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Eksergijska analiza parnih in sorpcijskih hladilnih procesov

Exergy Analysis of Vapour and Sorption Cooling Processes

ALOJZ POREDOŠ

Eksergija je dragocena energija. Po termodinamični analizi toplotnih procesov se lahko odločamo za eksergijsko bolj varčne narave. To je še posebej pomembno pri hladilnih procesih, pri katerih se poraba energije in eksergije z zniževanjem temperature hlajenja močno povečuje. V članku smo analizirali eksergijsko učinkovitost parnih in sorpcijskih hladilnih procesov. Takšna analiza mora biti temelj pri odločitvi za uporabo standardnih kompresorskih ali alternativnih, ekološko ustreznejših sorpcijskih hladilnih naprav.

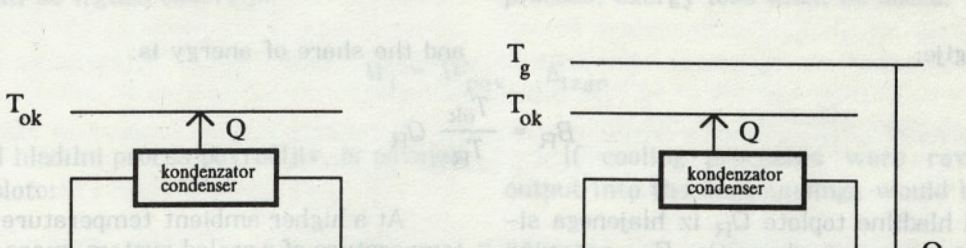
Exergy is precious energy. On the basis of thermodynamic analysis of thermal processes one can choose more exergy-saving devices. This is especially important in cooling processes in which the consumption of energy and exergy increases considerably with the falling of cooling temperature. The exergy efficiency of vapour and sorption cooling processes is analysed in the paper. Such an analysis should be the basis for deciding on the use of classic compressor cooling systems or alternative, ecologically more appropriate sorption cooling devices.

0 UVOD

Glavna naloga vsakega hladilnika je odvod toplote iz hlajenega sistema, ki je na nižji temperaturni ravni od okolice. Hipoteza R. Clausiusa, potrjena z drugim glavnim zakonom termodinamike nas uči, da teče toplota spontano samo z višje na nižjo temperaturno raven. Za nasproten proces potrebujemo dodatno energijo. Večina delujočih hladilnih naprav je izvedena s parnim hladilnim procesom in z mehanskim kompresorjem, ki porablja električno energijo (sl. 1a).

0 INTRODUCTION

The basic task of a cooling device is heat output from the cooled system, which is at a lower temperature level than its surroundings. The hypothesis of R. Clausius, confirmed by the Second Law of Thermodynamics, tells us that heat is transferred spontaneously only from a higher to a lower temperature level. Additional energy is needed for the reverse process. The majority of cooling devices utilize the vapour cooling process and a mechanical compressor driven by electric energy (Fig. 1a).



Sl. 1 *Shema parnega a) in sorpcijskega b) hladilnika*
Fig. 1. *A schematic of a) a vapour cooler, and b) a sorption cooler*

V današnjem času se povečuje delež hladilnikov na podlagi sorpcijskih procesov, ki so gnani s toplotnim kompresorjem (sl.1b). Oba hladilnika odvajata toploto iz hlajenega sistema s temperaturo T_R v okolico s temperaturo T_{ok}. Kompresorski hladilnik poganja mehanski kompresor, ki za dvig temperaturne in tlačne ravni toplote Q_R porablja tehnično delo W (električno energijo), ki je čista eksergija. Sorpcijski hladilnik deluje s toplotnim kompresorjem, ki ga poganja toplotna energija Q_g brez spremembe v električno ali mehansko energijo.

Sorpcijski hladilniki so ena od alternativ ekološko oporečnim hladilnim napravam. Za pogon takšnih hladilnikov je uporabna vsakršna toplota na ustrezni temperaturni ravni. Prednost sorpcijskih hladilnih naprav pred kompresorskimi je predvsem v možnosti uporabe eksergijsko revne odpadne toplote in v neposredni rabi alternativnih energijskih virov.

The share of coolers based on different sorption processes, driven by a heat compressor, has increased lately (Fig.1b). In both types of coolers heat is transferred from the cooled system with a temperature T_R into the surroundings. A compressor cooler is driven by a mechanical compressor utilizing technical work W (electric power), which is pure exergy, to increase the temperature and pressure level of the heat Q_R. A sorption cooler operates with a heat compressor driven by heat Q_g without its conversion into electrical or mechanical energy.

Sorption coolers are one of the alternatives for ecologically acceptable cooling. Any form of heat at an appropriate temperature level can be used to drive these coolers. One advantage of sorption cooling devices over compressor cooling devices is above all the possibility of utilizing waste heat with little exergy and the direct use of alternative energy sources.

