heat exchanger. We will discuss a simple hardware solution for a significant improvement.

We divide the batch reactors into several compartments, not with respect to the refrigerant side, but with respect to the heat transfer medium (heat exchanger loop). If these compartments have individual and arbitrary heat exchange possibilities with each other the efficiency of heat recovery can be improved from a co-flow characteristic to a cross-flow characteristic. We want to stress that this is different from a multi-bed or multistage arrangement.

The method is explained, and an algorithm for deriving the exchange efficiency is given. Although this paper is only meant for outlining the basic mechanism, a proposition for realisation of the external hydronic circuit is given in addition.

Keywords: Solid sorption; Chemical reaction; Adsorption; Heat exchange; Efficiency; Optimisation

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1. Introduction

Cooling is accomplished in most cases by using electrically driven compression chillers. If cheap heat is available heat driven sorption chillers are being used also. Adsorption chillers (using solid adsorbents) or chillers which make use of chemical reactions for heat transformation are not as commonly used as absorption chillers (using liquid absorbing solutions). Probably, a closed adsorption cycle will never be thermodynamically or economically competitive to a liquid sorption cycle in an application where both types of cycle are technically feasible. However, liquid sorption systems are not always feasible due to a restricted field of operation and, moreover, there might be an opportunity for open cycles such as desiccant systems.

The most significant feature of solid sorption systems is the fact that they operate in batch mode. As a consequence, an important drawback of solid sorption systems against liquid sorption systems is the imperfect heat exchange between loaded and unloaded adsorbent, as compared to the almost perfect counter-flow solution heat exchanger. We will discuss a simple hardware solution to this problem which gives rise for a significant improvement.

There is a huge amount of literature about sorption heat transformation devices which use solids. For further reading especially the proceedings of the respective conferences are recommended [1–10]. We will be very short about the fundamentals and concentrate on our specific problem.

Fig. 1 shows a simple process scheme of an adsorption cooling device. It mainly consists of evaporator V, condenser C, and two reactors SR1 and SR2. In the following, we always will use the word sorption reactor instead of adsorber because the process taking place may be as well an adsorption as well as a homogeneous chemical reaction. The thermodynamic corner-stones are schematically depicted in Fig. 2, a plot of dew point temperature against equilibrium temperature of the sorbent/refrigerant pair analogously to the Dühring-plot of so-

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Nomenclature

g	heat exchange efficiency
i	individual compartment
n	total number of compartments
Q_{loss}	energetic loss
T_A	minimum temperature of sorption reactor in adsorption
T_G	maximum temperature of sorption reactor in regeneration
T_m	intermediate temperature
$\Delta T_{\max}$	difference between highest and lowest reactor temperature
ΔT_i^n	remaining difference between temperature of compartment and maximum temperature
ΔT	remaining temperature difference
$\overline{\Delta T}$	temperature step
τ	loss number
τ^n	total loss number
τ_i^n	loss number of individual compartment

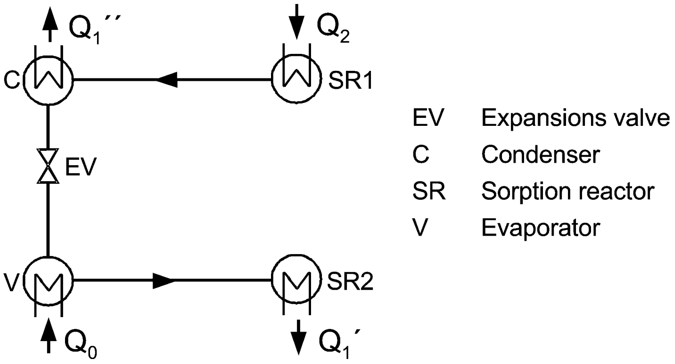

Fig. 1. Basic flow sheet of a solid sorption system.

