

Toplotni kompresor za adsorpcijsko hlajenje

Heat Compressor for Adsorption Cooling

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Pri adsorpcijskem načinu izvajanja hladilnih procesov se spoprijemamo s problemom neučinkovitega prenosa toplote in snovi v toplotnem kompresorju. Posledica tega je majhna specifična hladilna moč naprave, ki določa njeno velikost oziroma količino potrebnega adsorbenta za nemoten proces hlajenja. Z novimi izvedbami prenosnikov toplote v toplotnem kompresorju je lahko prenos toplote in snovi občutno učinkovitejši. Ena izmed možnih izvedb je prenosnik toplote s kompaktnim slojem adsorbenta. V članku je podan matematični model prenosa toplote in snovi v homogen kompakten sloj, ki je na cevi prenosnika toplote v toplotnem kompresorju adsorpcijske hladilne naprave. Opisano je tudi delovanje hladilne naprave in opravljena analiza rezultatov simuliranja za primer več vzporednih cevi v toplotnem kompresorju. Podana je tudi analiza vrednosti toplotnih števil hlajenja v odvisnosti od števila vzporednih cevi in debeline sloja. Ugotovili smo, da na intenzivnost procesa v toplotnem kompresorju bistveno vpliva izbira snovi kompaktnega sloja, manj pa njegova struktura.

Ključne besede: kompresorji toplotni, hlajenje adsorpcijsko, prenos toplote, modeli matematični

In adsorption cooling processes, the engineer faces the problem of inefficient heat and mass transfer in the heat compressor. This results in small specific cooling power of the device, which determines its size or the amount of adsorbent necessary for an undisturbed cooling process. With new designs of heat exchangers in heat compressors, heat and mass transfer can be considerably more efficient. One possible design is a heat compressor with a compact layer of adsorbent. The paper presents a mathematical model of heat and mass transfer into a compact homogeneous layer located on the heat exchanger tube in the compressor of an adsorption cooling device. The operation of the cooling device is described and the results of simulation for a case concerning several parallel tubes in a heat compressor are analysed. The values of the coefficient of performance are analysed with regard to the number of tubes and layer thickness. It was established that the intensity of the process which takes place in the heat processor is influenced to a considerable extent by the type of material from which the compact layer is made, and less by the layer's structure.

Keywords: heat compressor, adsorption cooling, heat transfer, mathematical model

0 UVOD

Raziskave prenosa toplote in snovi pri adsorpcijskem procesu so se okrepile v zadnjih nekaj letih zaradi povečanega zanimanja za adsorpcijski način hlajenja. Poleg preprostejših modelov [1] do [3], ki so popisovali povprečno ravnotežno stanje (p , T , x) v celotnem sloju adsorbenta, so se v zadnjem času pojavili tudi zahtevnejši modeli [4] do [6], ki popisujejo tudi lokalno ravnotežno stanje znotraj sloja adsorbenta. Eichengrün je v svojem delu [4] postavil matematični model, s katerim je računal potek temperatur in tlakov po globini kompaktnega sloja adsorbenta. Ker je imel toplotni kompresor oblikovan tako, da je fluid, s katerim je grel in hladil sloj adsorbenta, oblival kompresor z zunanjé strani, je lahko zanemaril porazdelitev temperatur in tlakov v vzdolžni smeri. Mamiya [5] se je lotil popisa temperaturnega polja z metodo končnih elementov. Kot segment si je izbral orebren del ravne ploskve. Med rebra je nasul adsorbent in računal temperaturno polje v segmentu. Proses adsorpcije je upošteval s členom generacije toplote v diferencialnem elementu,

0 INTRODUCTION

Research of heat and mass transfer in the adsorption cooling process has been intensified in recent years due to increased interest in the adsorption cooling method. In addition to simple models [1] to [3] which describe the average equilibrium state (p , T , x) in the entire layer of the adsorbent, more complex ones have appeared lately [4] to [6], which also model the local equilibrium in the adsorbent layer. In his work [4], Eichengrün set up a mathematical model for the calculation of the variations of temperatures and pressures along the depth of the compact adsorbent layer. Since his heat compressor design was such that the fluid he used to heat and cool the adsorbent layer flowed around the compressor on its outside, the distribution of temperatures and pressures in the longitudinal direction could be neglected. Mamiya [5] undertook modelling of the temperature field with the finite element method. He selected a finned part of a flat surface as the segment to be studied. He poured an adsorbent between the fins and calculated the temperature field in the seg-

kjer je uporabil isto metodo kakor Suzuki [1] s spremembom adsorbirane količine po času. Zheng [6] je postavil model za popis temperaturnega polja vzdolž toplotnega kompresorja ter prečno na tok prenosnega fluida. V nasprotju z Eichengrūnom [4] je predpostavil tlak enak znotraj celotnega toplotnega kompresorja. Ker teče prenosni fluid čez nasutje adsorbenta, je upošteval gradient temperature prenosnega fluida vzdolž toplotnega kompresorja. V našem primeru smo se odločili za način modeliranja, kakor ga je izvedel Eichengrūn, vendar za spremenjeno geometrijsko obliko toplotnega kompresorja.

1 ADSORPCIJSKI HLADILNI PROCES

Poglavitna razlika med običajnim in adsorpcijskim hladilnim procesom je v načinu izvedbe kompresije hladiva. Ta poteka pri običajnem z mehanskim kompresorjem, pri adsorpcijskem hlajenju pa s toplotnim kompresorjem.

Da lahko zadovoljivo popišemo delovanje toplotnega kompresorja, moramo poznati termodinamično ravnotežno stanje delovne dvojice v njem. Stanje v toplotnem kompresorju popišemo s tlakom p in temperaturo T . Določitev ravnotežnega stanja v adsorbantu, v katerem poteka fizikalna adsorpcija, je povezano s poznavanjem adsorbirane količine x . To lahko določimo iz adsorpcijskih izoterm, ki jih podaja proizvajalec [7], v odvisnosti od temperature in tlaka:

$$x = x(p, T) \quad (1).$$

Adsorbirano količino x , ki pomeni tretji parameter ravnotežja v adsorbantu, lahko popišemo kot funkcijo temperature in tlaka, zato izvedemo totalni diferencial adsorbirane količine x po tlaku p in temperaturi T :

$$\frac{\partial x}{\partial \tau} = \left(\frac{\partial x}{\partial p} \right)_T \cdot \frac{\partial p}{\partial \tau} + \left(\frac{\partial x}{\partial T} \right)_p \cdot \frac{\partial T}{\partial \tau} \quad (2)$$

ter tega vstavimo v diferencialni enačbi za popis prenosa toplote in snovi v adsorbent. Tako določimo ravnotežno stanje v sloju adsorbenta z dvema diferencialnima enačbama, ki sta podani v nadaljevanju.