1 EKSERGIJA HLADILNE TOPLOTE

Za delovanje hladilne naprave na temelju parnih ali sorpcijskih procesov potrebujemo natanko določeno zmes eksergije in anergije [1], [2]. V splošnem je hladilna toplota sestavljena iz eksergije in anergije:

1 EXERGY OF COOLING ENERGY

A precisely determined mixture of exergy and anergy is required for the functioning of a cooling device on the basis of vapour and sorption processes [1], [2]. In general, the cooling energy consists of exergy and anergy:

$$Q_R = E_R + B_R \quad (1),$$

pri tem je delež eksergije:

whereby the share of exergy is:

$$E_R = \left(\frac{T_{ok}}{T_R} - 1\right)|Q_R| \quad (2)$$

in delež anergije:

and the share of anergy is:

$$B_R = \frac{T_{ok}}{T_R} Q_R \quad (3).$$

Za odvod hladilne toplote Q_R iz hlajenega sistema potrebujemo več eksergije E_R, pri višji temperaturi okolice in pri nižji temperaturi hlajenega sistema.

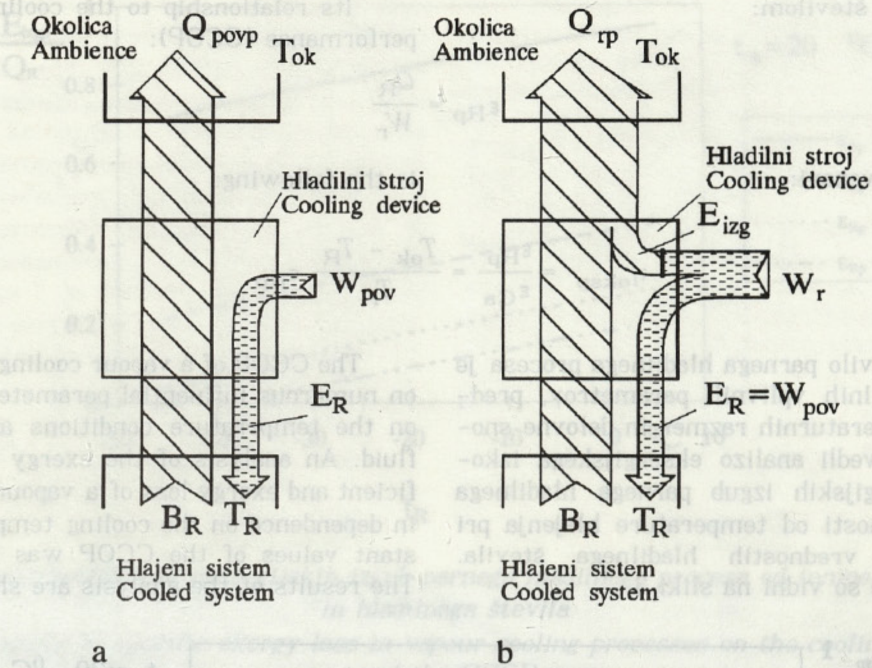
At a higher ambient temperature and a lower temperature of a cooled system, more exergy E_R is needed for heat output Q_R from the cooled system.

2 IZGUBE EKSERGIJE PRI PARNIH HLADILNIH PROCESIH

Parna hladilna naprava deluje med temperaturo hlajenega sistema T_R in temperaturo okolice T_{ok}. Njena naloga je dovod potrebnega deleža eksergije E_R v hlajeni objekt za odvod anergije B_R iz hlajenega objekta. Na sliki 2 vidimo Rantov diagram povračljive in nepovračljive hladilne naprave.

2 EXERGY LOSS IN VAPOUR COOLING PROCESSES

A vapour cooling device operates in the temperature range between the temperature of the cooled system T_R and ambient temperature T_{ok}. Its task is the input of the necessary share of exergy E_R into the cooled system for the output of anergy B_R from the cooled system. Figure 2 shows the Rant diagram of a reversible and an irreversible cooling devices.



