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Analiza eksergijskih tokov absorpcijske hladilne naprave

An Analysis of Exergy Flows in an Absorption Chiller

Vasilije Vasić - Jurij Krope - Darko Goričanec

V prispevku je podan postopek analize eksergijskih in anergijskih tokov v enostopenjski absorpcijski hladilni napravi z delovnim medijem LiBr/H_2O ter postopek izračuna eksergijskega izkoristka v odvisnosti od stopnje uporabe naprave.

Nakazana je prednost absorpcijske hladilne naprave pred kompresijsko hladilno napravo, ki se izkazuje v možnosti uporabe eksergijsko revne odpadne toplote in v rabi alternativnih energetskih virov.

(Ključne besede: naprave hladilne, naprave absorpcijske, tok energijski, izkoristek eksergijski)

This paper presents our analysis of the exergy and anergy flows and exergy efficiency of an absorption chiller which has been calculated for all areas of the device's exploitation. This analysis has been implemented on a single-stage absorption chiller with LiBr/H_2O as a working media.

We wish to show the advantages of sorption chillers, in our case absorption chillers, in comparison to compressor chillers in utilizing low exergy, rejected heat and in the use of alternative energy sources.

(Keywords: thermodynamics, absorption chiller, exergy flow, efficiency)

0 UVOD

Potreba po hlajenju postaja v sodobnem svetu vedno večja zaradi večjih zahtev po bivalnem ugodju, kar pa je povezano z zahtevnejšimi tehnološkimi procesi. Hlad tako postaja enakovreden produkt električni energiji in toploti.

Hlad se pridobiva najpogosteje s kompresorskimi hladilnimi napravami, katerim postajajo vse bolj konkurenčne absorpcijske hladilne naprave in namesto mehanske (električne) energije uporablja toploto.

Absorpcijska hladilna naprava (sl. 1) je sestavljena iz dveh obtokov – gretja in hlajenja, ki sta med seboj povezana. Posebnost naprave je toplotni kompresor, medtem ko so elementi hladilnega obtoka enaki kakor pri kompresorski hladilni napravi.

Delovne snovi absorpcijske hladilne naprave so okolju precej bolj prijazne od tistih pri kompresijski hladilni napravi. Najpogosteje se uporabljata delovni snovi – binarna zmes LiBr/H_2O ali H_2O/NH_3.

0 INTRODUCTION

The demand for cooling is growing as peoples' expectations of a more comfortable life, surrounded by technology continues to increase. Cooling is becoming a product equivalent to electricity and heat.

The cooling process is most frequently carried out compressor chillers, of which absorption chillers are becoming increasingly significant. In contrast to the compressor chillers, absorption chillers are driven by heat rather than electricity.

An absorption chiller (Figure 1) works using two interconnected cycles - heating and cooling. The device's speciality is its thermal compressor, while the cooling cycle is undertaken using the same components found in compressor chillers.

The working media of absorption chillers are environmentaly friendly compared to those used by compressor chillers because the most frequently used working media for absorption chillers are binary mixtures of LiBr/H_2O and H_2O/NH_3.

1 DELOVANJE NAPRAVE

Delovanje absorpcijske hladilne naprave poteka, prikazano posplošeno, na dveh tlačnih nivojih, treh temperaturnih nivojih in treh nivojih koncentracije hladiva [1].

Generatorju in uparjalniku se toplota dovaja na najvišjem oz. najnižjem temperaturnem nivoju, medtem ko se okolici toplota predaja na srednjem temperaturnem nivoju iz kondenzatorja in absorberja (sl. 1).

Vezava zunanjega obtoka kondenzatorja in absorberja je lahko ločena (vzporedna vezava) ali pa povezana (serijska vezava). Učinkovitejši način je serijska vezava [1], ki je uporabljena v primeru analize eksergijskih tokov.