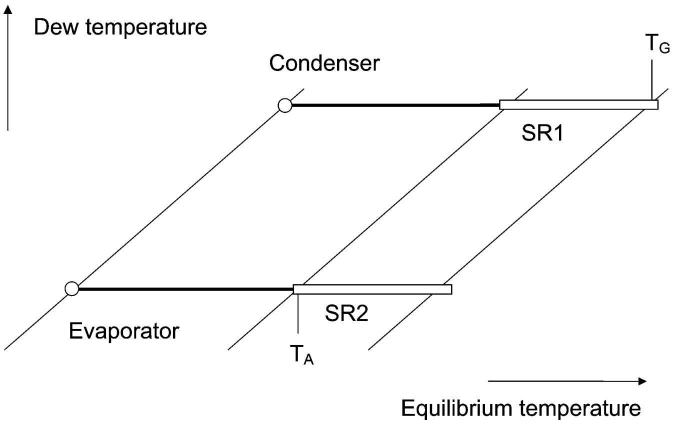

Fig. 2. Dühring-plot of a solid sorption system.

lutions. The straight lines are lines of constant composition, the isosteric lines.

We will now explain the ongoing batch process. During one period of time (phase 1) the reactor 1 which in this phase is coupled to the condenser is regenerated by external heating. Refrigerant is desorbed in the reactor and condensed in the condenser by rejecting heat to a heat sink. After pressure release in the expansion device EV the condensed refrigerant is evaporated again in the evaporator by consuming heat, which is the useful cold. The evaporator is connected to the reactor 2; consequently, vapour is adsorbed in reactor 2, which is rejecting the heat of adsorption to the heat sink. If this is an adsorption process and not a homogeneous reaction, during regeneration the temperature of reactor 1 has to be increased eventually because the loading with refrigerant diminishes and, consequently, the state point shifts to another isosteric line. During adsorption the temperature of reactor 2 has to be decreased. The phase is finished when the desorption temperature reaches its maximum, T_G, and the adsorption temperature reaches its minimum, T_A.

During the second period of time (the internal heat-recovery phase), in most cases evaporator and condenser are disconnected from the reactors and reactor 1 exchanges heat with reactor 2. Reactor 1 cools down, reactor 2 heats up. We will discuss these isosteric phases later in this paper. Afterwards reactor 2 is connected to the condenser and reactor 1 is connected to the evaporator. A third phase—which is analogous to phase 1—starts with the reactors having exchanged their respective function. In a forth phase the heat exchange is reversed and afterwards the first phase starts again.

2. Layout of the concept

The temperature rise of the reactors in the second and forth phase never exceeds half of the difference between the equilibrium temperatures on the isosteres of the loaded reactor at condenser pressure and evaporator pressure, T_G and T_A. As such it is analogous to a co-flow heat exchange. This is the main source of efficiency reduction of the process: not only the adsorbent but also the reactor shell and the heat exchanging devices inside the reactor have to be heated up. A more detailed discussion of this effect can be found in [11].

Phases 2 and 4 are loss-producing phases. Moreover, they are non-productive phases also: no cold is being produced during the heat exchange. This may be altered by adding additional internal recovery means such as the mass exchange [12,13]. In any case, in order to increase the power density, the heat exchange should be fast. Thus, the heat exchange phase is a heavily transient procedure and the amount of exchanged heat and, consequently, the temperature rise of the cold batch reactor is dependent on the duration of the exchange phase. The closest approach of the temperatures of the two reactors will never be zero due to the finite exchange time. The remaining temperature difference will be smaller for long exchange phases, but the energy density will be low. Efficiency must be optimised against power density, as always. We will focus on efficiency first.

Of course, there have been attempts to improve this situation. One possibility is the exchange of vapour between the reactors as opposed to heat [12,13]. This is a very fast process. Another possibility is the use of the concept of thermal wave, which may in addition lead to a kind of multistage arrangement [14–18] thus increasing efficiency predominantly. It is effective if the length of the reactor bed is large as compared to the length of the temperature front in the heat carrier when it passes the reactor. Finally, by using additional (more than one) reactor pairs the non-productive phases two and four can be levelled off and more time can be given to accomplish the heat exchange. This helps especially in solving the conflict between efficiency and power density. In this paper we will discuss a quite conventional approach with two reactors and no thermal wave being used.

