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Eksperimentalno preskušanje prenosa toplote v Lorenzovem postopku z uporabo zeotropnih zmesi

Experimental Testing of the Heat Transfer in a Lorenz Process Using Zeotropic Mixtures

Vladimir Soldo - Tonko Ćurko - Vlasta Zanki

Za sistem, ki deluje pri enakih pogojih je bila opravljena primerjava med termodinamičnim izkoristkom za enokomponentno hladivo R22 ter za njegovo zamenjavo z zeotropno zmesjo R407C. Predstavljena je konstrukcija hladilnega sistema, ki omogoča delovanje z R22 ter R407C, skupaj z meritvami vseh ustreznih podatkov (temperatura, tlak in pretok), njihovim zapisom ter analizo.

Dobljeni rezultati kažejo, da je hladivo R407C dobra zamenjava za R22 pri višjih temperaturah uparjanja. Čeprav so teoretični rezultati vodili k predpostavki, da bo R407C v primerjavi z R22 povečal izkoristek, tega eksperimentalni rezultati niso potrdili. Razlog za to dejstvo je v nižjih toplotnih prestopnostih v primeru uporabe hladiva R407C.

(Ključne besede: zmesi zeotropske, procesi Lorentz, izkoristki termodinamični, prenos toplote)

A comparison has been made between the thermodynamic efficiency of a single-component refrigerant R22 and a substitute zeotropic mixture R407C in a system operating under the same conditions. The construction of a refrigerating system that uses R22 and R407C is presented, along with measurements of all the relevant data (temperature, pressure and flow rate), their acquisition, and their analysis.

Our results show that the refrigerant R407C is a good substitute for the refrigerant R22 at higher evaporation temperatures. Although the theoretical results suggest that R407C will increase efficiency compared to R22, the experimental results did not confirm it. This because in the process with the refrigerant R407C the heat-transfer coefficients are lower.

(Keywords: zeotropic mixtures, Lorentz process, thermodynamic efficiency, heat transfer)

1 DEFINICIJA PROBLEMA

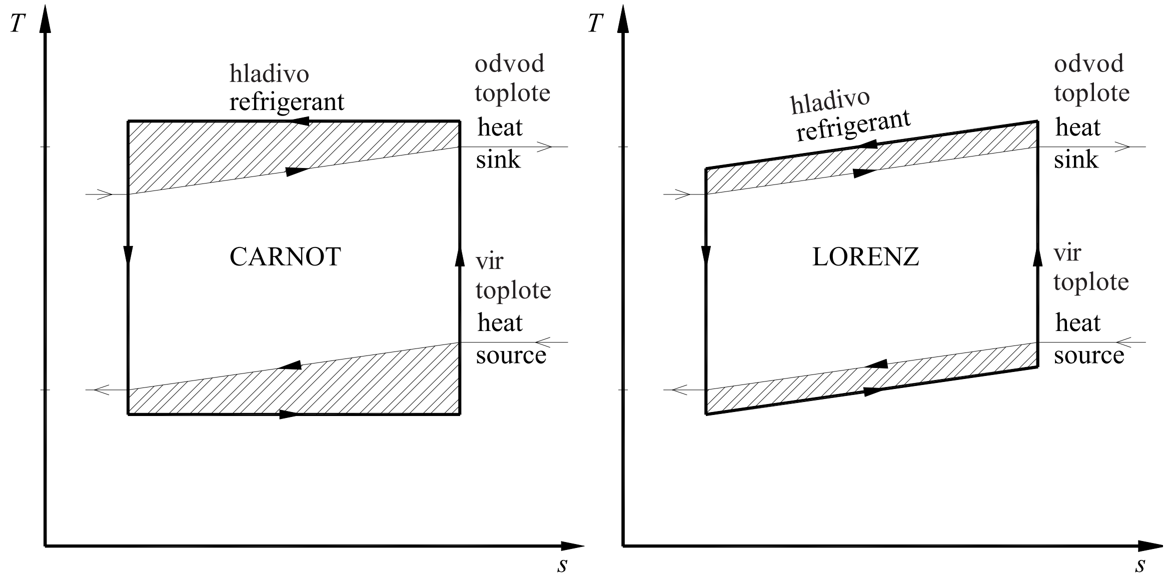
Teoretične in eksperimentalne študije so pokazale, da lahko termodinamični izkoristek hladilnega sistema izboljšamo z uporabo zeotropnih zmesi [1]. Zeotropne zmesi so uporabljene tako, da se povečanje temperature med uparjanjem ujema s hlajenim sredstvom, oziroma da se zmanjšanje temperature pri kondenzaciji ujema s temperaturo okolice in tako omogočajo Lorenzov postopek. Torej glede na Lorenzov postopek je tu največja prednost hladilnega postopka (celo večja kakor pri Carnotovem postopku) ta, da se ta postopek najbolj učinkovito prilagaja temperaturnim spremembam hlajenega sredstva ali okolice.

Slika 1 daje kakovostno predstavo Carnotovega in Lorenzovega procesa pri enakih

1 PROBLEM DEVELOPMENT

Theoretical and experimental studies have shown that the thermodynamic efficiency of a refrigerating system can be improved by using a zeotropic mixture [1]. Zeotropic mixtures are used in such a way that the temperature increase during evaporation coordinates with the cooled medium, while at the same time the temperature decrease of the condensation coordinates with the temperature medium of the environment, and in this way the Lorenz process is enabled. According to Lorenz, the most advantageous refrigerating process, even more advantageous than Carnot's process, would be the one that is the most effectively adapted to the temperature changes of the cooled medium, or to the medium of the environment.