Sl. 2. *Diagram energijskih tokov povračljivega a) in nepovračljivega b) parnega hladilnega procesa*
Fig. 2. *Diagram of energy flows in a) a reversible and b) an irreversible vapour cooling process*

V obeh primerih je hladilna toplota enaka Q_R in velja enačba (1). V primeru povračljivega hladilnega procesa je potrebna pogonska energija:

In both cases the cooling energy equals Q_R and eq. (1) is applied. In the case of a reversible cooling process, the necessary driving energy is:

$$W_{pov} = E_r \quad (4).$$

Pri nepovračljivem ali stvarnem procesu pa moramo dodati še izgube eksergije:

However, in an irreversible, i.e. a real process, exergy loss must be added:

$$W_r = W_{pov} + E_{izgp} \quad (5).$$

Če bi bil hladilni proces povračljiv, bi odvajali v okolico toploto:

If cooling processes were reversible, heat output into the surroundings would be:

$$Q_{povp} = B_R + W_{pov} \quad (6),$$

pri stvarnem procesu pa:

and in real processes:

$$Q_{rp} = B_R + W_r = B_R + W_{pov} + E_{izgp} \quad (7).$$

Termodinamično oceno stvarnih hladilnih procesov dobimo z eksergijskim izkoristkom, ki pomeni stopnjo povračljivosti procesa:

A thermodynamic assessment of real cooling processes can be obtained through the exergy efficiency coefficient, which represents the degree of reversibility of the process:

$$\eta_{eksp} = \frac{E_R}{W_r} = \frac{E_r}{W_{pov} + E_{izgp}} \leq 1 \quad (8).$$

S hladilnim številom:

Its relationship to the cooling coefficient of performance (CCOP):

$$\varepsilon_{Rp} = \frac{Q_R}{W_r} \qquad (9)$$

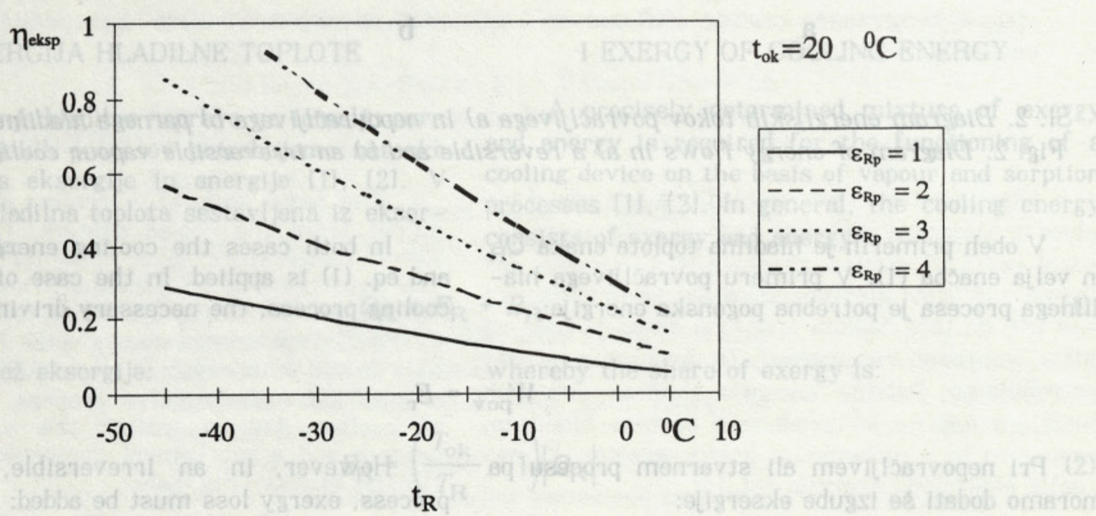
je v naslednji povezavi:

is the following:

$$\eta_{eksp} = \frac{\varepsilon_{Rp}}{\varepsilon_{Ca}} = \frac{T_{ok} - T_R}{T_R}\,\varepsilon_{Rp} \qquad (10).$$

Hladilno število parnega hladilnega procesa je odvisno od številnih vplivnih parametrov, predvsem pa od temperaturnih razmer in delovne snovi. Zato smo izvedli analizo eksergijskega izkoristka in eksergijskih izgub parnega hladilnega procesa v odvisnosti od temperature hlajenja pri nespremenjenih vrednostih hladilnega števila. Rezultati analize so vidni na sliki 3.

The CCOP of a vapour cooling process depends on numerous influential parameters and above all on the temperature conditions and the working fluid. An analysis of the exergy efficiency coefficient and exergy loss of a vapour cooling process in dependence on the cooling temperature at constant values of the CCOP was therefore made. The results of the analysis are shown in figure 3.



Sl. 3. *Odvisnost eksergijskega izkoristka parnega hladinega procesa od temperature hlajenja in hladilnega števila*

Fig. 3. *Dependence of the exergy efficiency coefficient of a vapour cooling process on the temperature of cooling and the CCOP*

Eksergijski izkoristek z naraščajočo temperaturo hlajenja pada in z naraščajočim hladilnim številom narašča. Podobne ugotovitve so dane v [3].