One of the main differences between co- , cross-, and counter-flow heat exchange is the fact that in cross- and counter-flow the outlet temperature of the cold stream may exceed the outlet temperature of the hot stream. By searching a possibility to realise this in batch systems as well we will divide the reactors into several (n) compartments. The heat exchanger loop inside the bed is arranged in such a way that all compartments are interconnected in a conventional manner during desorption and adsorption phases. However, during the heat exchange phase the heat exchangers in the compartments are used individually. The compartments may or may not be separated on the refrigerant vapour side during the heat exchange phase. Separation is better for performance, but expensive. We assume that the heat exchange is fast and, consequently, the interdependence of the compartments via desorbing and adsorbing refrigerant vapour will be small even without separation on the vapour side.

We will apply one more important simplification in order to keep the basic idea straight. We assume that the heat capacity of unloaded and loaded reactor (construction and heat exchange material including sorbent bed and refrigerant) are identical. This is especially correct when the thermal mass of construction material and sorbent is large as compared to that of the refrigerant which is contained in the sorbent. In most cases our assumption will not be too bad. Also the latent heat is not evenly distributed across the isosteres. However, as our purpose is to exchange mainly sensible heat (only marginal desorption and adsorption taking place due to the non-zero void volume) this assumption may be tolerable as a first guess, too.

Then, the heat which could be exchanged in a perfect counter-flow heat exchanger between two batch reactors at T_G and T_A is proportional to

$$\Delta T_{\max} = T_G - T_A \tag{1}$$

However, we have no counter-flow. The cold reactor will be heated up by a temperature step $\overline{\Delta T}$ to some intermediate temperature T_m,

$$\overline{\Delta T} = T_m - T_A \tag{2}$$

The energetic loss due to imperfect heat exchange (as compared to perfect counter-flow) is proportional to the complement of this temperature difference:

$$\dot{Q}_{\text{loss}} \propto \Delta T = \Delta T_{\max} - \overline{\Delta T} \tag{3}$$

ΔT is the remaining temperature difference to heat the formerly cold reactor (SR2) to maximum temperature T_G. It is identical to the remaining temperature difference to cool the formerly hot reactor (SR1) to minimum temperature T_A.

Finally, we define a non-dimensional loss number:

$$\tau = \frac{\Delta T}{\Delta T_{\max}} \tag{4}$$

In the conventional system, this number will always be above 0.5, meaning that more than 50% of sensible heat cannot be recovered.

3. Heat exchange between two batch reactors with two compartments each

Our two batch reactors SR1 and SR2 are nothing else than two pieces of matter with same mass and specific heat capacity (Fig. 3). Piece a1 is at a temperature T_G which is higher than the temperature T_A of piece b1. If we bring them into thermal contact they will eventually reach an intermediate temperature, the arithmetic mean, as shown in Fig. 3.

We now divide the two pieces into two parts each: a1 and a2, and b1 and b2 (Fig. 4). We first bring into thermal contact a1 and b1 and exchange as much heat as possible (step I). In a second step we exchange as much heat as possible between a1 and b2 on the one hand, and between a2 and b1 on the other hand. It is obvious that b1 will attain a higher temperature than just the mean temperature between T_G and T_A (step II). Finally, the temperatures of a2 and b2 are set into thermal equilibrium (step III). As a result we have exchanged significantly more heat than with undivided pieces: half of the loss has been reduced by 50%, i.e. a loss reduction of 25% overall.

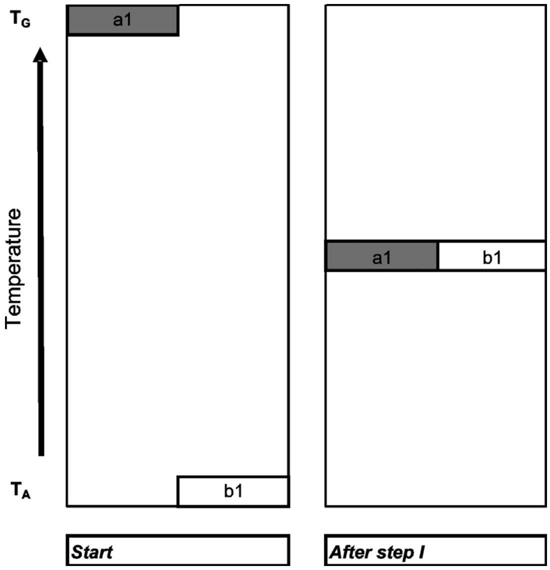

Fig. 3. Temperatures before and after ideal heat exchange between two reactors at T_G and T_A.