Figure 1 gives a qualitative presentation of the Carnot and Lorenz processes for the same



Sl. 1. *Kakovostna primerjava Carnotovega in Lorenzovega postopka v diagramu T-s*
Fig. 1. *Qualitative comparison of the Carnot and Lorenz processes, presented on T-s diagrams*

temperaturah toplotnega vira in ponora. Šrafirana površina predstavlja izgubo eksergije v prenosnikih toplote. Če gledamo sliki, je očitno, da bo Lorenzov postopek termodinamično bolj učinkovit, toda pod pogojem, da prenos toplote poteka v protitočnih prenosnikih toplote z majhno temperaturno razliko.

temperature of heat source and heat sink. The hatched surface represents the exergy loss on the heat exchangers. It is obvious from the figures that the Lorenz process will be thermodynamically more efficient, but on condition that the heat transfer takes place in counter-flow heat exchangers with a small driving temperature difference.

2 EKSPERIMENTALNA OPREMA IN MERITVE

Slika 2 opisuje eksperimentalno opremo s hladilnim sistemom, ki omogoča obratovanje sistema po Lorenzovem (uporaba zeotropne zmesi) ter Carnotovem postopku (uporaba azeotropne zmesi ter čistega hladiva). Osnovni elementi sistema so polzaprti batni kompresor, protitočni uparjalnik cev v cevi, kondenzator in termoekspanzijski ventil. Sistem je opremljen z inštrumenti in zaznavala, ki merijo vse ustrezne parametre (temperatura, tlak in pretok) in so povezani z zapisovalnikom podatkov ter analizatorjem ([2] in [3]).

2 EXPERIMENTAL RIG AND MEASUREMENTS

Figure 2 is a schematic diagram of the experimental rig with a refrigerating system that can operate according to the Lorenz (zeotropic mixture application) and Carnot (application of azeotropic mixture and pure refrigerant) processes. The basic system elements are a semi-hermetic reciprocating compressor, a counterflow tube-in-tube evaporator, a condenser and a thermoexpansion valve. The system is equipped with instruments and sensors that measure all the relevant data (temperature, pressure and flow rate), and is connected to a data-acquisition and analysis system ([2] and [3]).

3 ANALIZA REZULTATOV MERITEV

Opravljena je bila primerjava rezultatov meritev med postopkom s čistim hladivom R22 in med postopkom z zeotropno zmesjo R407C.

Preskus na hladilnem sistemu sestoji iz meritev temperature na vstopu in izstopu hladiva iz prenosnika, hladiva in hladilne vode, meritev pretoka v primarni zanki in v obeh sekundarnih zankah, tlaka uparjanja in kondenzacije ter električne moči motorja kompresorja.

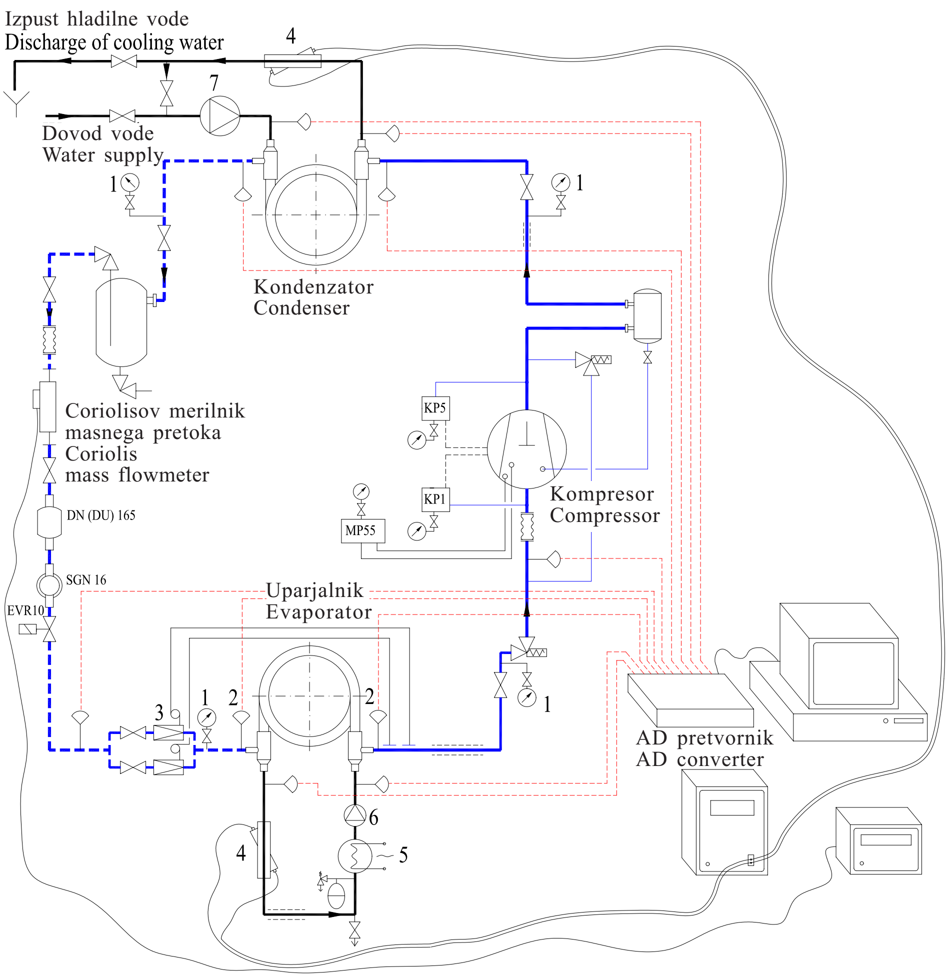
Izmerjene temperature, tlaki in vrednosti pretokov so obdelani s programom LabVIEW, ki uporablja kot vir program bazo podatkov REFPROP ([4] in [5]) za izračun termodinamičnih in fizikalnih

3 ANALYSIS OF THE MEASUREMENT RESULTS

A comparison between the process with the pure refrigerant R22 and the process with the zeotropic mixture R470C was carried out.

The experiment on the refrigerating system consists of temperature measurements, at the exchanger inlets and outlets, of the refrigerant, the coolant and cooling water, flow measurements in the primary loop and in both secondary loops, evaporation and condensation pressure and the electric power of the compressor motor.