1.1 Izvedba toplotnega kompresorja

Toplotni kompresor je del sorpcijske naprave, v katerem je delovno sredstvo - adsorbent. Toplotni kompresor dvigne hladivo na višji tlačni in temperaturni nivo brez mehanske energije, z dovodom toplote. Toplotni kompresor deluje v dveh fazah: v fazi adsorpcije se hladivo veže na trdno snov, v fazi desorpcije pa se hladivo izloča iz nje.

The process of adsorption was taken into account through a heat generation term in the differential element, where he used the same method as Suzuki [1], with the variation of quantity adsorbed vs. time. Zheng [6] set up a model for the temperature fields along the heat compressor and transversely to the direction of flow of the heat transfer fluid. In distinction to Eichengrūn [4], Zheng assumed that pressure is equal over the entire heat compressor. Since the fluid flows over the adsorbent, he took into account the fluid's temperature gradient along the heat compressor. In our case it was decided that modelling would be performed in the same manner as Eichengrūn did it, but for a different heat compressor geometry.

1 ADSORPTION COOLING PROCESS

The basic difference between a classical cooling process and an adsorption one is in the way the refrigerant is compressed. In classical devices, compression is performed using a mechanical compressor, while in adsorption cooling, heat compressors are used for this purpose.

In order to be able to satisfactorily model the operation of a heat compressor, one must know the thermodynamic equilibrium of the working pair inside it. The state of the heat compressor is modelled through pressure p and temperature T . Determination of the equilibrium in the adsorbent, in which physical adsorption takes place, relies on the knowledge of the quantity adsorbed, x . This can be determined from adsorption isotherms given by the manufacturer [7], depending on temperature and pressure:

$$x = x(p, T) \quad (1).$$

The adsorbed quantity x , which is the third parameter of the equilibrium in the adsorbent, can be described as a function of temperature and pressure, therefore a total differential of adsorbed quantity x over pressure p and temperature T is calculated:

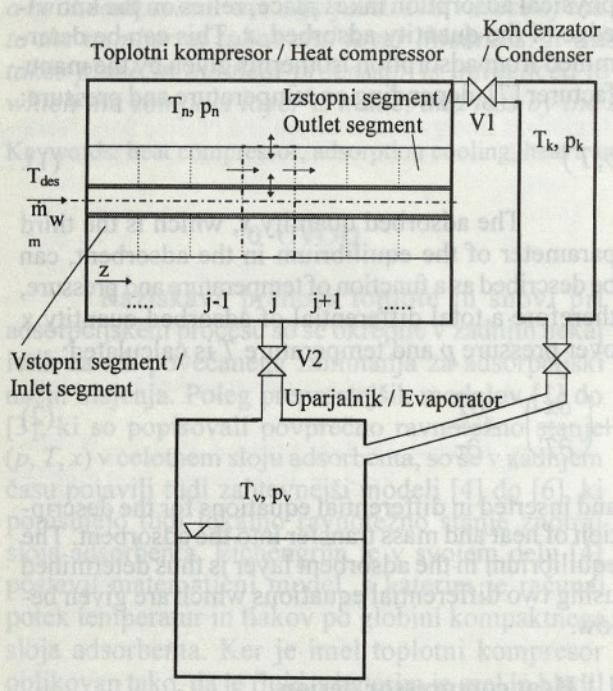
$$\frac{\partial x}{\partial \tau} = \left(\frac{\partial x}{\partial p} \right)_T \cdot \frac{\partial p}{\partial \tau} + \left(\frac{\partial x}{\partial T} \right)_p \cdot \frac{\partial T}{\partial \tau} \quad (2)$$

and inserted in differential equations for the description of heat and mass transfer into the adsorbent. The equilibrium in the adsorbent layer is thus determined using two differential equations which are given below.

1.1 Heat compressor design

A heat compressor is the part of a sorption device which contains the working fluid, i.e. an adsorbent. The heat compressor raises the refrigerant to a higher pressure and temperature level without mechanical energy, by mere heat input. Heat compressors operate in two phases: in the adsorption phase, the refrigerant is bound to a solid substance, while in the desorption phase it is released from it.

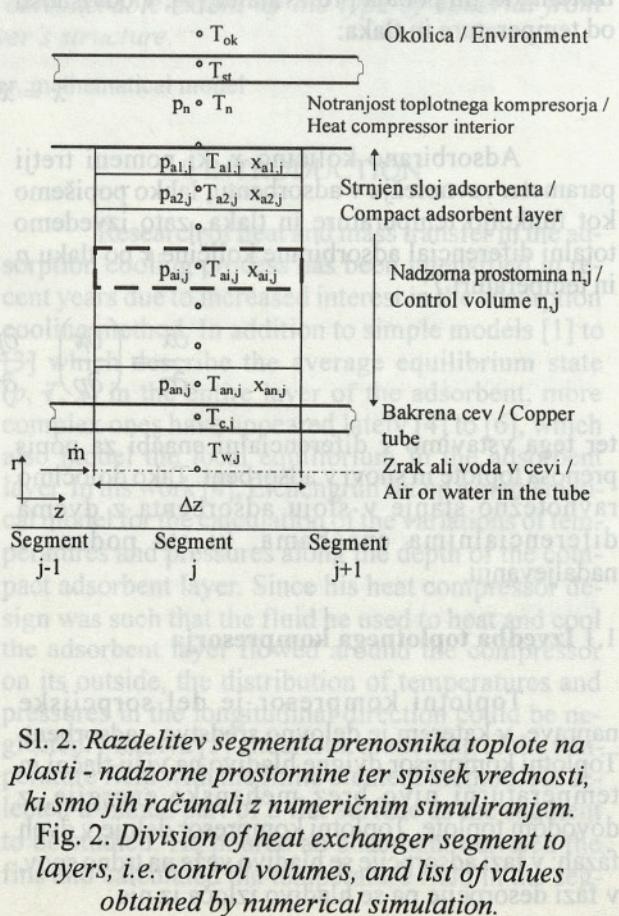
Za simuliranje delovanja toplotnega kompresorja smo izbrali valjasto obliko trdnega adsorbenta. V toplotnem kompresorju je prenosnik toplote, ki je v našem primeru ena ali več bakrenih cevi enakih dimenzijs, na katerih je strnjeno sloj delcev adsorbenta. Za tak sloj lahko predpostavimo, da poteka difuzija med delci makroporno, medtem ko za paro adsorbata v delcev adsorbenta ni upora prenosu snovi, torej da mikroporna difuzija pomeni zanemarljiv upor prenosu snovi. Za numerično simuliranje celotnega adsorpcijskega hladilnega procesa smo si izbrali tudi temperaturi v kondenzatorju T_k in v uparjalniku T_v . Zato smo toplotni kompresor, kakor je prikazano na sliki 1, namišljeno povezali s posodama, potrebnima za delovanje adsorpcijske hladilne naprave. Obravnavali smo temperaturno polje in polje koncentracij vzdolž prenosnika toplote, zato smo ga razdelili na več segmentov z indeksom j . Delitev segmenta prenosnika toplote na nadzorne prostornine, za katere smo računali lokalno adsorpcijsko ravnotežje (p, T, x), je prikazana na sliki 2. Simulirali smo le za delovno dvojico zeolit WE894 - voda.