Iz enačb (4) in (5) ter z upoštevanjem eksergije hladilne toplote dobimo enačbo za specifične eksergijske izgube [3]:

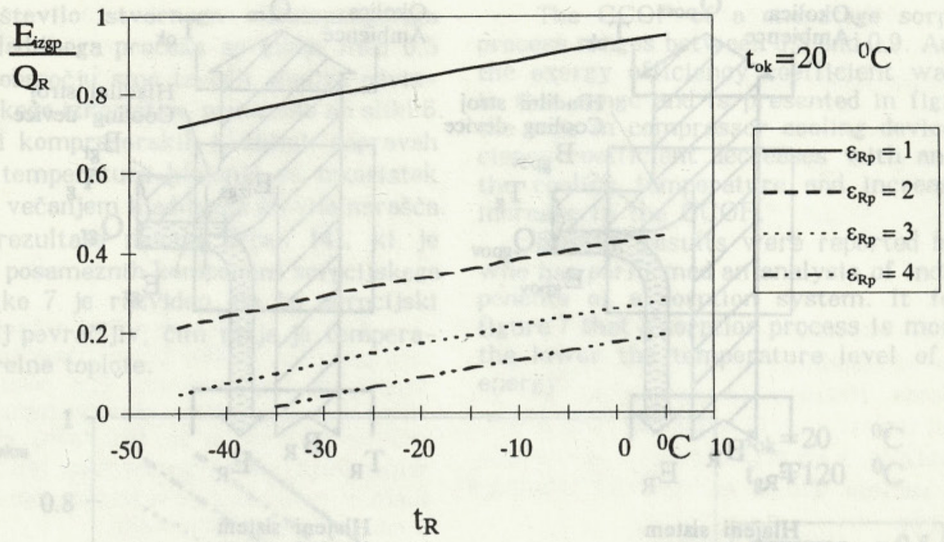
The exergy efficiency coeficient falls with an increase in the cooling temperature and rises with an increase in the CCOP. Similar findings are given in [3].

The equation for specific exergy loss is obtained by combining eqs. (4) and (5) and by taking into account the exergy of the cooling energy [3]:

$$\frac{E_{izgp}}{Q_R} = \frac{1}{\varepsilon_{Rp}} - \frac{T_{ok}}{T_R}\frac{T_R}{T_R} \qquad (11).$$

Na sliki 4 so prikazane specifične eksergijske izgube pri različnih vrednostih hladilnega števila in v odvisnosti od temperature hlajenja.

Figure 4 shows specific exergy loss for different values of the CCOP and in dependence on the cooling temperature.



Sl. 4. *Odvisnost specifičnih eksergijskih izgub parnega hladilnega procesa od temperature hlajenja in hladilnega števila*

Fig. 4. *Dependence of specific exergy loss in vapour cooling processes on the cooling temperature and the CCOP*

Eksergijske izgube so močno odvisne od hladilnega števila in nekoliko manj od temperature hlajenja. Torej imajo na nepovračljivosti parnega hladilnega procesa močan vpliv tudi drugi delovni parametri hladilne naprave, ki so zajeti v ε_{Rp}.

The exergy loss depends to a large extent on the CCOP and slightly less on the cooling temperature. Other operational parameters of a cooling process, comprised in ε_{Rp} also have a strong effect on the irreversibility of the vapour cooling process.

3 IZGUBE EKSERGIJE SORPCIJSKIH HLADILNIH PROCESOV

3 EXERGY LOSS IN SORPTION COOLING PROCESSES

Toplota, ki jo uporabimo za pogon sorpcijskih hladilnih naprav je običajno eksergijsko revna energija. Pri parnih hladilnih procesih smo ugotovili, da potrebujemo za odvod hladilne energije Q_R iz hlajenega sistema natančno določeno količino eksergije E_R. Enako velja tudi za sorpcijske hladilne procese.

Glede na Rantov diagram na sliki 5a za povračljivi sorpcijski hladilni proces, kjer smo prikazali energijske tokove, moramo v proces dovajati grelno energijo:

Heat used to drive sorption cooling devices usually has little exergy. It was established in vapour cooling processes that a precisely determined amount of exergy E_R is needed for cooling energy Q_R output from a cooled system. The same applies to sorption cooling processes.