The measured temperature, pressure and flow values are processed using the LabVIEW program, which uses the source program REFPROP databank ([4] and [5]) for the refrigerant's thermodynamic and



1 – tlačno zaznavalo
2 – termopar Cu-Ko, tip T
3 – termoekspanzijski ventil TEX2-04 (03)
4 – prostorninski merilnik pretoka etilen - glikola (hladilne vode)
5 – električni grelnik El-Cm, 2-15 kW
6 – črpalka hladilnega sredstva etilen – glikol
7 – elektronska črpalka hladilne vode

1 – pressure transducer
2 – thermocouples Cu-Ko, T-type
3 – thermoexpansion valve TEX2-04 (03)
4 – volumetric flowmeter of ethylene-glycol (cooling water)
5 – electric heater El-Cm, 2-15 kW
6 – pump of coolant ethylene-glycol
7 – electronic pump of cooling water

Sl. 2. *Shema eksperimentalne naprave*
Fig. 2. *Schematic diagram of the experimental rig*

Preglednica 1. *Natančnost zaznaval in parametrov*
Table 1. *Accuracy of the sensors and parameters*

Zaznavala Sensors		Parametri Parameters	
temperatura temperature	0.3 °C	sposobnost, toplotni tok capacity, heat flux	± 0.32 %
absolutni tlak absolute pressure	± 0.2 f.s.	ε COP	± 0.91 %
pretok hladiva refrigerant flow rate	± 0.2 %	srednja logaritemska temperaturna razlika log mean-temperature difference	± 4.63 %
moč elektromotorja power of electrical motor	± 1.5 %	koeficient prenosa toplote heat-transfer coefficient	± 9.76 %

lastnosti hladiva in daje kot rezultat hladilno moč Φ_0 in grelno moč Φ_C za obe hladivi.

physical properties calculation, and obtains the results of the cooling capacity Φ_0 and the heating capacity Φ_C for both refrigerants.

3.1 Celotni izkoristek

3.1 Overall performance

Med hladilno sposobnostjo hladiv R22 in R407C pri visokih temperaturah uparjanja (sl. 3) ni nobenih razlik. Ko so temperature uparjanja nižje, je hladilna sposobnost pri R22 večja kakor pri R407C.

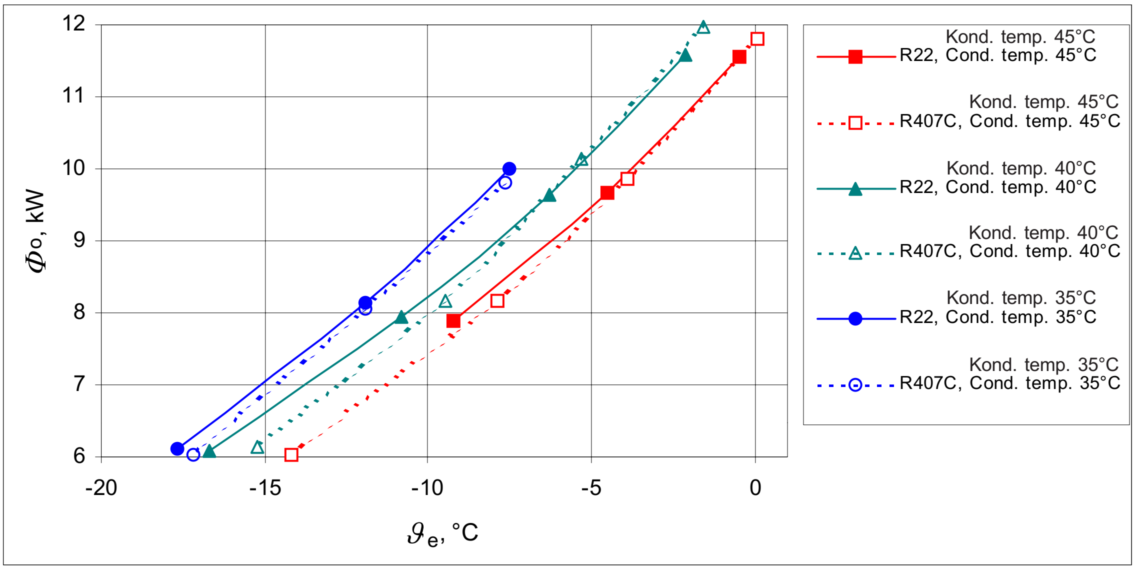
Moč kompresorja, ki obratuje z R407C, je do 3 odstotke večja kakor pri R22 (sl. 4).

Razlogi za zmanjšanje celotnega izkoristka (hladilne sposobnosti ter moči kompresorja) postopka s hladivom R407C so nižji koeficienti