Sl. 1. Shema adsorpcijske hladilne naprave, za katero smo izvedli numerično simuliranje.

Fig. 1. Schematic of the adsorption cooling device for which numerical simulation was performed.

A cylindrically shaped solid adsorbent was selected for the simulation of heat compressor operation. Heat compressors contain a heat exchanger, which in our case consisted of one or several copper tubes of equal dimensions, coated with a compact layer of an adsorbent, compact denoting a homogeneous, compressed layer of adsorbent particles. The diffusion between particles in such a layer can be assumed to be macroporous. However, the resistance to mass transfer in microporous diffusion is negligible, i.e. for the adsorbate vapour there is no resistance to mass transfer into the adsorbent particles. The temperatures in the condenser T_k and evaporator T_v were selected for numerical simulation of the entire adsorption cooling process. As presented in Figure 1, the heat compressor was virtually connected with two vessels required for the operation of the adsorption cooling device. The temperature and concentration fields along the heat exchanger were analysed and were therefore divided into several segments designated by index j . The division of heat exchanger segments to individual control volumes, for which local adsorption equilibria were calculated (p, T, x), is presented in Figure 2. Simulation was performed only for the working couple zeolite WE894 - water.

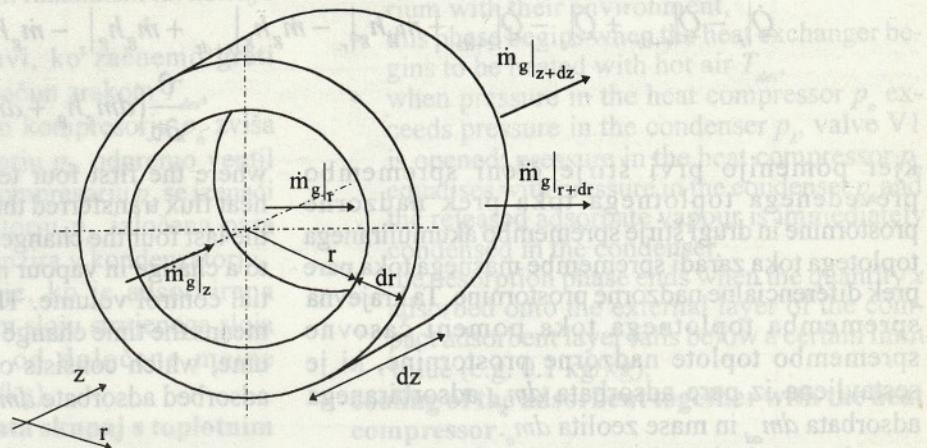


Sl. 2. Razdelitev segmenta prenosnika toplote na plasti - nadzorne prostornine ter spisek vrednosti, ki smo jih računali z numeričnim simuliranjem.

Fig. 2. Division of heat exchanger segment to layers, i.e. control volumes, and list of values obtained by numerical simulation.

1.2 Prenos snovi in toplote v strnjen sloj adsorbenta

1.2 Heat and mass transfer into a compact adsorbent layer



Sl. 3. Masni tokovi v diferencialni nadzorni prostornini sloja adsorbenta

Fig. 3. Mass flows in a differential control volume of the adsorbent layer

Osnovno obliko enačbe masnega ravnotežja smo za diferencialno nadzorno prostornino sloja adsorbenta, narisane na sliki 3, zapisali v obliki:

$$\dot{m}_g|_r - \dot{m}_g|_{r+dr} + \dot{m}_g|_z - \dot{m}_g|_{z+dz} = \frac{\partial m_g}{\partial \tau} + \frac{\partial m_{ad}}{\partial \tau} \quad (3),$$

kjer je sprememba masnega toka v radialni smeri r in osni smeri z , enaka časovni spremembi mase pare adsorbata dm_g :

$$dm_g = \rho \cdot dV = \frac{M_g}{RT} p \cdot \epsilon_{sl} \cdot dV \quad (4)$$

in adsorbiranega adsorbata dm_{ad} :

$$dm_{ad} = x \cdot \rho_a dV \quad (5).$$

Količino pare adsorbata v določeni nadzorni prostornini sloja adsorbenta smo določili po prvem Fickovem zakonu. Če predpostavimo, da imamo v toplotnem kompresorju samo paro adsorbata in ne zmesi plinov, lahko uporabimo plinsko enačbo za idealen plin in zapišemo:

$$\dot{m}_g = -A \cdot D_p \cdot \epsilon_{sl} \cdot \frac{M_g}{RT} \frac{\partial p}{\partial r} \quad (6).$$

Ob upoštevanju totalnega diferenciala adsorbirane količine x po temperaturi T in tlaku p , sledi končna oblika diferencialne enačbe za popis prenosa snovi v nadzorni prostornini:

$$\frac{1}{r} \frac{\partial p_{i,j}}{\partial r} + \frac{\partial^2 p_{i,j}}{\partial r^2} + \frac{\partial^2 p_{i,j}}{\partial z^2} = \left[\frac{1}{D_p} + \frac{\rho_a}{M_g \epsilon_{sl} D_p} \frac{\partial x}{\partial T} \right] \frac{\partial p_{i,j}}{\partial \tau} + \left[\frac{\rho_a}{M_g \epsilon_{sl} D_p} \frac{\partial x}{\partial T} \right] \frac{\partial T_{i,j}}{\partial \tau} \quad (7).$$