Izhodišče vsake termodinamične analize procesa ali postroja je energijska bilanca (prvi glavni zakon termodinamike). V apsorbcijski hladilni napravi

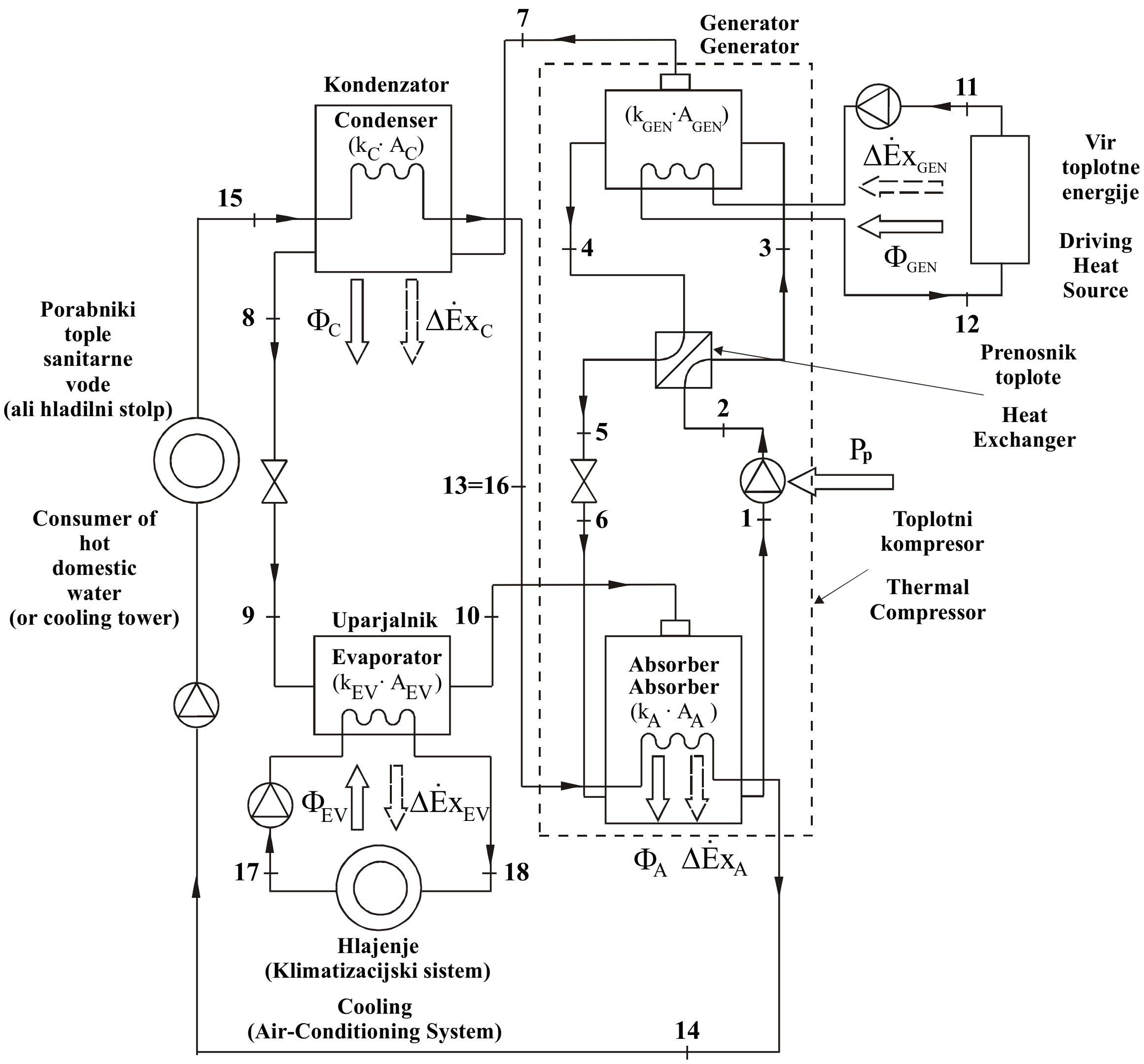
1 THE PERFORMANCE OF THE ABSORPTION CHILLER

The functioning of an absorption chiller can be described simply as a process between two pressure levels, three temperature levels and three levels of coolant concentration [1].

Heat is provided to the generator and evaporator at either the highest or lowest temperature levels, respectively. In the mean time, heat is delivered from the absorber and the condenser to the surroundings at the medium temperature level (Figure 1).