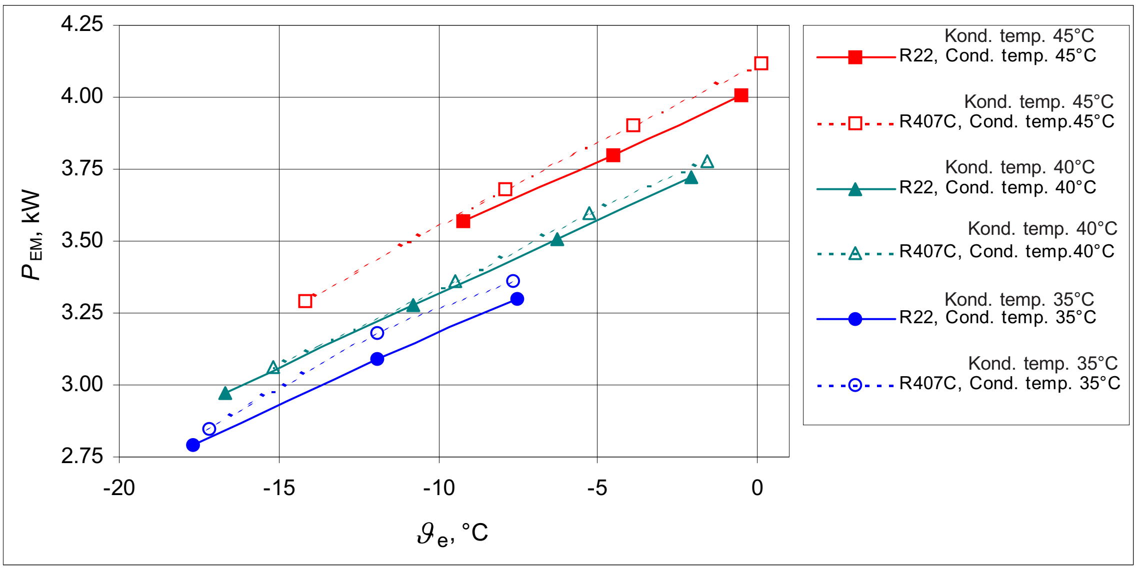
There is no difference between the cooling capacity for the refrigerants R22 and R407C at high evaporation temperatures (Fig. 3). For lower evaporation temperatures the cooling capacity of R22 is higher than that of R407C.

The compressor's operating power with R407C is up to 3 % higher than with R22 (Fig. 4).

The reasons for the degradation of the overall performance (cooling capacity and compressor power) in the process with refrigerant R407C are lower



Sl. 3. *Hladilna moč Φ_0 kot funkcija temperature uparjanja ϑ_e*
Fig. 3. *Cooling capacity Φ_0 as a function of the evaporation temperature ϑ_e*



Sl. 4. *Moč kompresorja P_{EM} kot funkcija temperature uparjanja ϑ_e*
Fig. 4. *Compressor power P_{EM} as a function of the evaporation temperature ϑ_e*

prenosa toplote (glej pogl. 3.2) kakor pri R22. Zmanjšanje koeficienta prenosa toplote pri delovanju z R407C se pojavi zaradi razstavitve zeotropne zmesi, različnih topljivosti komponent in mazalnega olja ter spremembe lastnosti med uparjanjem in kondenzacijo (glej pogl. 4).

Hladilno število (COP - ε) je definirano v razmerju z močjo električnega motorja P_{EM}, ki poganja kompresor.

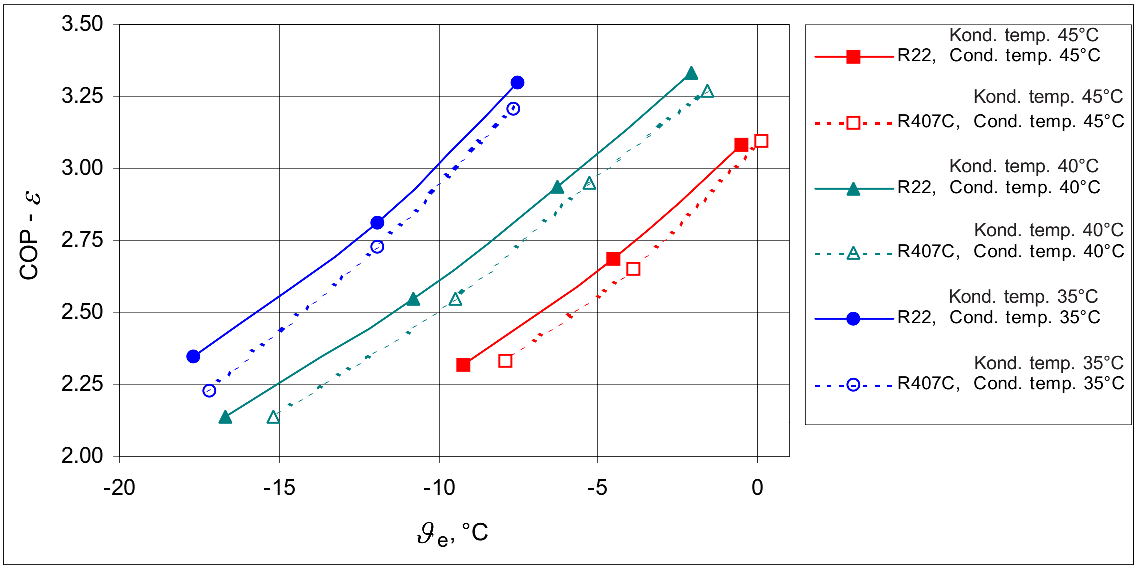
heat-transfer coefficients (see section 3.2), than with the R22. This decrease in the heat-transfer coefficient when working with R407C is due to the fractionation of the zeotropic mixture, the different solubilities of the components and the lubricating oil, and the change in the properties during evaporation and condensation (see section 4).

The coefficient of performance for cooling (COP-ε) is defined in terms of the power of the electrical motor (P_{EM}) that runs the compressor:

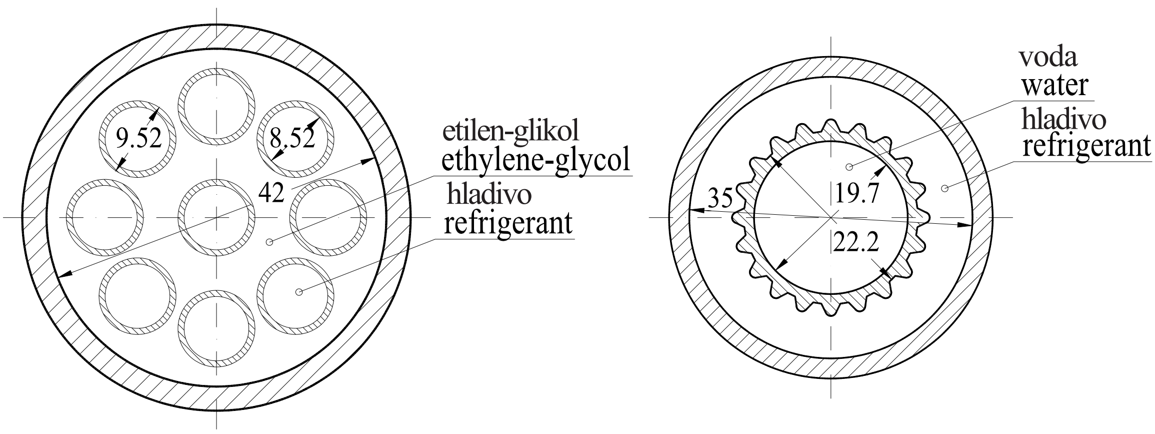
$$\varepsilon = \frac{\Phi_o}{P_{EM}} \quad (1).$$