The basic form of a mass equilibrium equation for a differential control volume of the adsorbent layer from Figure 3 is written as follows:

where the sum of mass flow changes in the radial r and axial z directions equals the time change in the adsorbate vapour mass dm_g :

$$dm_g = \rho \cdot dV = \frac{M_g}{RT} p \cdot \epsilon_{sl} \cdot dV \quad (4)$$

and adsorbed adsorbate dm_{ad} :

$$dm_{ad} = x \cdot \rho_a dV \quad (5).$$

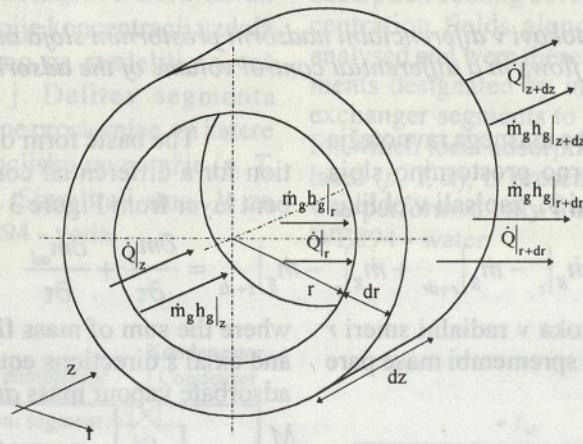
The quantity of the adsorbate in a certain control volume of the adsorbent layer was determined according to Fick's first law. Assuming that the heat compressor contains only adsorbate vapour and not a mixture of gases, the ideal gas equation can be used:

Taking into account the total differential of adsorbed quantity x over temperature T and pressure p , the final form of the differential equation to describe mass transfer in the control volume is:

Osnovna oblika energijske bilančne enačbe za diferencialno nadzorno prostornino sloja adsorbenta (i, j), narisano na sliki 4, je:

$$\dot{Q}|_r - \dot{Q}|_{r+dr} + \dot{Q}|_z - \dot{Q}|_{z+dz} + \dot{m}_g h_g|_r - \dot{m}_g h_g|_{r+dr} + \dot{m}_g h_g|_z - \dot{m}_g h_g|_{z+dz} = \frac{\partial}{\partial \tau} (dm_g h_g + dm_{ad} h_{ad} + dm_a h_a) \quad (8),$$

kjer pomenijo prvi štirje členi spremembo prevedenega toplotnega toka prek nadzorne prostornine in drugi štirje spremembo akumuliranega toplotega toka zaradi spremembe masnega toka pare prek diferencialne nadzorne prostornine. Ta krajevna sprememba toplotnega toka pomeni časovno spremembo topote nadzorne prostornine, ki je sestavljena iz pare adsorbata dm_g , adsorbiranega adsorbata dm_{ad} in mase zeolita dm_a .



Sl. 4. Energijski tokovi v diferencialni nadzorni prostornini sloja adsorbenta

Fig. 4. Energy fluxes in a differential control volume of the adsorbent layer

Ob upoštevanju vseh parametrov in odvisnosti entalpij h_g , h_{ad} in h_a od temperature T smo kot rezultat dobili diferencialno enačbo, s katero popišemo prenos toplote v notranji nadzorni prostornini sloja adsorbenta (i, j):

$$(9) \quad \left[\frac{M_g \varepsilon_{sl}}{RT} h_g + \rho_a h_{ad} \frac{\partial x}{\partial p} \right] \frac{\partial p_{i,j}}{\partial \tau} + \left[\frac{M_g \varepsilon_{sl}}{RT} c_g \cdot p_{i,j} + \rho_a \left(h_{ad} \frac{\partial x}{\partial T} + x c_{ad} + c_a \right) \right] \frac{\partial T_{i,j}}{\partial \tau}$$

The basic form of the energy-balance equation for the differential control volume of the adsorbent layer (i, j) from Figure 4 is:

where the first four terms represent the change in heat flux transferred through the control volume and the last four the change in heat flux accumulated due to a change in vapour mass flow through a differential control volume. This local change in heat flux means the time change in the heat of the control volume, which consists of the adsorbent vapour dm_g , adsorbed adsorbate dm_{ad} and zeolite mass dm_a .

Taking into account all parameters and variations of enthalpies h_g , h_{ad} and h_a with temperature T , the result was a differential equation which describes heat transfer in the internal control volume of the adsorbent layer (i, j):

2 SIMULIRANJE DELOVANJA TOPLOTNEGA KOMPRESORJA

Proces adsorpcijskega hlajenja s periodično delajočo napravo poteka v treh fazah:

2 SIMULATION OF HEAT COMPRESSOR OPERATION

The process of adsorption cooling within a periodically operating device takes place in three phases:

- faza desorpcije

- * celotni toplotni kompresor s prenosnikom toplote je v toplotnem in fizikalnem ravnotežju z okolico,
- * začetek faze se pojavi, ko začnemo greti prenosnik toplote z vročim zrakom T_{des} ,
- * ko se tlak v toplotnem kompresorju p_n zviša nad tlak v kondenzatorju p_k , odpremo ventil V1; tlak v toplotnem kompresorju p_n se izenači s tlakom v kondenzatorju p_k , izločena para adsorbata takoj kondenzira v kondenzatorju,
- * konec faze desorpcije, ko je adsorbirana količina x na zunanjem sloju strnjenega sloja adsorbenta manjša od določene mejne vrednosti (npr. 0,1 kg/kg),

- faza ohlajanja adsorbenta skupaj s toplotnim kompresorjem

- * dovod hladilne vode v prenosnik toplote za ohladitev toplotnega kompresorja,
- * ko je tlak v toplotnem kompresorju p_n nižji od tlaka v kondenzatorju p_k , ventil V1 zapremo,
- * konec faze ohlajanja, ko je temperatura na zunanjem robu strnjenega sloja nižja od določene mejne vrednosti (npr. 25°C),

- faza adsorpcije

- * začetek faze adsorpcije z odprtjem ventila V2,
- * prenosnik med potekom faze hladimo z vodo,
- * konec faze adsorpcije, ko adsorbirana količina x na zunanjem robu prenosnika toplote doseže določeno mejno vrednost (npr. 0,3 kg/kg).

Ker se prva faza desorpcije začne z vnaprej določenimi začetnimi pogoji, se vrednosti temperatur in tlakov po končani prvi fazi adsorpcije ne ujemajo z začetnimi pogoji desorpcije. Vrednosti se ujamejo šele po nekaj ciklih simuliranja.

2.1 Začetni in robni pogoji

Z računalniškim programom smo simulirali potek temperatur in tlakov v sloju adsorbenta in v toplotnem kompresorju v celoti. Pri tem smo uporabili dimenzijske toplotnega kompresorja in prenosnika toplote ter začetne pogoje, ki so podani v preglednici 1.