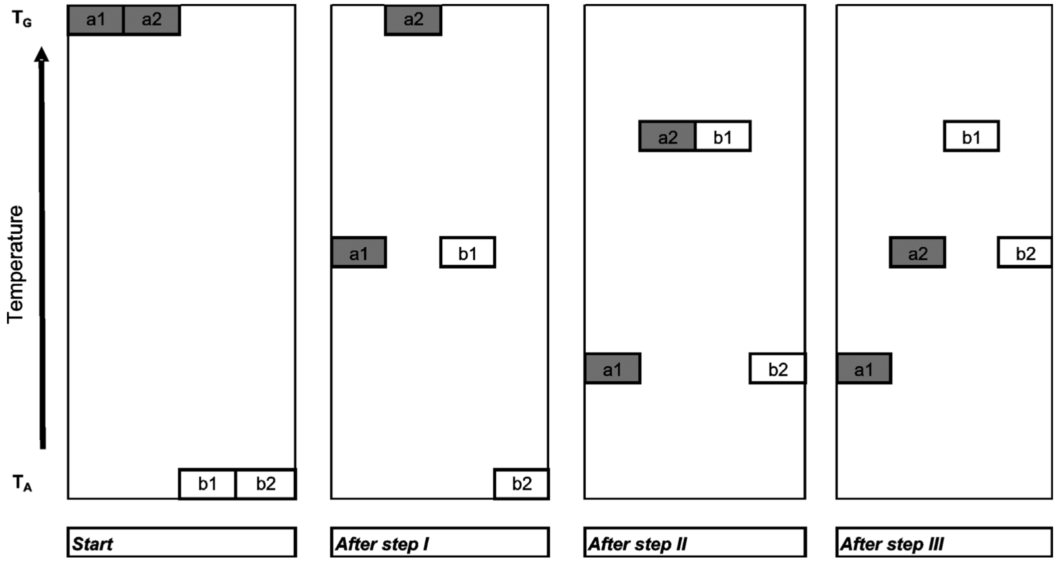

Fig. 4. Temperatures before and after ideal heat exchange between two reactors at T_G and T_A with two compartments each.

4. Heat exchange between two batch reactors with three compartments each

In Fig. 5 the same procedure is shown with three divisions. In step I, II, and III, the division a1 is cooled by exchanging heat with b1, b2, and b3 respectively. b1 is heated by exchange with a1, a2, and a3. After step III, a1 cannot be cooled further, b1 cannot be heated further. In step IV and V a2 is cooled by exchange with b2 and b3, b2 is heated by exchange with a2 and a3. Finally, in step VI, a3 exchanges heat with b3. Again, we have exchanged more heat than before.

5. Heat exchange between two batch reactors with *n* compartments each

We now discuss the behaviour of the cold compartments of the reactor which have just finished the adsorption phase. The behaviour of the hot reactor is just reciprocal. Each of the n compartments of the reactor is heated up to its individual maximum. Then, some heat exchanger loss which is proportional to a remaining temperature difference ΔT_i^n can be attributed to each ith compartment of a reactor with a total of n compartments. A relative loss number can be defined also for each compartment:

$$\tau_i^n = \frac{\Delta T_i^n}{\Delta T_{\max}} \tag{5}$$

A total loss number can be derived as a sum of the individual losses by taking into account the fact that each compartment contains the nth fraction of thermal mass only. It is the complement of the heat exchanger efficiency g:

$$\tau^n = \sum_{i=1}^{n} \frac{\Delta T_i^n}{n\Delta T_{\max}} = \frac{\sum_{i=1}^{n} \tau_i^n}{n} = 1 - g \tag{6}$$