Manjša hladilna moč in večja moč kompresorja v postopku z R407C se kaže s 3 odstotki (pri višjih temperaturah uparjanja) do 5 odstotkov (pri nižjih temperaturah uparjanja) nižjim ε glede na R22.

A lower cooling capacity and a larger compressor power in the process with R407C results in a 3% (at a high evaporation temperature) to 5 % (at a low evaporation temperature) lower COP than with R22.



Sl. 5. *Hladilno število ε kot funkcija temperature uparjanja ϑ_e*
Fig. 5. *COP-ε cooling as a function of the evaporation temperature ϑ_e*



Sl. 6. *Prerez cevi prenosnika*
Fig. 6. *The cross-section of the exchanger tubes*

3.2 Prenos toplote

Za določitev koeficienta prenosa toplote v uparjalniku in kondenzatorju (sl. 6) je bila uporabljena celovita metoda srednje logaritemske temperaturne razlike ([6] in [7]).

3.2 Heat Transfer

To determine the heat-transfer coefficient in the evaporator and condenser (Figure 6), the integral method of a log mean-temperature difference is used ([6] and [7]).

$$k = \frac{\Phi}{A_o \Delta \vartheta_m} \quad (2).$$

Koeficient prenosa toplote na strani hladiva (α_i) v uparjalniku (kondenzatorju) je definiran z enačbo toplotne upornosti:

The heat-transfer coefficient on the refrigerant side (α_i) of the evaporator (condenser) is defined from the thermal resistance equation:

$$\frac{1}{kA_o} = \frac{1}{\alpha_o A_o} + R_w + \frac{1}{\alpha_i A_i} \quad (3)$$

α_i in α_0 sta povprečna koeficienta prenosa toplote v cevi in kolobarju, R_w je upornost stene cevi.

Celotna upornost temelji na zunanji površini cevi ($d_0 \pi L$), kjer je d_0 zunanji premer notranjega kolobarja in L je dejanska dolžina prenosa toplote. Določevanje koeficienta prenosa toplote na notranji strani (α_i) v enačbi (3) zahteva poznavanje koeficienta prenosa toplote na zunanji strani (α_0). To izračunamo glede na znane enačbe iz literature o toku čistega sredstva [8]. Enačbo (3) lahko potem spremenimo in dobimo:

where α_i and α_o are the average heat-transfer coefficients in the tube and annulus, and R_w is the wall resistance of the tube.

The overall resistance is based on the outer surface of the tube ($d_o \pi L$), where d_o is the outside diameter of the inner tube, and L is the effective heat-transfer length. The determination of the inner heat-transfer coefficient (α_i) in Equation (3) requires knowledge of the outside heat-transfer coefficient (α_o). This is calculated according to equations from the literature on the flow of a pure medium [8]. Equation (3) can then be altered to give:

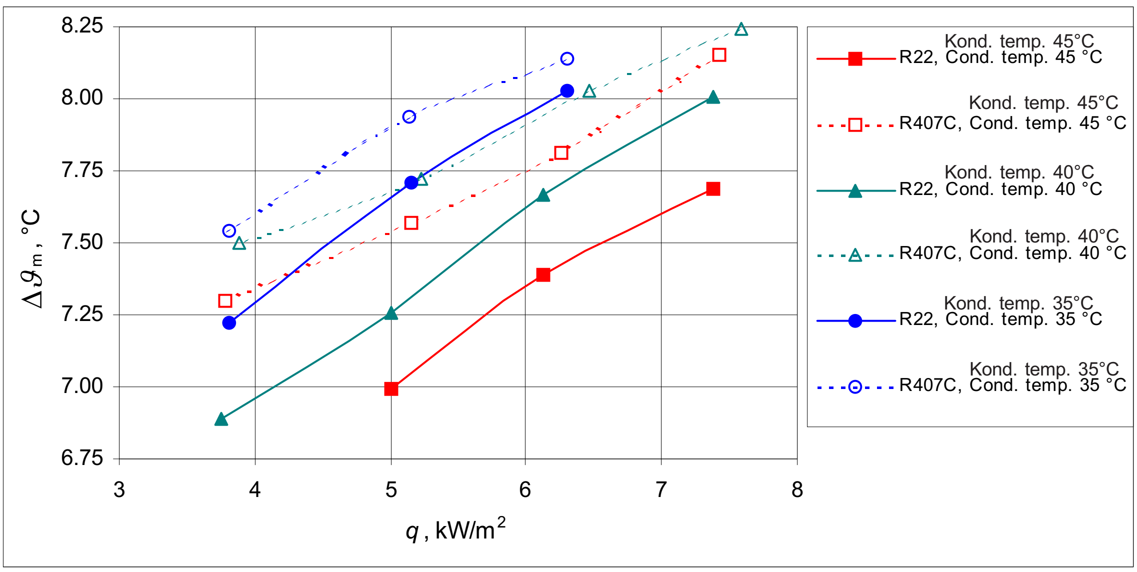
$$\alpha_i = \frac{1}{\frac{d_i}{d_o}\left[\frac{1}{k} - \frac{1}{\alpha_o} - \frac{d_o}{2\lambda_{Cu}} \ln \frac{d_o}{d_i}\right]} \quad (4).$$

Slika 7 predstavlja odvisnost merjene srednje logaritemske temperaturne razlike ($\Delta\vartheta_m$) na uparjalniku kot funkcijo toplotnega toka

Slika 10 prikazuje odvisnost povprečnega koeficienta prenosa toplote kot funkcijo toplotnega toka. Vrednosti toplotnega toka so v mejah

Figure 7 shows the dependence of the measured log mean-temperature difference ($\Delta\vartheta_m$) on the evaporator as a function of the heat flux.