The external-flow connection to the condenser and the absorber can be either independent (parallel flow) or connected (serial flow). Serial connection has proved to be the more efficient method [1] and has been adopted when presenting our analysis of exergy flows.

At the beginning of each thermodynamic analysis of thermal processes or a thermal plant we use the energy balance (First Law of Thermodynam-



Sl. 1. *Shema absorpcijske hladilne naprave*
Fig. 1. *Model of the absorption chiller*

imamo različne oblike energij (npr. toplotna, električna), katerih vrednost se kaže v stopnji zmožnosti za pretvarjanje v druge oblike energij. Popolnoma spremenljiv del energije v druge oblike energij se imenuje eksergija, nespremenljiv del pa anergija.

Vse energije preračunamo na enako osnovo – eksergijo. Analiza eksergijskih tokov, ki temelji na drugem glavnem zakonu termodinamike, ima nalogo določiti: mesta nepovračljivosti, velikost nepovračljivosti, smer odvijanja procesov in celotno učinkovitost naprave.

Pri analizi eksergijskih tokov se ne omejimo samo na analizo popolnosti procesov v napravi, temveč tudi na procese s toplotno menjavo delovne snovi s toplotnimi prejemniki in medsebojnimi vplivi na okolje [2].

Velikost nepovračljivosti – anergijskih tokov je praviloma odvisna od vrste opreme, delovne snovi in pogojev obratovanja.

Osnovni vzroki nepovračljivosti energijskih procesov v absorpcijski hladilni napravi so [3]:

- ohlajanje pare s temperature v generatorju na temperaturo kondenzacije,
- dušenje hladilnega sredstva z dušilnim ventilom s tlaka kondenzacije na tlak uparjanja,
- segrevanje pare z uparjalne temperature na temperaturo absorpcije,
- prenos toplote v prenosniku toplote termičnega kompresorja,
- segrevanje s hladivom bogate raztopine,
- dušenje s hladivom revne raztopine za prenosnikom toplote in
- prenos toplote na zunanje nosilce toplote v zunanjih obtokih.

Kljub želji po zmanjšanju ali celo preprečitvi nastanka nepovračljivosti procesov imamo v dejanski absorpcijski hladilni napravi na nekatere nepovračljivosti zelo malo ali povsem nobenega vpliva.

ics). In the absorption chiller different forms of energy occur (e.g. heat, electricity), their values are reflected through their ability to convert to other forms of energy. The fully convertible part of energy as another form of energy is called exergy (availability) and the unconvertible is called anergy.

We therefore calculate all energy forms on the same basis – exergy. The analysis of exergy flows, according to the Second Law of Thermodynamics, is the a task of determining: places of irreversibility, the direction of occurred processes and the effectiveness of the whole device.

When performing the analysis of exergy flows we did not only analyze the perfection of the processes in the device, but we also focussed on the processes which consider heat interaction with the working media and the heat recipients as well as the device's mutual interaction with the environment [2].

How big are the irreversibilities – anergy flows usually depend on the type of equipment, the working fluid and the operating conditions.

The basic causes of irreversibilities of the energy processes in absorption chillers are [3]:

- steam cooling from the temperature in the generator at the condensing temperature;
- throttling the cooling media with a throttle valve from the condensing pressure to the evaporation pressure;
- warming up the vapor from the evaporation temperature up to the absorption temperature;
- warming up with coolant-rich solution;
- throttling with coolant-poor solution behind the solution heat exchanger;
- heat exchange on the working media in external circulation loops.

Despite the desire for a reduction of or even prevention of irreversibilities occurring in the process, in the real absorption chiller there is avery small or no influence on the irreversibilities.

2 PRERAČUN EKSERGIJSKIH TOKOV

Preračun eksergijskih tokov je izveden na podlagi podatkov s preglednice 1 in literature ([1] in [4]) z določitvijo specifične eksergije snovnega toka, v karakterističnih točkah naprave (sl. 1 in 2).

Specifična eksergija snovnega toka pove, koliko dela pridobi enota masnega toka pri povračljivem medsebojnem delovanju z okoljem [2].