2.1.1 Faza desorpcije

Tlok v toplotnem kompresorju p_{des0} smo na začetku faze določili glede na temperaturo in je bil nižji od tlaka v kondenzatorju, zato da smo imeli povezovalni ventil V1 zaprt. Ob desorpciji vode iz zeolita je tlak v kompresorju naraščal in, ko je presegel tlak v kondenzatorju, smo ventil V1 odprli. Tlok smo nato predpostavili do konca faze enak tlaku v kondenzatorju. Začetni pogoji faze desorpcije so: $\tau = 0$, $i: 1 \dots \text{št. plasti}$, $j: 1 \dots \text{št. segmentov}$

- desorption phase

- * the entire heat compressor with a heat exchanger are in a thermal and physical equilibrium with their environment,
- * this phase begins when the heat exchanger begins to be heated with hot air T_{des} ,
- * when pressure in the heat compressor p_n exceeds pressure in the condenser p_k , valve V1 is opened; pressure in the heat compressor p_n equalises with pressure in the condenser p_k and the released adsorbate vapour is immediately condensed in the condenser,
- * the desorption phase ends when the quantity x adsorbed onto the external layer of the compact adsorbent layer falls below a certain limit value (e.g. 0.1 kg/kg),

- cooling of the adsorbent together with the heat compressor

- * input of coolant water into the heat exchanger to cool the heat compressor,
- * when pressure in the heat compressor p_n falls below pressure in the condenser p_k , valve V1 is closed,
- * this phase ends when temperature on the external edge of the compact layer falls below a certain limit value (e.g. 25°C),

- adsorption phase

- * begins with opening of the V2 valve,
- * heat exchanger is cooled with water throughout this phase,
- * the phase ends when the quantity x adsorbed onto the external layer of the heat exchanger reaches a certain limit (e.g. 0.3 kg/kg).

Since the first desorption phase begins under predetermined initial conditions, the values of temperatures and pressures after completion of the first adsorption phase do not match the initial conditions of desorption; they will fit only after a few cycles of simulation have been completed.

2.1 Initial and boundary conditions

A computer program was used to simulate the variation of temperatures and pressures in the adsorbent layer and the heat compressor in entirety. The heat compressor, exchanger dimensions and initial conditions given in Table 1 were used.

2.1.1 Desorption phase

The pressure in the heat compressor p_{des0} was determined at the beginning of the phase with regard to temperature, and it was lower than pressure in the condenser, so that the connection valve V1 was closed. During desorption of water from the zeolite, pressure in the compressor increased. When it exceeded pressure in the condenser, valve V1 was opened. All the way up to the end of this phase, pressure was assumed to be equal to that in the condenser. Initial conditions for the desorption phase were: $\tau = 0$, $i: 1 \dots \text{no. of layers}$, $j: 1 \dots \text{no. of segments}$

Preglednica 1. Dimenzijs topotnega kompresorja in vrednosti nekaterih parametrov
Table 1. Heat compressor dimensions and values of certain parameters

Zunanji premer topotnega kompresorja	100 mm
External heat compressor diameter	
Debelina stene topotnega kompresorja	1 mm
Heat compressor wall thickness	
Dolžina topotnega kompresorja L	600 mm
Heat compressor length L	
Cev prenosnika toplotne	Cu $\phi 12/14$ mm
Heat exchanger tube	
Debelina sloja adsorbenta s	1-5 mm
Adsorbent layer thickness s	
Temperatura okolice T_{ok}	20°C
Ambient temperature T_{ok}	
Temperatura desorpce - vroč zrak T_{des}	270°C
Temperature of desorption - hot air T_{des}	
Temperatura hladilne vode T_{hv}	15°C
Temperature of coolant water T_{hv}	
Temperatura kondenzacije T_k	25°C
Temperature of condensation T_k	
Temperatura uparjanja T_v	15°C
Temperature of evaporation T_v	
Masni tok vročega zraka m_{zr}	
Mass flow of hot air m_{zr}	0,0016 kg/s
Masni tok hladilne vode m_{hv}	
Mass flow of coolant water m_{hv}	0,001 kg/s
Število plasti v sloju adsorbenta	
Number of layers in the adsorbent	5
Število segmentov vzdolž prenosnika toplotne	
Number of segments along the heat exchanger	12

$$P_n, \quad P_a|_{i,j} = P_{des0}$$

(10).

$$T_{st}, \quad T_n, \quad T_r|_j, \quad T_w|_j, \quad T_a|_{i,j} = T_s(P_{des0})$$

(10).

Robne pogoje za zgornjo in spodnjo plast smo popisali z bilančnima enačbama prenosa toplotne in snovi. Pri zgornji plasti smo upoštevali konvektivni prenos toplotne v notranjost topotnega kompresorja, pri spodnji plasti pa prehod toplotne na cev prenosnika toplotne, kjer smo upoštevali tudi kontaktne upor med slojem adsorbenta in cevjo.

Drugi robni pogoji so pri $\tau > 0$:

- vstopna temperatura grelnega zraka:

Boundary conditions for the upper and lower layer were described with balance equations for heat and mass transfer. For the upper layer, convective heat transfer to the interior of the heat compressor was taken into account, and, for the lower layer, also heat transfer to the heat exchanger tube, including contact resistance between the adsorbent layer and the tube.

Other boundary conditions for $\tau > 0$ were:

- input temperature of hot air:

$$T_w|_{z=0} = T_{des} \quad (11),$$

- ni prenosa snovi skozi steno nosilne cevi:
- začetek in konec toplotnega kompresorja smo vzeli kot adiabatno izolirani in neprepustni steni:

$$\dot{m}|_{r=r_n} = 0 \Rightarrow \frac{\partial p}{\partial r}\Big|_j = 0 \quad (12),$$

$$\dot{Q}|_{z=0, z=L} = 0 \Rightarrow \frac{\partial T}{\partial z}\Big|_i = 0 \quad (13),$$

$$\dot{m}|_{z=0, z=L} = 0 \Rightarrow \frac{\partial p}{\partial z}\Big|_i = 0 \quad (14).$$

2.1.2 Faza ohlajanja

Začetni pogoji faze ohlajanja so vrednosti temperatur in tlakov v trenutku, ko se faza desorpkcije konča. Tako smo lahko simulirali nepretrgano delovanje naprave. Robni pogoji so enaki kakor pri fazi desorpkcije, s to razliko, da v cev prenosnika toplote začnemo dovajati hladilno vodo. Ta robni pogoj zapišemo kot:

2.1.3 Faza adsorpcije

Faza adsorpcije sledi, ko odpremo ventil V2, ki povezuje uparjalnik s toplotnim kompresorjem. Začetni pogoji so določeni podobno kakor v prejšnji fazi, in sicer so enaki vrednostim tlakov in temperatur na koncu faze ohlajanja. Robni pogoji so podobni pogojem faze ohlajanja, razlika je v tem, da smo predpostavili tlak v toplotnem kompresorju enak tlaku v uparjalniku, ki je odvisen od temperature uparjanja:

$$T_w|_{z=0} = T_{ohl} \quad (15).$$

2.1.3 Adsorpcion phase

This phase began when valve V2, which connected the evaporator with the heat compressor, was opened. The initial conditions were taken from the previous step, similarly as before; they were therefore equal to the values of pressures and temperatures at the end of the cooling phase. The boundary conditions were similar to those from the cooling phase, with one difference: pressure in the heat compressor was assumed to be equal to that in the evaporator, which depended on the evaporation temperature:

$$p_g|_{z=0} = p_s(T_v) \quad (16).$$

3 ANALIZA REZULTATOV SIMULIRANJA

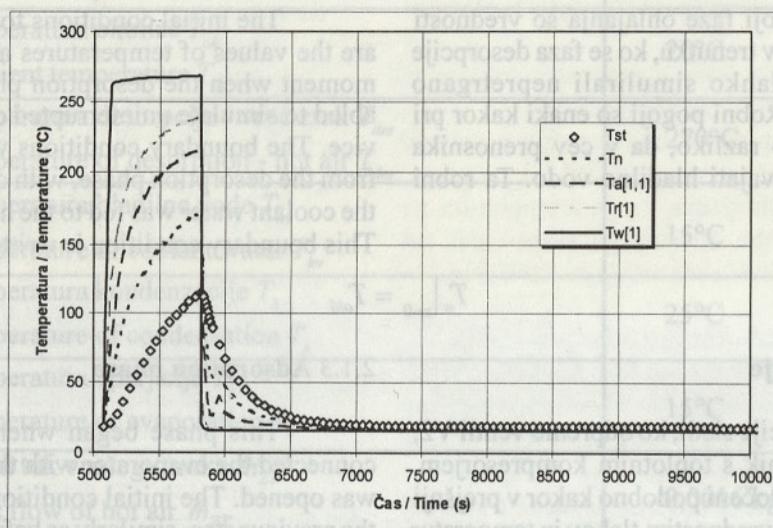
Simuliranje smo izvedli za več različnih debelin slojev in različna števila enakih vzporednih cevi v toplotnem kompresorju. Zaradi omejenosti prostora smo se omejili le na en primer simuliranja, za pogoje, podane v preglednici 1. Izbrali smo takšno število vzporednih cevi prenosnika toplote, da bi najbolj izkoristili notranjo prostornino toplotnega kompresorja. Predpostavili smo, da je v toplotnem kompresorju 16 vzporednih cevi, enakih dimenzijs ($r_z = 9\text{mm}$). S tem se prostornina toplotnega kompresorja povsem zapolni in pridobljena hladilna toplota poveča. Povečanje hladilne toplote je 13-kratno glede na toplotni kompresor z eno cevjo. Opazi

3 ANALYSIS OF SIMULATION RESULTS

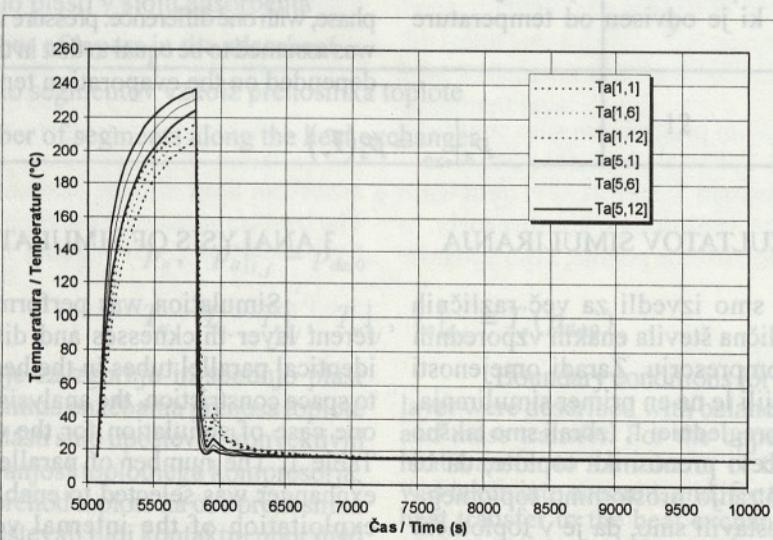
Simulation was performed for several different layer thicknesses and different numbers of identical parallel tubes in the heat compressor. Due to space constriction, the analysis was limited to only one case of simulation for the conditions given in Table 1. The number of parallel tubes in the heat exchanger was selected to enable the best possible exploitation of the internal volume of the heat compressor. The heat compressor was assumed to contain 16 parallel tubes with equal dimensions ($r_z = 9\text{ mm}$). The volume of the heat compressor was thus completely filled and the acquired coolant heat increased. The coolant heat increase was 13-fold in compari-

se, da povečanje ni premosorazmerno številu cevi, kajti upoštevati je treba tudi različne razmere (p, T) v topotnem kompresorju. Razlike simuliranja topotnega kompresorja z eno cevjo so predvsem v temperaturi notranjosti topotnega kompresorja T_n , ki se zaradi večjega števila cevi zviša do 170°C (sl. 5). Posredno je zaradi višje temperature v topotnem kompresorju višja tudi temperatura stene topotnega kompresorja T_{st} . Ker se temperatura T_n počasneje niža, je faza ohlajanja malo daljša, proces adsorpcije pa poteka zaradi višjih temperatur manj intenzivno (sl. 6 do 8). Slike 6 do 8 predstavljajo drugi krog numeričnega simuliranja, katerih začetne vrednosti so izračunane končne vrednosti faze adsorpcije prvega cikla.