Figure 10 shows the dependence of the average heat-transfer coefficient as a function of the heat flux. The readings of the heat flux are within the



Sl. 7. *Srednja logaritemska temperaturna razlika $\Delta\vartheta_m$ uparjalnika kot funkcija toplotnega toka*
Fig. 7. *Log mean-temperature difference $\Delta\vartheta_m$ of the evaporator as a function of the heat flux*

q = 3,8 do 7,5 kW/m²K. Rezultati kažejo, da je pri postopku s hladivom R407C toplotni tok 10 do 25 odstotkov manjši kakor z R22.

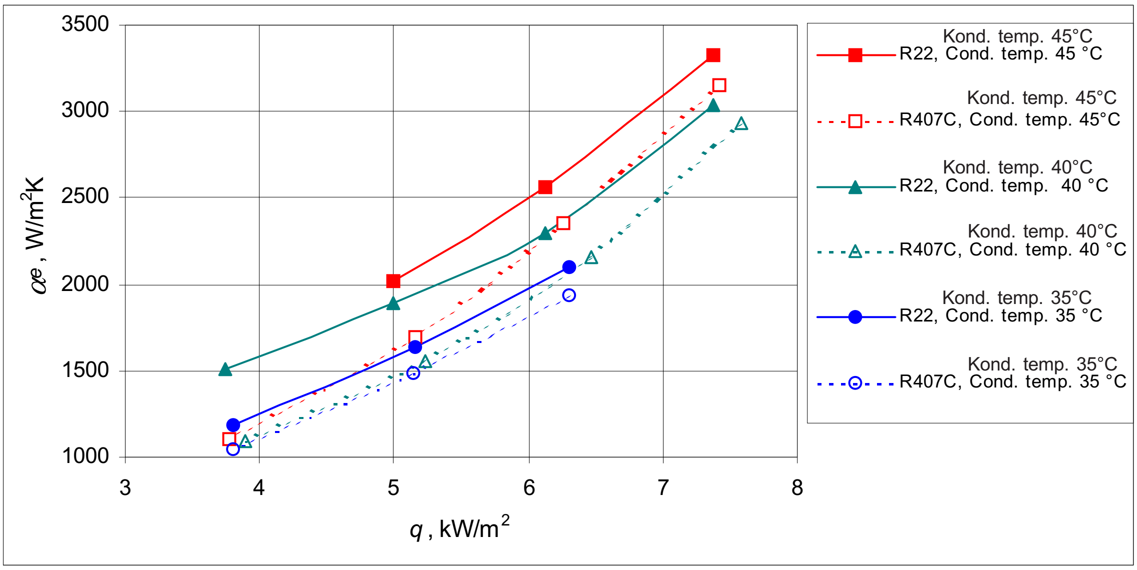
Slika 9 predstavlja odvisnost srednje logaritemske temperaturne razlike ($\Delta\vartheta_m$) na kondenzatorju kot funkcijo toplotnega toka.

Povprečni koeficient prenosa toplote v kondenzatorju je predstavljen kot funkcija toplotnega toka. V primerjavi z uparjalnikom je razlika v prenosu toplote primerjanih hladiv celo bolj očitna. V postopku s hladivom R22 je prenos toplote za 35 odstotkov večji kakor z R407C.

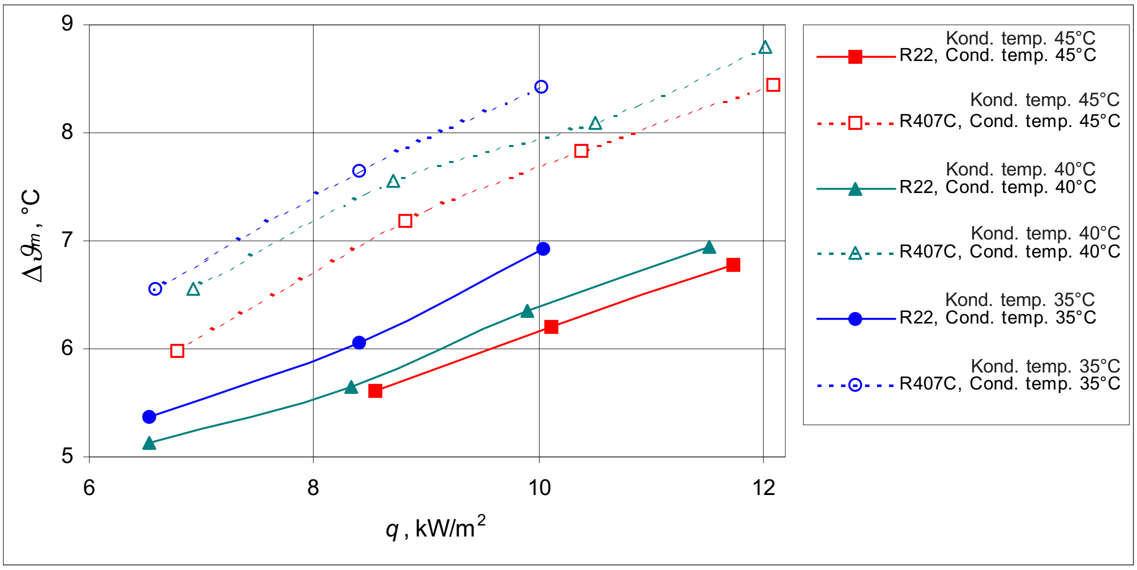
limits q = 3.5 to 7.5 kW/m²K. The results show that in the process with the refrigerant R407C, the heat transfer is 10 to 25% lower than with the R22.