Specifična eksergija snovnega toka v karakterističnih točkah naprave v hladilnem in zunanjem tokokrogu določimo z enačbo:

2 CALCULATION OF EXERGY FLOWS

The calculation of exergy flows is performed using the data from Table 1 and any available literature ([1] and [4]) with a determination of specific flow exergy in labelled positions of the chiller (Fig. 1 and 2).

The specific flow exergy tells us how much work has been produced with the unit of mass flow by reversible and mutual interaction with the environment [2].

The specific flow exergy in the device's labelled positions, in the cooling and heating cycle is determined by the equation:

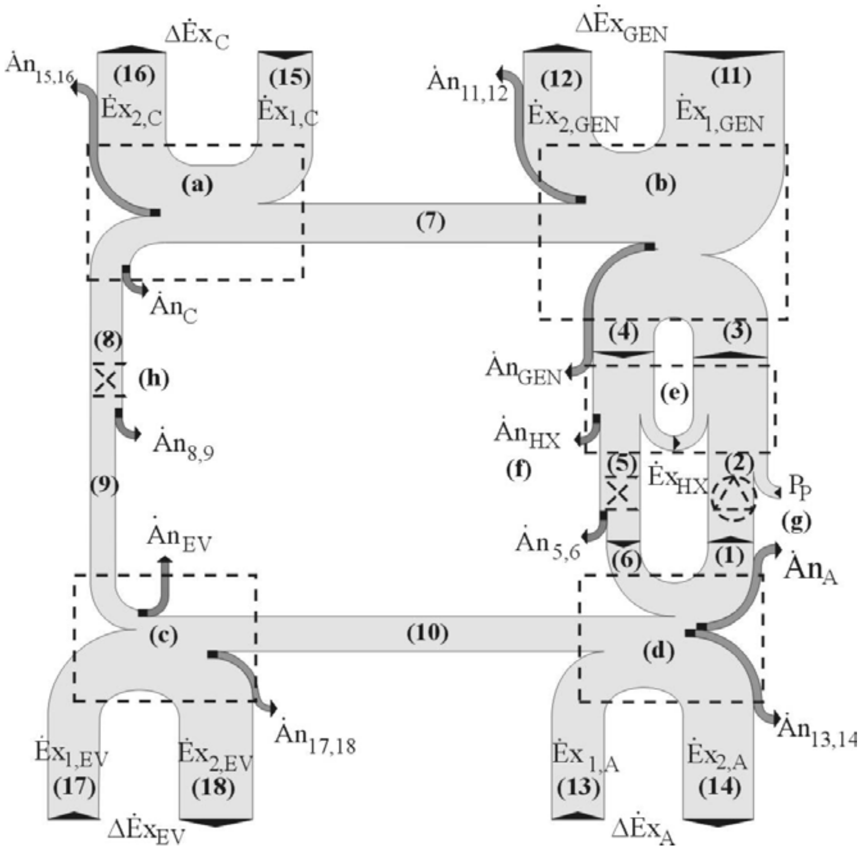
$$e_x = h - h_o - T_o \cdot (s - s_o) \qquad (1).$$

Za določitev vrednosti specifične eksergije v toplotnem kompresorju običajno uporabimo eksergijski diagram na sliki 3.

Usually we use the exergy diagram (Fig. 3) to determine values of specific flow exergy in the thermal compressor.