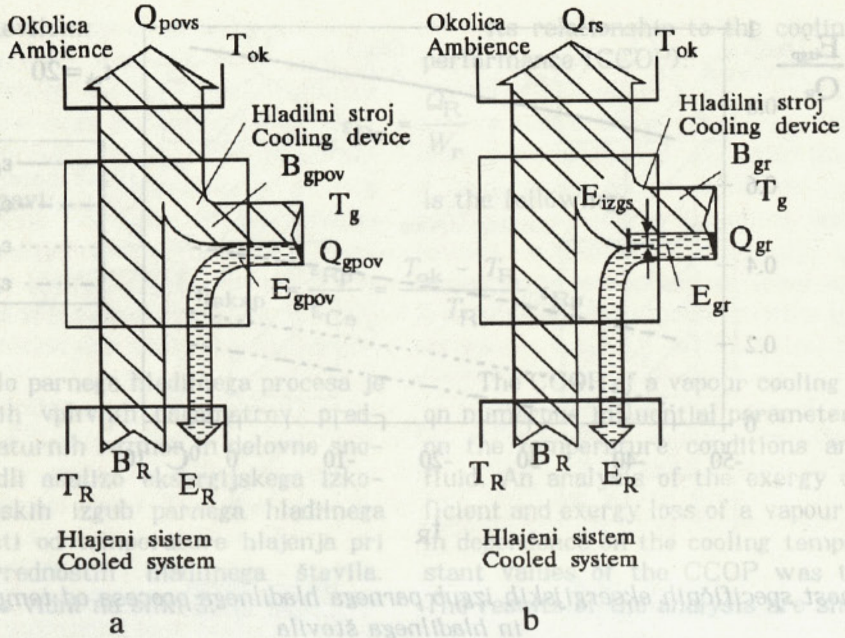
According to the Rant diagram presented in figure 5a for a reversible sorption cooling process, in which energy flows were presented, the necessary energy input is:

$$Q_{gpov} = E_{gpov} + B_{gpov} \qquad (12).$$

Ta energija mora biti na višji temperaturni ravni od okolice. V primeru stvarnega sorpcijskega hladilnega procesa na sliki 5b, se pojavijo izgube eksergije in zato se poveča količina grelne energije, za E_{izgs} in pripadajoči delež anergije. Torej velja:

This energy has to be at a temperature level higher than that of the surroundings. In the case of a real sorption cooling process according to figure 5b, exergy loss occurs, so the amount of energy for heating is increased by E_{izgs} and by the appertaining share of anergy. Thus:

$$Q_{gr} = E_{gr} + B_{gr} = E_{gpov} + E_{izgs} + B_{gr} \qquad (13).$$



Sl. 5. *Diagram energijskih tokov povračljivega a) in nepovračljivega b) sorpcijskega hladilnega procesa*

Fig. 5. *Diagram of energy flows in a) a reversible and b) an irreversible sorption cooling process*

Skupna odvedena energija iz stvarnega procesa in hlajenega sistema v okolico je vsota anergije grelne toplote, izgub eksergije v procesu in anergije hladilne toplote:

The total energy output from a real process and a cooled system into its surroundings is a sum of the anergy of heat, exergy loss in the process and the anergy of the cooling energy:

$$Q_{rs} = B_{gr} + E_{izgs} + B_R \tag{14}$$

Eksergijski izkoristek sorpcijskega hladilnega procesa je definiran podobno kakor pri parnem procesu, s tem, da zamenjamo mehansko vloženo delo z grelno toploto:

The exergy efficiency coefficient of a sorption cooling process is defined analogously as in the vapour cooling process: the mechanical work input is replaced by heat:

$$\eta_{ekss} = \frac{E_R}{E_{gr}} = \frac{E_R}{E_{gpov} + E_{izgs}} \leq 1 \tag{15}$$

Z upoštevanjem izraza za hladilno število sorpcijskega hladilnega procesa:

Taking into account the expression for the CCOP of a sorption cooling process:

$$\varepsilon_{Rs} = \frac{Q_R}{Q_{gr}} \tag{16}$$

in enačbe (2) dobimo zvezo med eksergijskim izkoristkom sorpcijskega hladilnega procesa in hladilnim številom ter temperaturnimi razmerami:

and eq. (2), the relationship between the exergy efficiency coefficient of a sorption cooling process and the CCOP on one hand, and temperature conditions on the other can be obtained:

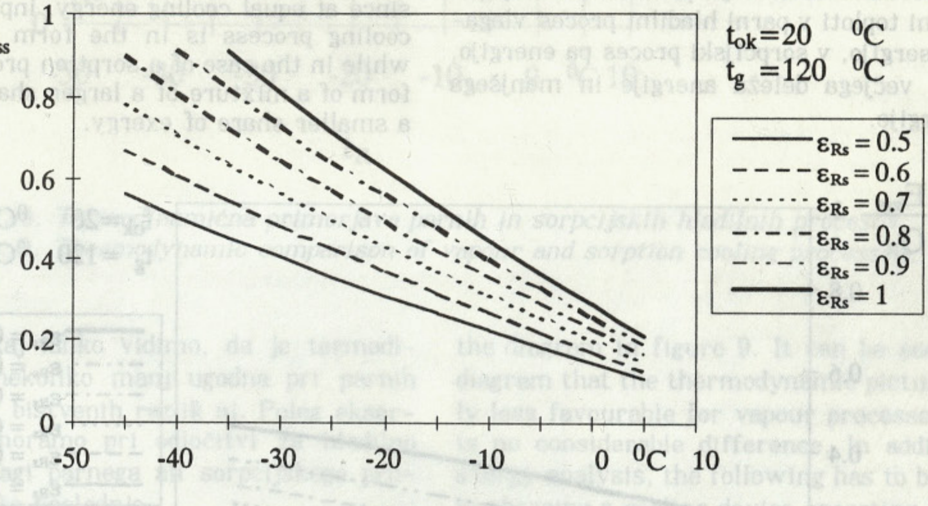
$$\eta_{ekss} = \frac{Q_R\left(\dfrac{T_{ok} - T_R}{T_R}\right)}{Q_{gr}\left(\dfrac{T_g - T_{ok}}{T_g}\right)} = \varepsilon_{Rs}\,\frac{T_{ok} - T_R}{T_R}\cdot\frac{T_g}{T_g - T_{ok}} \tag{17}$$