Figure 9 shows the dependence of the log mean-temperature difference ($\Delta\vartheta_m$) on the condenser as a function of the heat flux.

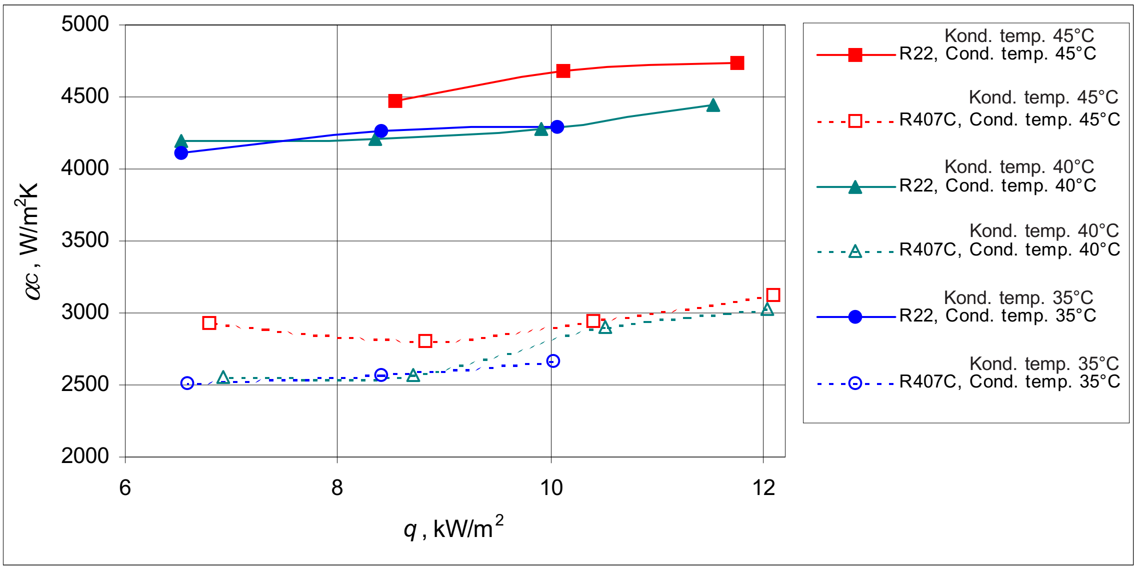
The average heat-transfer coefficient in the condenser is presented as the heat-flux function. In relation to the evaporator, the difference in the heat transfer of the compared refrigerants is even more obvious. In the process with the refrigerant R22 the heat transfer is 35 % higher than with the R407C.



Sl. 8. *Povprečni koeficient prenosa toplote α_e v uparjalniku kot funkcija toplotnega toka q*
Fig. 8. *Average heat-transfer coefficient α_e in the evaporator as a function of the heat flux q*



Sl. 9. *Srednja logaritemska temperaturna razlika $\Delta\vartheta_m$ na kondenzatorju kot funkcija toplotnega toka q*
Fig. 9. *Log mean-temperature difference $\Delta\vartheta_m$ on the condenser as a function of the heat flux q*



Sl. 10. *Povprečni koeficient prenosa toplote* α_c *v kondenzatorju kot funkcija toplotnega toka q*
Fig. 10. *Average heat-transfer coefficient* α_c *in the condenser as a function of the heat flux q*

4 SKLEP

V tem prispevku so bili primerjani celotni toplotni izkoristki ter povprečni koeficienti prenosa toplote, dobljeni na sotočnem prenosniku toplote cev v cevi pri delovanju z R407C in R22.

Dobljeni rezultati so naslednji:

- Da bi Lorenz-ov delovni postopek tekel, je nujno treba zagotoviti temperaturno spremembo (temperaturni zdrs 5 ^{0}C do 7 ^{0}C) zeotropne zmesi R407C, ki je enaka temperaturni spremembi zunanjega sredstva (hlajeni etilen - glikol v uparjalniku in hladilna voda v kondenzatorju).
- Lorenzov postopek lahko izvedemo samo z uporabo protitočnih prenosnikov toplote. Uporabiti je treba istoosni ali ploščni tip prenosnika. Izogibati se moramo poplavljenih prenosnikov, zato je treba uporabiti suhe uparjalnike.
- Hladilna sposobnost in ε z R407C sta približno 3 do 5 odstotkov nižja, poraba energije kompresorja med testiranjem R407C je za 3 odstotke večja kakor pri testih z R22 v enakih razmerah.
- Čeprav so teoretične analize za sisteme z zeotropnimi zmesmi pokazale povečanje toplotnih učinkovitosti (ε in hladilne moči), tega eksperimentalni rezultati niso potrdili [1]. Razlog za to so manjši koeficienti prenosa toplote v postopku s hladivom R407C ([6] in [7]). Eksperimentalni rezultati so potrdili, da so povprečni koeficienti prenosa toplote pri uparjanju za R407C od 10 do 25 odstotkov manjši ter do 35 odstotkov manjši za kondenzacijo v primerjavi z R22. Razlika glede na čisto hladivo je zaradi razstavitve zeotropnih zmesi, kar je posledica spremembe kapljevite in parne faze v uparjalniku in kondenzatorju ([2] in [3]). Nadalje, mešanice so zmesi dveh ali več komponent hladiva, ki imajo precej različne temperature uparjanja. Torej,

4 CONCLUSION

In this paper the overall thermal performances and the average heat-transfer coefficients obtained on coaxial tube-in-tube exchangers operating with R407C and R22 were compared.