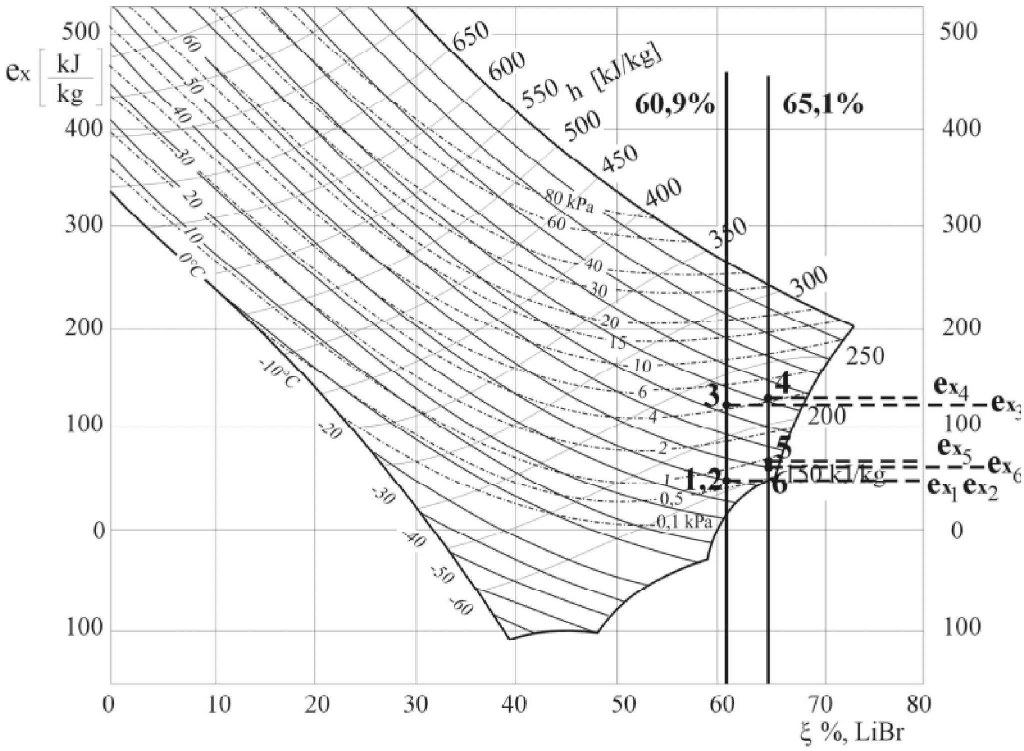
Preglednica 1. *Osnovni podatki absorpcijske hladilne naprave*
Table 1. *Basic data for the absorption chiller*

Osnovni podatki prenosnikov toplote Basic data for the heat exchangers			
$k{\cdot}A_{EV}$ =	11,9 kW/K	$k{\cdot}A_{HX}$ =	2,0 kW/K
$k{\cdot}A_{C}$ =	17,9 kW/K	$k{\cdot}A_{A}$ =	6,1 kW/K
$k{\cdot}A_{Gen}$ =	8,5 kW/K		
masni pretok zunanjega obtoka mass flow in the external circuits:			
kondenzator in absorber condenser and absorber	$q_{m,k} = q_{m,a}$ = 4,2 kg/s		
uparjalnik evaporator	$q_{m,up}$ = 2,3 kg/s		
generator generator	$q_{m,gen}$ = 3,2 kg/s		
koncentrirana raztopina with coolant-rich solution	$q_{m,rr} = q_{m,1}$ = 0,45 kg/s		



(a)	Kondenzator	(a)	Condenser
(b)	Generator	(b)	Generator
(c)	Uparjalnik	(c)	Evaporator
(d)	Absorber	(d)	Absorber
(e)	Izmenjevalnik toplote	(e)	Solution heat exchanger
(f)	Dušilni ventil 2	(f)	Throttle valve 2
(g)	Črpalka raztopine	(g)	Solution pump
(h)	Dušilni ventil 1	(h)	Throttle valve 1

Sl. 2. *Diagram pretoka eksergij v absorpcijski hladilni napravi*
Fig. 2. *Exergy flow diagram in the absorption chiller*



Sl. 3. *Diagram e_x,ξ delovne snovi LiBr/H_2O [5]*
Fig. 3. *e_x,ξ diagram for working media LiBr/H_2O [5]*

Negativni predznak specifične eksergije dobimo v primeru, ko se povečuje entropija toka snovi pri hkratnem padcu tlaka pod tlak okolice [2]. To se pojavi, v analiziranem primeru, za stanja v točki 9 in 10 (slika 1). Rezultati preračuna eksergijskih tokov absorpcijske hladilne naprave so podani v preglednicah 2 in 3, kjer oznake posameznih veličin ustrezajo oznakam na sliki 1 in diagramu eksergijskih tokov na sliki 2.

A negative sign for specific flow exergy was obtained for the case where the entropy of flow increased with a simultaneous pressure drop below the value of the environment's pressure [2]. This occured, in our case, for positions 9 and 10 (Fig. 1). The calculated results of exergy flows in the absorption chiller are given in Table 1 and Table 2, where the thermodynamic properties correspond to those named in Figure 1 and exergy flow diagram in Figure 2.