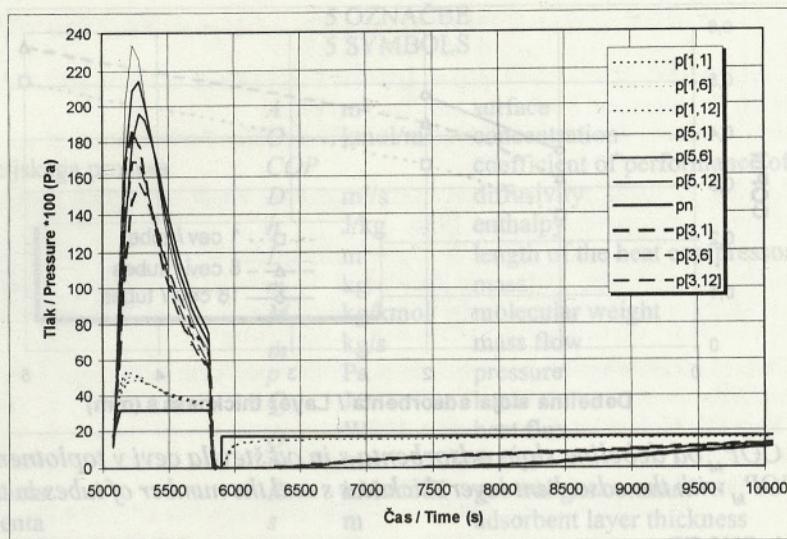
son with a single-tube heat exchanger. It can be noticed that this increase is not proportional to the number of tubes, because the conditions in the heat compressor (p, T) also need to be taken into account. The difference from simulation of a single-tube heat compressor lies above all in the temperature inside the heat compressor T_n , which increases to 170°C due to a greater number of tubes (Fig. 5). Indirectly, due to a higher temperature in the heat compressor, the temperature of the heat compressor wall T_{st} is also higher. Since T_n decreases more slowly, the cooling phase is slightly longer and the adsorption process is less intense due to higher temperatures (Fig. 6 to 8). Figures 6 to 8 present the second cycle of numerical simulation, the initial values of which are in fact the calculated final values of the first cycle's adsorption phase.



Sl. 5. Potek temperatur v vstopnem segmentu (1) ter stene T_{st} in notranjosti topotnega kompresorja T_n
Fig. 5. Variation of temperatures in the input segment (1), wall T_{st} and interior of the heat compressor T_n

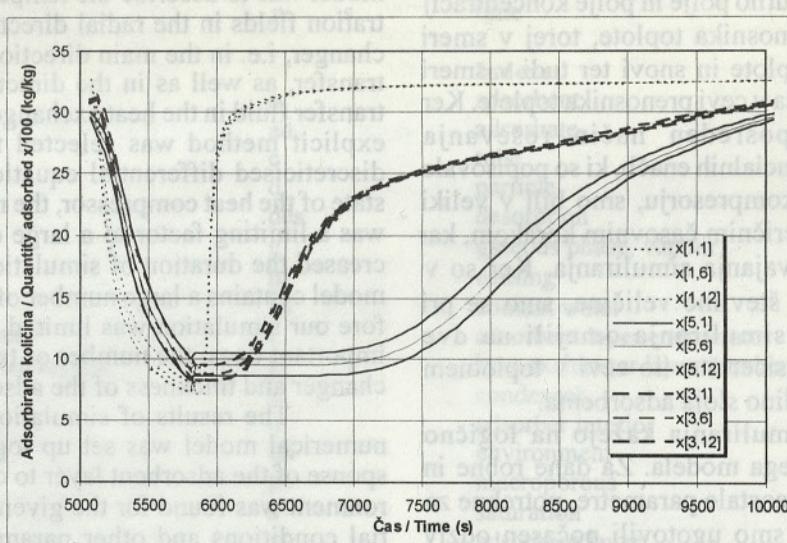


Sl. 6. Potek temperatur v zgornji in spodnji plasti (1), (5) vstopnega (1), srednjega (6) in izstopnega segmenta (12) sloja adsorbenta
Fig. 6. Variation of temperatures in the upper and lower layers (1), (5) of the input (1), middle (6) and output (12) segments of the adsorbent layer



Sl. 7. Potek tlakov med procesom v zgornji, srednji in spodnji plasti (1), (3), (5) sloja adsorbenta: vstopni (1), srednji (6) in izstopni segment (12) ter tlaka v notranjosti toplotnega kompresorja p_n

Fig. 7. Variation of pressures during the process in the upper, middle and lower layers of the adsorbent (1), (3), (5) of the input (1) middle (6) and output (12) segments of the adsorbent layer, and in the interior of the heat compressor p_n

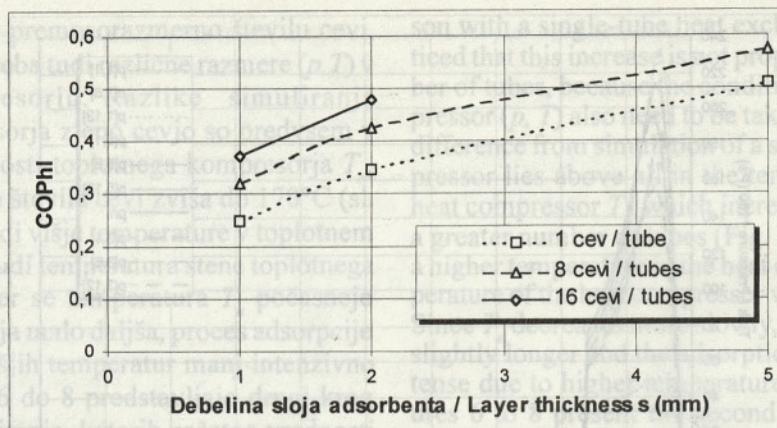


Sl. 8. Potek adsorbirane količine x med procesom v zgornji, srednji in spodnji plasti (1), (3), (5) sloja adsorbenta: vstopni (1), srednji (6) in izstopni segment (12)

Fig. 8. Variation of the quantity adsorbed x during the process in the upper, middle and lower layers of the adsorbent (1), (3), (5) of the input (1) middle (6) and output (12) segments

Na sliki 9 je prikazana odvisnost toplotnega števila procesa (COP_{hl}) od debeline sloja adsorbenta s in od števila cevi v toplotnem kompresorju. Vidimo, da je toplotno število nižje pri tanjem sloju, kar se ujema z našim pričakovanjem. Zaradi tanjšega sloja se več toplote porabi za segrevanje toplotnega kompresorja ter njegove toplotne izgube na okolico in ne za desorpcijo adsorbata. S povečanjem števila vzporednih cevi prenosnika toplote v toplotnem kompresorju se učinkoviteje zapolni njegova prostornina in s tem poviša toplotno število hlajenja procesa COP_{hl} .

Figure 9 shows the variation of coefficient of performance (COP_{hl}) with the adsorbent layer thickness s and the number of tubes in the heat compressor. It can be seen that for thinner layers the COP_{hl} is lower, which fits our expectations. Since the adsorbent layer is thinner, more heat is used to heat the compressor and for its heat loss into the environment, and not for the desorption of the adsorbate. With an increase in the number of parallel tubes in the compressor's heat exchanger, its volume is filled to a greater extent, thereby increasing the COP_{hl} of the process.