The obtained results are as follows:

- In order to run the Lorenz process it is necessary to provide a temperature change (temperature glide 5 to 7 °C) of the zeotropic mixture R407C equal to the temperature change of the external medium (cooled ethylene-glycol in the evaporator and cooling water in the condenser).
- The Lorenz process can only be realized when the counter-flow heat exchangers are applied. It is necessary to use a coaxial or a plate-type exchanger. Flooded heat exchangers must be avoided, dry evaporators should be used instead.
- The cooling capacity and COP with R407C are approximately 3 to 5 % lower, and the compressor power consumption during the R407C tests is up to 3 % higher than the R22 tests under the same conditions.
- Although a theoretical analysis showed an increase in thermal performances (COP and cooling capacity) for the system using zeotropic mixtures, the experimental results did not confirm this [1]. The reason is the lower heat-transfer coefficients in the process with refrigerant R407C ([6] and [7]). The experimental results confirmed that the average heat-transfer coefficients for R407C are 10 to 25 % lower for evaporation and 35 % lower for condensation, compared to R22. The variation with respect to the pure refrigerant is a fractionation of the zeotropic mixtures, which is the effect of the change in the liquid and vapor phases in the evaporator and condenser ([2] and [3]). Furthermore, the blends are mixtures of two or more single-component refrigerants that have significantly different evaporation

delež pare se med uparjanjem nasiti z večjim deležem topljive sestavine, medtem ko se delež manj topljive sestavine v preostali tekočini poveča. Da bi zmanjšali ta vpliv, je sistem načrtovan brez kakršnihkoli zbiralnih posod ter vodnih prenosnikov toplote. V uparjalniku hladivo teče skozi cevi in pojavi se suho uparjanje. Dvig koncentracije zeotropne zmesi je lahko odvisen od različne topljivosti komponente in mazalnega olja [3].

- Razstavitev in različna topljivost sestavin hladiva povzroči slabši prenos toplote. Zaradi teh razlogov je pri uporabi R407C za dosego enake zmogljivosti treba uporabiti večjo temperaturno razliko na prenosnikih toplote (uparjalnik in kondenzator) kakor pri R22.
- Iz tega lahko povzamemo, da je R407C dobra zamenjava za R22 pri uporabah z višjimi temperaturami (od -5 ^{0}C do 10 ^{0}C), toda njegova učinkovitost se glede na R22 z zmanjšanjem temperature uparjanja zmanjšuje. Pri tem moramo opozoriti, da so bili ti preskusi opravljeni s protitočnimi prenosniki toplote (uparjalnik in kondenzator) in da lahko pričakujemo manjše učinkovitosti za prenosnike s križnim tokom, ki ne izkoriščajo kakršnegakoli zdrsa temperature.

temperatures. Thus, the vapor content during the evaporation becomes saturated with the more volatile component, while the content of the less volatile component in the residual liquid increases. In order to avoid this influence, the system is designed without any receiver and flooded heat exchangers. In the evaporator, the refrigerant flows through the tubes and the dry evaporation is used. Also, the composition shift of the zeotropic mixture may result from the different solubility of its components and lubricating oil [3].

- The fractionation and different solubility of the refrigerant components causes lower heat-exchange characteristics. For these reasons, when R407C is used to achieve the same capacity, a bigger temperature difference on the heat exchangers (evaporator and condenser) than for R22 is necessary.
- We can conclude that R407C is a good replacement for R22 in higher temperature applications (from -5 to 10 °C), but its performance does degrade with respect to R22 as the evaporator temperature is decreased [3]. It should also be noted that these tests were carried out with counter-flow heat exchangers (evaporator and condenser) and the performances would be expected to be lower for cross-flow exchangers, which are unable to benefit from any temperature glide.

5 SIMBOLI
5 SYMBOLS

zunanja površina prenosa toplote na cevi	A_o	m	external heat-transfer area of the tube
notranja površina prenosa toplote na cevi	A_i	m^2	internal heat-transfer area of the tube
zunanji premer cevi	d_o	m	external diameter of the tube
notranji premer cevi	d_i	m	internal diameter of the tube
toplotna prehodnost	k	W/m^{2}K	overall heat-transfer coefficient
dejanska dolžina ogrevanja	L	m	effective heating length
moč elektromotorja	P_{EM}	W	electrical motor power
tlak	p	Pa	pressure
toplotni tok	q	W/m^2	heat flux
upornost stene	R_w	m^{2}K/W	wall resistance
specifična entropija	s	J/kgK	specific entropy
absolutna temperatura	T	K	absolute temperature
koeficient prenosa toplote na notranji strani	α_i	W/m^{2}K	internal heat-transfer coefficient
koeficient prenosa toplote v kolobarju	α_o	W/m^{2}K	heat-transfer coefficient on the annulus side
toplotna prevodnost	λ_{Cu}	W/mK	thermal conductivity
temperatura	ϑ	°C	temperature
srednja logaritemska temperaturna razlika	$\Delta\vartheta_m$	°C	log mean-temperature difference
koeficient učinkovitosti hlajenja	ε / COP		coefficient of performance-cooling
hladilna moč	Φ_0	W	cooling capacity
grelna moč	Φ_C	W	heating capacity

Indeksi		**Subscript**
kondenzacija	C	condensation
uparjanje	e	evaporation
etilen glikol	EG	ethylene glycol
ogrevanje	h	heating

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Naslov avtorjev: mag. Vladimir Soldo
prof.dr. Tonko Ćurko
mag. Vlasta Zanki
Fakulteta za strojništvo in ladjedelništvo
Univerza v Zagrebu
Ivana Lučića 5
10000 Zagreb, Hrvaška
vladimir.soldo@fsb.hr
tonko.curko@fsb.hr
vlasta.zanki@fsb.hr

Authors' Address: Mag. Vladimir Soldo
Prof.Dr. Tonko Ćurko
Mag. Vlasta Zanki
Faculty of Mechanical Eng. and Naval Architecture
University of Zagreb
Ivana Lučića 5
10000 Zagreb, Croatia
vladimir.soldo@fsb.hr
tonko.curko@fsb.hr
vlasta.zanki@fsb.hr

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