Preglednica 2. *Vrednosti specifične eksergije, masnega pretoka in temperature v posameznih točkah naprave*
Table 2. *Values of mass flow, temperature and specific flow exergy in the labelled position of the absorption chiller*

	Masni pretok Mass flow	**Temperatura Temperature**	**Specifična eksergija Specific exergy**
	$q_{m,i}$ kg/s	t °C	$e_{x,i}$ kJ/kg
1	0,4500	41,9	48,3000
2	0,4500	41,9	48,3000
3	0,4500	71,1	120,7000
4	0,4216	85,7	131,0500
5	0,4216	52,5	69,0000
6	0,4216	50,3	62,1000
7	0,0287	76,2	102,6000
8	0,0287	31,5	0,8369
9	0,0287	2,1	- 5,1740

	Masni pretok Mass flow	**Temperatura Temperature**	**Specifična eksergija Specific exergy**
	$q_{m,i}$ kg/s	t °C	$e_{x,i}$ kJ/kg
10	0,0287	2,1	-155,1000
11	3,2000	95,0	34,6500
12	3,2000	88,3	29,1200
13	4,2000	29,3	0,5079
14	4,2000	34,5	1,4550
15	4,2000	25,0	0,0737
16	4,2000	29,3	0,5079
17	2,3000	12,0	0,4333
18	2,3000	5,0	1,7700

Preglednica 3. *Vrednosti eksergijskih in anergijskih tokov enostopenjske absorpcijske hladilne naprave*
Table 3. *Values of exergy and anergy flows in the single-stage absorption chiller*

Sestavina naprave Component of device	Sestavina Component		Zunanji obtok External loop	
	Eksergijski tok Exergy flow	Anergijski tok Anergy flow	Eksergijski tok Exergy flow	Anergijski tok Anergy flow
	$\dot{E}xi$ kW	$\dot{A}n$ kW	$\Delta\dot{E}x_i$ kW	$\Delta\dot{A}n$ kW
kondenzator condenser	3,1200	-68,47	1,54	69,73
absorber absorber	67,7200	-85,87	3,59	82,98
prenosnik toplote heat exchanger	6,6100	6,77	-	-
generator generator	13,5700	75,48	-18,4	75,48
uparjalnik evaporator	3,7900	71,41	3,05	71,41
dušilni ventil – 1 throttle valve – 1	-	0,11	-	-
dušilni ventil – 2 throttle valve – 2	-	0,85	-	-
črpalka raztopine solution pump	0,001033			

2.1 Razlaga rezultatov

Splošno je znano, da se pri termodinamični analizi toplotnih procesov odločamo za eksergijsko bolj varčne naprave.

Med naštetimi vrstami nepovračljivosti, ki se pojavljajo v napravi (sl. 2), se izkaže, da se največje nepovračljivosti pojavljajo v generatorju in absorberju (pregl. 3), kjer se namreč poleg nepovračljivosti pri prenosu toplote pojavljajo še nepovračljivosti zaradi mešanja delovne snovi.

Na sliki 1 opažamo nasprotno smer toplotnega in eksergijskega toka v uparjalniku. Ta pojav je specifičen v tem, da se telesom, katerih temperatura je pod temperaturo okolice in se jim toplota odvaja, vrednost eksergije veča in nasprotno [6]. Prav zaradi tega se lahko utemeljeno sklepa, da lahko termodinamično pravilno zapišemo izkoristek vložene energije v napravo, v kateri hkrati potekata gretje in hlajenje, samo z eksergijskim izkoristkom.

Za absorpcijsko hladilno napravo, pri kateri izkoriščamo samo hlad, lahko določimo eksergijski izkoristek z enačbo:

2.1 Comments on the results

It is a well-known fact, that with a thermodynamic analysis of thermal processes we are concentrating on the more exergy-saving type of plants.

The named forms of irreversibilities, which occurred in the device – Figure 2, become obvious according to the presented analysis, because the greatest irreversibilities occured in the generator and absorber (Table 3). Besides the irreversibilities in the heat transfer, irreversibilities due to the mixture processes were also present.