Hladilno število stvarnega enostopenjskega sorpcijskega hladilnega procesa se giblje med 0,5 in 0,9. V tem območju smo izvedli analizo odvisnosti eksergijskega izkoristka, prikazano na sliki 6. Tako kakor pri kompresorskih hladilnih napravah z naraščajočo temperaturo hlajenja se izkoristek zmanjšuje in z večanjem hladilnega števila narašča.

Podobne rezultate navaja Erçan [4], ki je opravil analizo posameznih komponent sorpcijskega sistema. S slike 7 je razvidno, da bo sorpcijski proces tem bolj povračljiv, čim nižja je temperaturna raven grelne toplote.

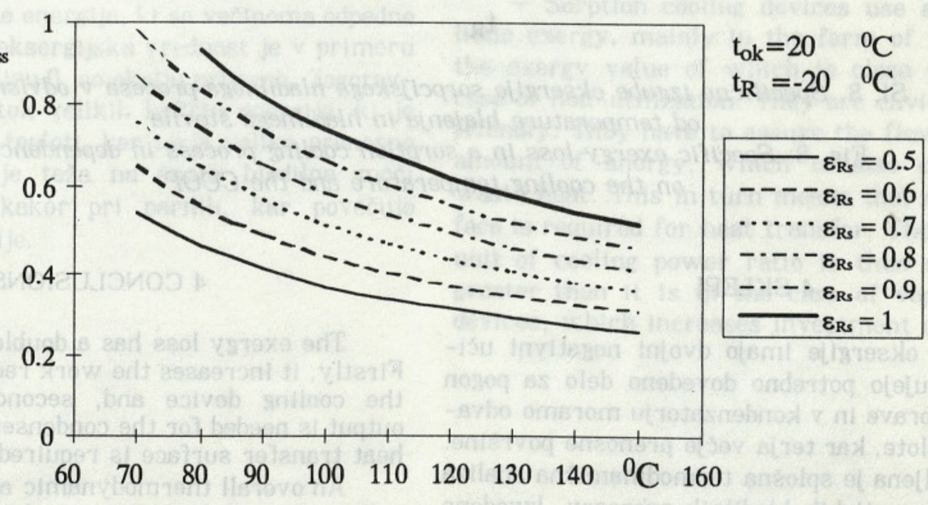
The CCOP of a one-stage sorption cooling process ranges between 0.5 and 0.9. An analysis of the exergy efficiency coefficient was performed in this range and is presented in figure 6. As is the case in compressor cooling devices, the efficiency coefficient decreases with an increase in the cooling temperature and increases with an increase in the CCOP.

Similar results were reported by Erçan [4], who has performed an analysis of individual components of a sorption system. It follows from figure 7 that a sorption process is more reversible the lower the temperature level of the heating energy.



Sl. 6. *Odvisnost eksergijskega izkoristka sorpcijskega hladilnega procesa od temperature hlajenja in hladilnega števila*

Fig. 6. *Dependence of the exergy efficiency coefficient of a sorption cooling process on the cooling temperature and the CCOP*



Sl. 7. *Odvisnost eksergijskega izkoristka sorpcijskega hladilnega procesa od temperaturne ravni grelne toplote in hladilnega števila*

Fig. 7. *Dependence of exergy efficiency coefficient of a sorption cooling process on the temperature level of the heating energy and the CCOP*