Let us now look at the first cold compartment b1 (Fig. 5). By heat exchange with the first warm compartment a1 its temperature is increased (in the ideal case) by $\Delta T_{\max}/2$. It can then exchange heat with the second warm compartment a2 and increases its temperature by additional $\Delta T_{\max}/4$. By exchanging with compartment a3 we add another $\Delta T_{\max}/8$. We see that the compartment b1 can be heated by

$$\Delta T_{\max}\left(1/2 + 1/4 + 1/8 + \cdots + 1/2^n\right) \tag{7}$$

The remaining temperature difference ΔT_1^n is:

$$\Delta T_1^n = \Delta T_{\max}\left(\frac{1}{2}\right)^n \tag{8}$$

The last (nth) compartment can be heated only by $\Delta T_{\max}/2$. The remaining temperature difference is

$$\Delta T_n^n = \Delta T_{\max}\left(\frac{1}{2}\right) \tag{9}$$

The remaining losses of the other compartments can be determined in a recurring way. As an example (Fig. 6) let us assume that we had performed the maximum heat exchange with 2 compartments. Afterwards, we have got a1, a2, b1, b2 on their respective final temperatures. Now we add a compartment to desorber (a3) and adsorber (b3). In the three following steps I to III a3 is cooled by heat exchange with b1, then b2, then b3. b3 is heated by exchanging with a1, a2, finally a3. We attain exactly the same temperature distribution as shown in Fig. 5.

Let us now assume we had performed the maximum heat exchange with $(n-1)$ compartments. Each ith cold departments of SR1 (bi) will have been heated up partly and will feature an individual remaining exchanger loss proportional to ΔT_i^{n-1}. After adding an additional nth compartment all $(n-1)$ compartments of SR2 (b1 to b$(n-1)$) can exchange heat with the new compartment of SR1 (a(n)) one after the other and vive versa. The first compartment b1 reduces its loss from $\Delta T_{\max}/2^{(n-1)}$ to $\Delta T_{\max}/2^n$. The new compartment (a(n)) steps down to the same temperature. Then it is brought into contact with b2, which before arrived at a remaining loss of ΔT_2^{n-1}. So, b2 will be heated up further to a temperature intermediate between its former temperature and the one which has been attained by b1 just now. The remaining loss, consequently, will be