In Figure 1 we can see the opposite directions of energy and exergy flows by evaporator. This phenomenon is specific for the systems (bodies) whose temperature are below the surrounding's temperature and whilst they are rejecting heat (being cooled), their exergy value is growing and vice versa [6]. Therefore, this brings us to the using conclusion that thermodynamics is the only correct way to express the efficiency of consumed energy in the device where heating and cooling are simultaneously performed only with exergy efficiency.

For the absorption chiller, where we utilize only cooling, we can determine the exergy efficiency using the following equation:

$$\psi_{AHN} = \frac{\Delta \dot{E}x_{UP}}{\Delta \dot{E}x_{GEN} + P_p} = \frac{3,05}{18,4} = 0,166 \qquad (2).$$

V primeru, da poleg hladu izkoriščamo še oddano toploto kondenzatorja in absorberja (npr. segrevanje sanitarne vode), lahko eksergijski izkoristek absorpcijske hladilne naprave določimo z enačbo:

In the case where we also utilize rejected heat from the absorber and the condenser, we can determine the exergy efficiency with the following equation:

$$\psi_{AHN} = \frac{\Delta \dot{E}x_{UP} + \Delta \dot{E}x_K + \Delta \dot{E}x_A}{\Delta \dot{E}x_{GEN} + P_p} = \frac{3,59+1,54+3,05}{18,4} = 0,445 \qquad (3).$$

Moč potrebne črpalke se zaradi doslednosti definicije v enačbah (2) in (3) zapiše, vendar se zaradi majhne vrednosti, (pregl. 3) v računu ne upošteva.

We have to consider the power of the pump to obtain the correct definitions, equation (2) and (3), which due to its small value, is unimportant.

3 SKLEP

Prednost sorpcijskih hladilnih naprav, v obravnavanem primeru absorpcijskih hladilnih naprav, pred kompresorskimi hladilnimi napravami je v možnosti uporabe eksergijsko revne odpadne toplote in rabe alternativnih energijskih virov.

Kompresorske hladilne naprave so sicer energetsko učinkovitejše in manjše, vendar eksergijsko manj učinkovite in porabljajo čisto eksergijo [7].

Za pogon absorpcijskih hladilnih naprav se lahko uporablja tudi odpadna toplota postroja soproizvodnje. Postroj sočasne proizvodnje električne energije in toplote ter hladu imenujemo trigeneracijski postroj [8].

Pri trigeneracijskih postrojih je zaželeno, da ima absorpcijska hladilna naprava kar se da velik eksergijski izkoristek in s tem dosežemo večji eksergijski izkoristek celotnega trigeneracijskega postroja [8].

3 CONCLUSION

The advantage of sorption chillers, in our case absorption chillers, in comparison to compressor chillers is in utilizing low exergy, rejected heat and in the use of alternative energy sources.

Compressor chillers have a higher energy efficiency and are more compact, but they are less exergy efficient and utilize pure exergy [7].

To drive the absorption chiller we can also utilize the rejected heat from the cogeneration plant. This kind of plant, with simultaneous production of heat, electricity and cooling is also called the trigeneration system [8].

In the trigeneration plant all the requirements are present, the absorption chiller has the highest possible exergy efficiency, which enables it to achieve higher exergy efficiency in the whole trigeneration plant [8].

4 OZNAKE
4 SYMBOLS

anergijski tok	$\dot{An}$	W	anergy flow
specifična eksergija snovnega toka	ex	J/kg	mass flow specific exergy
energijski tok	$\dot{Ex}$	W	exergy flow
specifična entalpija	H	J/kg	specific enthalpy
moč	P	W	power
masni pretok	q_m	kg/s	mass flow
temperatura	T	K	temperature
masni delež	ξ	%	mass ratio
eksergijski izkoristek	ψ	%	exergy efficiency

Indeksi:	**Subscripts:**	
absorber	A	absorber
absorbcijska hladilna naprava	AHN	absorption chiller
generator	Gen	generator
kondenzator	K	condenser
referenčno stanje okolice	o	reference state
črpalka	p	pump
prenosnik toplote	PT	heat exchanger
uparjalnik	UP	evaporator

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