Sl. 9. Ovisnost COP_{hl} od debeline sloja adsorbenta s in od števila cevi v toplotnem kompresorju
Fig. 9. Variation of COP_{hl} with the adsorbent layer thickness s and the number of tubes in the heat compressor

4 SKLEP

Razvili smo matematični model za popis stanja v toplotnem kompresorju adsorpcijske hladilne naprave. Poseben poudarek smo dali prenosu toplote in snovi v sloju adsorbenta. Model smo razvili tako, da popisuje temperaturno polje in polje koncentracij v radialni smeri prenosnika toplote, torej v smeri glavnega prenosa toplote in snovi ter tudi v smeri toka prenosnega fluida v cevi prenosnika toplote. Ker je bil izbran neposreden način reševanja diskretiziranih diferencialnih enačb, ki so popisovale stanje v toplotnem kompresorju, smo bili v veliki meri omejeni z numeričnim časovnim korakom, kar je podaljšalo čas izvajanja simuliranja. Ker so v simulirnem modelu številne veličine, smo se pri analizi rezultatov simuliranja omejili na dve najpomembnejši, in sicer število cevi v toplotnem kompresorju in debelino sloja adsorbenta.

Rezultati simuliranja kažejo na logično postavitev numeričnega modela. Za dane robne in začetne pogoje ter preostale parametre, potrebne za numerični preračun smo ugotovili počasen odziv sloja adsorbenta na spremembe okolice, kar pomeni, da je treba iskati izvedbo kompaktnega sloja z višjo toplotno prevodnostjo in difuzivnostjo. To je mogoče v primeru, da omogočimo pari adsorbata lažji dostop do notranjosti sloja, kar lahko dosežemo z uporabo toplotno bolj prevodne nosilne strukture, npr. iz ekspandiranega grafita [8], v katero razporedimo adsorbent. Mogoča je tudi uporaba orehrenih cevi za prenosnik toplote, s katerimi pa ne moremo v večji meri vplivati na učinkovitost prenosa snovi v notranjost sloja.

4 CONCLUSIONS

A mathematical model was developed of the state in the heat compressor of an adsorption cooling device, with special emphasis on heat and mass transfer in the adsorbent layer. The objective of the model was to describe the temperature and concentration fields in the radial direction of the heat exchanger, i.e. in the main direction of heat and mass transfer, as well as in the direction of the flow of transfer fluid in the heat exchanger's tubes. Since an explicit method was selected for the solving of discretised differential equations describing the state of the heat compressor, the numerical time step was a limiting factor to a large extent, and this increased the duration of simulation. The simulation model contains a large number of parameters, therefore our simulation was limited to two of the most important ones: the number of tubes in the heat exchanger and thickness of the adsorbent layer.

The results of simulation showed that the numerical model was set up logically. A slow response of the adsorbent layer to changes in its environment was found for the given boundary and initial conditions and other parameters required for numerical calculations. This means that a compact layer with higher thermal conductivity and diffusivity should be sought. This will be possible only if easier access to the interior side of the layer is provided for the adsorbate vapour, which can be achieved by using a material with higher thermal conductivity, e.g. expanded graphite (8), and placing the adsorbent in it. The use of finned tubes for the heat exchanger is also possible, but in this case it will not be possible to influence the effectiveness of mass transfer into the interior side of the layer to any considerable extent.

Absorpcijske naprave za hlajenje in toplostevanje hlađenja in toplotne 5 OZNAČBE / 5 SYMBOLS

površina	A	m^2	surface
koncentracija snovi	C	kmol/m^3	concentration
toplotno število sorpcijskega procesa	COP		coefficient of performance of the sorption process
difuzivnost	D	m^2/s	diffusivity
entalpija	h	J/kg	enthalpy
dolžina	L	m	length of the heat compressor
masa	m	kg	mass
molna masa	M	kg/kmol	molecular weight
masni tok	\dot{m}	kg/s	mass flow
tlak	p	Pa	pressure
toplota	Q	J	heat
toplotski tok	\dot{Q}	W	heat flux
radij	r	m	radius
splošna plinska konstanta	R	kJ/kmolK	general gas constant
debelina sloja adsorbenta	s	m	adsorbent layer thickness
temperatura	T	K	temperature
vzdolžna koordinata	z	m	longitudinal coordinate
adsorbirana količina fluida na trdno telo	x	kg/kg	quantity of fluid adsorbed onto the solid body
toplotska prestopnost	α	$\text{W/m}^2\text{K}$	heat transfer coefficient
poroznost	ε		porosity
toplotska prevodnost	λ	W/mK	heat conductivity
gostota	ρ	kg/m^3	density
čas	τ	s	time

Indeksi

adsorbent	a
adsorbat	ad
cev	c
delec	d
desorpcija	des
plinasta faza, para	g
hlajenje	hl
hladilna voda	hv
števec plast adsorbenta	i
št. segmenta prenosnika toplote	j
kondenzator	k
notranjost adsorberja	n
okolica	ok
makroporen	p
nasičenje	s
sloj adsorbenta	sl
stena	st
uparjanje	v
grelni zrak	zr
fluid v cevi prenosnika toplote	w
začetna vrednost	0

komponente, ki sestavljajo toplotski transformator (VAT). Tako je večnamenski absorpcijski toplostevnik (VAT) naprava, ki je primerna za industrijsko uporabo odpadnih toplot [2].

Vse ved je razmerja za absorpcijske hladilne naprave (AHN), ki so zgrajene s toplotno energijo. V poletnih mesecih je te dovolj na voljo in takrat obstajajo možnosti, da se uporabni vodi za klimatizacijo zadržajo za uporabo toplote iz industrijskih procesov. Torej naprave delajo klad, ta zamenjajo stare, bolj povezane naprave in veljavno

Indexes

adsorbent	a
adsorbate	ad
tube	c
particle	d
desorption	des
gaseous phase, vapour	g
cooling	hl
coolant water	hv
adsorbent layer enumerator	i
heat exchanger layer number	j
condenser	k
adsorber interior	n
environment	ok
macroporous	p
saturation	s
adsorbent layer	sl
wall	st
evaporation	v
heating air	zr
fluid in the tube of the heat exchanger	w
initial value	0

potrebovanih. To se dogaja, ker so razmerji med potrebovanimi in dostopnimi viri energije neločljivi. Tako je razmerje med potrebovanimi in dostopnimi viri energije, ki je v tem primeru toplotno energijo, neločljivo. Tako je razmerje med potrebovanimi in dostopnimi viri energije, ki je v tem primeru toplotno energijo, neločljivo.

The absorption cooling devices (AHN) driven by heat energy are arousing greater interest than ever. The summer months offer this energy sufficiently, not to mention the increased requirements of cooled water for either air conditioning or water outlet from the industrial processes. The fact that the cold is produced by

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