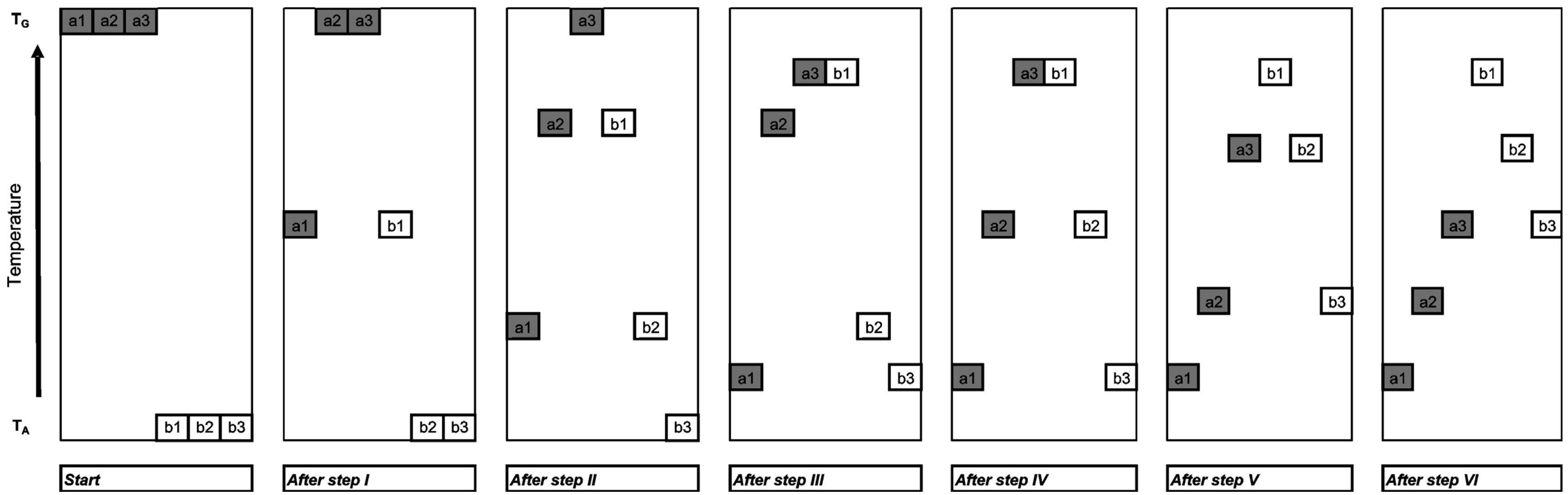

Fig. 5. Temperatures before and after ideal heat exchange between two reactors at T_G and T_A with three compartments each.

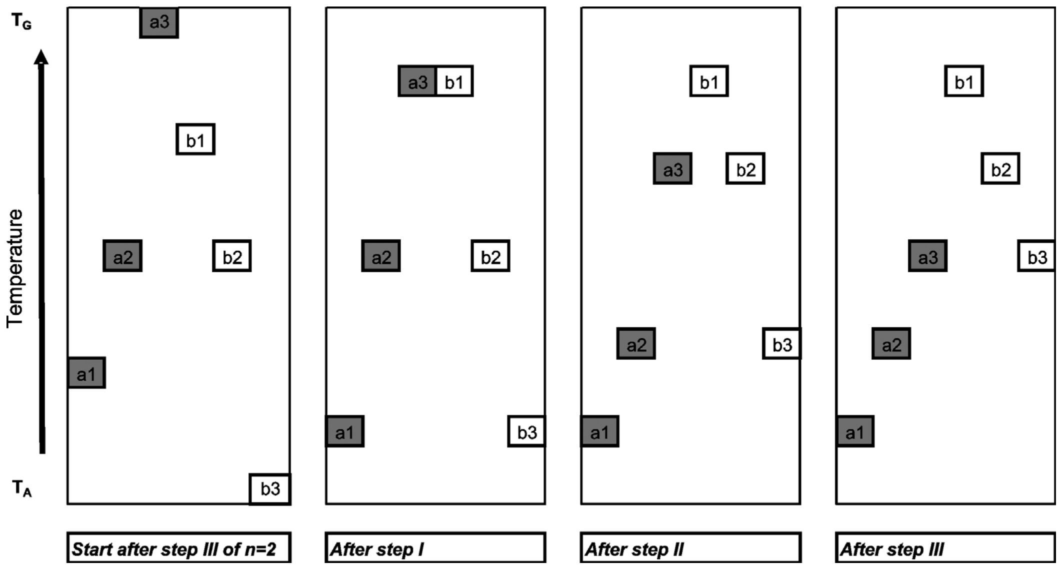

Fig. 6. Temperatures before and after ideal heat exchange between two reactors at T_G and T_A by adding a third compartment.

equal to the arithmetic mean of the former loss of b2, ΔT_2^{n-1}, and the actual loss of b1, ΔT_1^n. We state as a common rule: each ith compartment starts with a loss proportional to ΔT_i^{n-1} and exchanges heat with a compartment which has a temperature corresponding to ΔT_{i-1}^n. It will attain a temperature which is the arithmetic mean of the temperature which it had reached before (with only $(n-1)$ compartments present) and the temperature which has been reached by the nth compartment in the preceding steps of heat exchange. We can formulate:

$$\Delta T_i^n = \left(\Delta T_i^{n-1} + \Delta T_{i-1}^n\right)/2 \tag{10}$$

With this equation we can derive the loss factors τ_i^n of an arbitrary number of compartments (Fig. 7). The loss factors of an individual compartment are linked with a straight line in order to demonstrate the reduction of the remaining temperature difference by adding compartments. The relative loss of the individual compartments, τ_i^n/n (full symbols), and the sum according to Eq. (6) (open symbols) is shown in Fig. 8. By using 5 compartments the loss is reduced to about half of the standard arrangement without compartments. It should be stated that no analogy to a counter-flow heat exchange is attained. However, the results show the characteristics of a cross-flow exchanger.