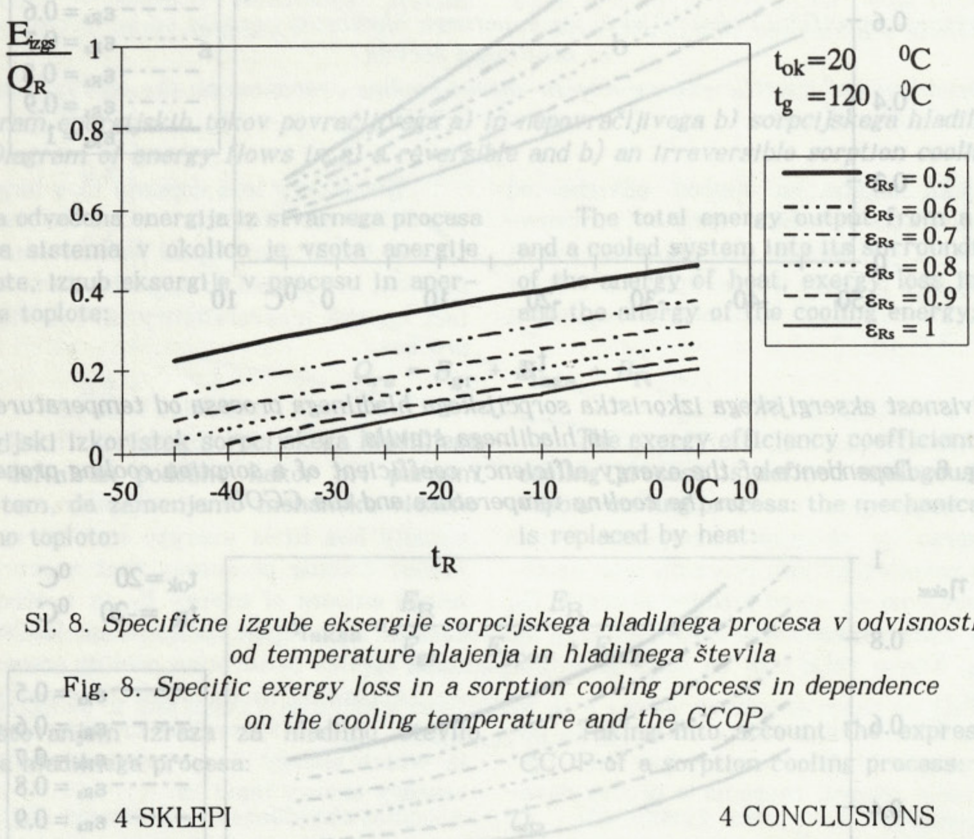
Iz enačbe (14) z upoštevanjem eksergije hladilne in grelne toplote dobimo za specifične izgube eksergije v sorpcijskem hladilnem procesu naslednji izraz:

The following expression is obtained from eq. (14) for specific exergy loss in a sorption cooling process by taking into account the exergy of the cooling energy and the heating energy:

$$\frac{E_{izgs}}{Q_R} = \frac{1}{\varepsilon_{Rs}}\left(1 - \frac{T_{ok}}{T_g}\right) - \left(\frac{T_{ok}}{T_R} - 1\right) \qquad (18).$$

Specifične eksergijske izgube po sliki 8 so manj odvisne od hladilnega števila kakor v primeru parnega procesa. Rezultat je pričakovan, saj pri enaki hladilni toploti v parni hladilni proces vlagamo čisto eksergijo, v sorpcijski proces pa energijo, ki je zmes večjega deleža anergije in manjšega deleža eksergije.

The specific exergy loss according to figure 8 depends less on the CCOP than is the case in a vapour cooling process. The result is expected, since at equal cooling energy, input into a vapour cooling process is in the form of pure exergy, while in the case of a sorption process it is in the form of a mixture of a larger share of anergy and a smaller share of exergy.



Sl. 8. *Specifične izgube eksergije sorpcijskega hladilnega procesa v odvisnosti od temperature hlajenja in hladilnega števila*

Fig. 8. *Specific exergy loss in a sorption cooling process in dependence on the cooling temperature and the CCOP*

4 SKLEPI

Izgube eksergije imajo dvojni negativni učinek. Povečujejo potrebno dovedeno delo za pogon hladilne naprave in v kondenzatorju moramo odvajati več toplote, kar terja večje prenosne površine.

Opravljena je splošna termodinamična analiza parnih in sorpcijskih hladilnih procesov. Izvedene preproste parne hladilne naprave delujejo s povprečnimi hladilnimi števili ε_{Rp} od 2 do 2,5, njim podobne sorpcijske hladilne naprave pa dosegajo dejanska hladilna števila ε_{Rs} med 0,6 in 0,8.