We want to conclude this section by stating that the purpose of this paper is not the layout of multi-adsorber or multieffect cycles as discussed in other papers [16,21,25]. However, the method which has been laid down here could be easily applied to more complex cycles and would increase efficiency there also.

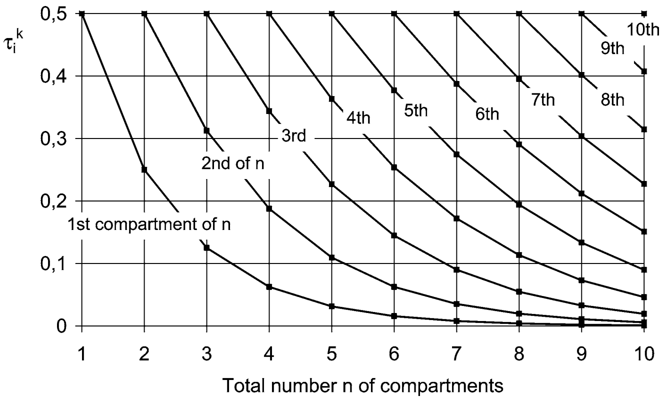

Fig. 7. Remaining loss factors of individual compartments after ideal heat exchange.

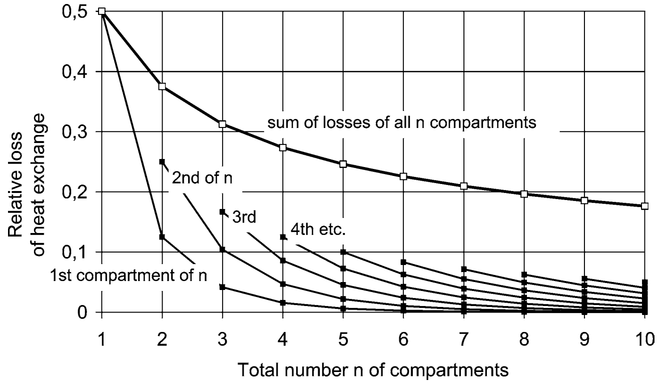

Fig. 8. Weighed remaining loss factors (■) of individual compartments after ideal heat exchange and total loss factor (□).

6. Practical considerations

In application the increase in complexity by dividing the reactors into compartments has to be balanced against the increase in efficiency. Probably only two or three compartments are economically feasible. The respective dimensionless losses are shown in Table 1 for up to 4 compartments.

We see that the exchanger efficiency rises by more than 20% against the standard case by using two compartments only. A third compartment rises the efficiency by another 10%. The fourth compartment increases the efficiency by 5%. The efficiency then is 73%. If we take into account that this is an upper limit on the one hand, and that it is an efficiency which is not too bad for a typical cross-flow heat exchanger on the other hand, we can derive that more than four compartments can only be economical if a very simple, reliable, and cost-effective mechanism for arranging and switching of the exchange loops can be found.

In Fig. 9 a schematic arrangement is displayed for reactors with 2 compartments. The switching between the different steps may be done with a kind of valve as used in hydraulics and pneumatics. It is shown in Fig. 10. The valve features 5 positions, starting with desorption and adsorption on the left, heat exchange in steps I to III according to Fig. 4 following, and adsorption/desorption on the right-hand side again. The valve will run from left to right and back again in order for the system to perform one total cycle.

Table 1
Loss numbers for up to 4 compartments

Number n of compartments	1	2	3	4
τ_1^n	0.50	0.25	0.13	0.06
τ_2^n	–	0.50	0.31	0.19
τ_3^n	–	–	0.50	0.34
τ_4^n	–	–	–	0.50
Total loss τ^n	0.5	0.38	0.31	0.27
Heat exchange efficiency	0.5	0.62	0.69	0.73

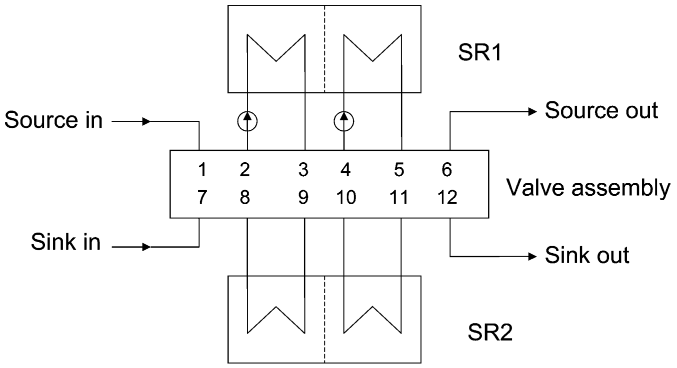

Fig. 9. Layout of the heat carrier loops of a system with 2 compartments.

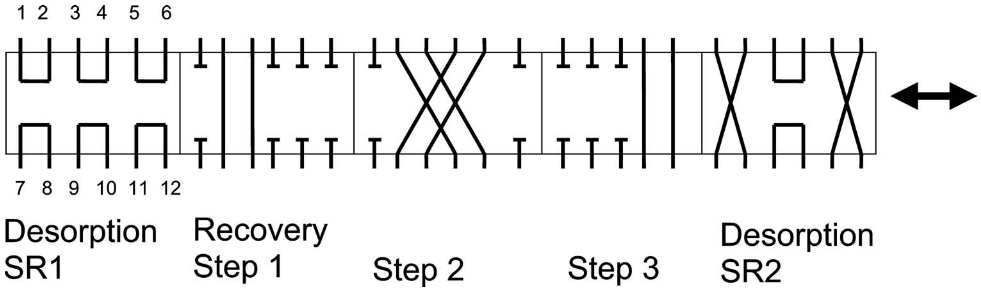

Fig. 10. Hydraulic valve for switching between the different heat exchange steps of a system with 2 compartments (each rectangle—thin lines—represents one position of the valve).

It is obvious that the hardware becomes more complex. The largest drawback is the necessity of several heat exchange loops with individual circulation pumps. This can be simplified quite a bit when (switchable) heat pipes are being used [19–22]. Also the possibility to optimise the heat flow should be mentioned: nonisotropic matrices [23,24] would allow a high heat flow in direction of the heat exchange, whereas heat flow between the compartments would be low.

Finally, it has to be mentioned that the exchange efficiency can be increased further when an additional mass exchange step is incorporated. This will not be discussed here. However, mass exchange in the individual compartments will take place automatically, if they are no refrigerant vapour valves in between. Of course, this brings about increased complexity. If these valves are not integrated there will be a levelling of pressure which is no exchange between the reactors SR1 and SR2 but within SR1 and SR2. It will diminish the heat exchange efficiency instead of increasing it. Therefore the exchange phases should be fast in order to avoid this negative impact. This brings us to another benefit: it is possible to use the division into compartments for speeding up the non-productive phases. This can be seen very easily: 50% exchange efficiency with single compartments is achieved in infinitely long time only asymptotically. With two compartments it definitely will be reached and surpassed in finite times. This effect may prove to be the most important application of the idea which has been presented in this paper.

7. Conclusion

In this paper we have presented a method of exchanging heat between batch reactors of adsorption cooling systems which allows to improving the efficiency of the heat exchange considerably by dividing the reactors into individual compartments. When we assume that the standard efficiency amounts to 50%, then we can attain with two compartments 62%, with three compartments 69%, and with four compartments 73% efficiency. The method can easily be applied and may be an important part of optimisation of heat and mass exchange, and of the total adsorption cooling system.

Acknowledgements

The basic idea to this paper was developed in the 1990s at the Bavarian Centre for Applied Energy Research (ZAE Bayern) within the context of some projects which we performed together with the late Professor Bernard Spinner.

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