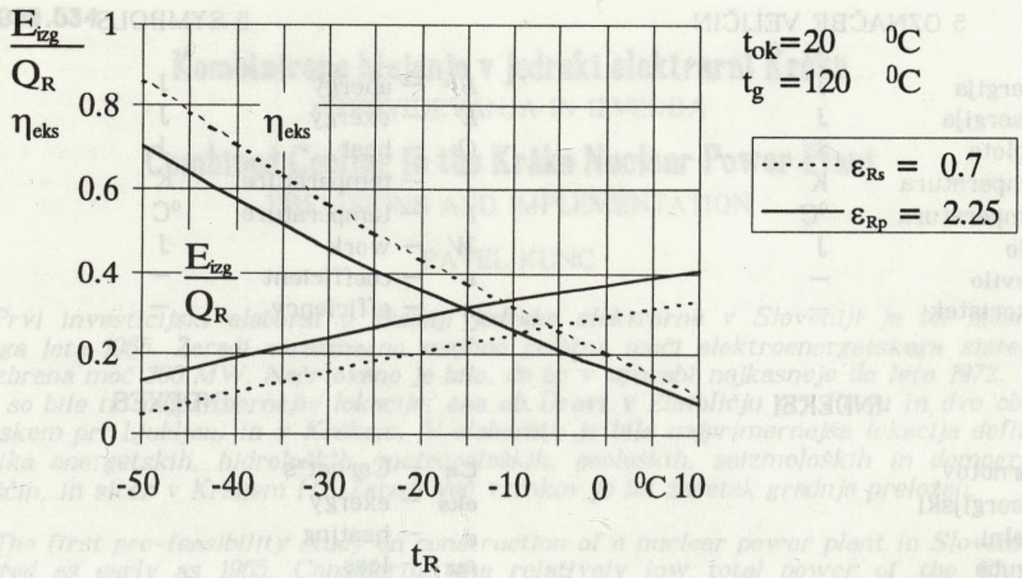
Za navedene povprečne vrednosti je narejena in v diagramu na sliki 9 prikazana eksergijska

4 CONCLUSIONS

The exergy loss has a double negative effect. Firstly, it increases the work required for driving the cooling device and, secondly, higher heat output is needed for the condenser, so that a larger heat transfer surface is required.

An overall thermodynamic analysis of vapour and sorption cooling processes has been performed. Simple vapour cooling devices operate with average CCOPs ε_{Rp} from 2 to 2.5; while analogous sorption cooling devices achieve real CCOPs ε_{Rs} from 0.6 to 0.8.

A comparison of exergy has been performed for the listed average values and is presented in



Sl. 9. *Termodinamična primerjava parnih in sorpcijskih hladilnih procesov*

Fig. 9. *Thermodynamic comparison of vapour and sorption cooling processes.*

primerjava. Tukaj lahko vidimo, da je termodinamična slika nekoliko manj ugodna pri parnih procesih, vendar bistvenih razlik ni. Poleg eksergijske analize moramo pri odločitvi za hladilno napravo na podlagi parnega ali sorpcijskega procesa upoštevati še naslednje,

– Parne hladilne naprave so energetsko učinkovitejše (večji ε_{Rp}) in eksergetsko nekoliko manj učinkovite (manjši η_{eks}). Porabljajo čisto eksergijo in so manjše.

– Sorpcijske hladilne naprave porabljajo eksergijsko revne energije, ki so večinoma odpadne toplote, katerih eksergijska vrednost je v primeru neizkoriščanja blizu 0, so okolju prijazne. Zagotavljati morajo pretok velikih količin anergije, ki je v odpadni grelni toploti, kar terja velike prenosne površine. Zato je teža na enoto hladilne moči bistveno večja kakor pri parnih, kar povečuje stroške investicije.

the diagram in figure 9. It can be seen from the diagram that the thermodynamic picture is slightly less favourable for vapour processes, but there is no considerable difference. In addition to the exergy analysis, the following has to be considered in choosing a cooling device operating on the basis of a vapour or a sorption process.

– Steam cooling devices are more efficient in terms of energy (a higher ε_{Rp}) and slightly less efficient in terms of exergy (lower η_{eks}). They consume pure exergy. They are more compact.

– Sorption cooling devices use energy with little exergy, mainly in the form of waste heat, the exergy value of which is close to 0 in the case of non-utilization. They are environmentally friendly. They have to assure the flow of a large amount of anergy, which is also contained in waste heat. This in turn means that a large surface is required for heat transfer. The weight per unit of cooling power ratio is thus considerably greater than it is in the case of vapour cooling devices, which increases investment costs.

5 OZNAČBE VELIČIN

B — anergija J
E — eksergija J
Q — toplota J
T — temperatura K
t — temperatura ^{0}C
W — delo J
ε — število —
η — izkoristek —

INDEKSI

Ca — Carnotov
eks — eksergijski
g — grelni
izg — izgube
ok — okolica
p — parni
pov — povračljivi
R — hladilni
r — realni
s — sorpcijski

5 SYMBOLS

B — anergy J
E — exergy J
Q — heat J
T — temperature K
t — temperature ^{0}C
W — work J
ε — coefficient —
η — efficiency —

INDEXES

Ca — Carnot's
eks — exergy
g — heating
izg — loss
ok — surroundings
p — vapour
pov — reversible
R — cooling
r — real
s — sorption

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