Experimental Analysis of the Performance of the Eco-Friendly R510A and R600a Refrigerants in a Retrofitted Vapour Compression Refrigerating System

Eksperimentalna analiza svojstava ekološki prihvatljivih radnih tvari R510A i R600a u modificiranome parnome kompresorskome rashladnom sustavu

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DOI 10.17818/NM/2018/1.2
UDK 621.56/.59
Preliminary communication / *Prethodno priopćenje*
Paper accepted / *Rukopis primljen:* 2. 9. 2017.

Summary

Halocarbon refrigerants have been scheduled for total phase out because they contributed significantly to the two major global environmental problems - ozone layer depletion and global warming. In this study, the performances of the environmentally friendly R510A and R600a in a retrofitted domestic refrigerating system were investigated experimentally and compared with the performance of R134a. The results obtained showed that R510A has the lowest discharge pressure with an average value of 13,4 % lower than that of R134a. The average pressure ratios of R510A and R600a were 16,91 and 12,17 %, respectively, lower than that of R134a. The Volumetric Cooling Capacity obtained for R510A was 5,34 % higher than that of R134a. R510A and R600a exhibited higher refrigerating effect and Coefficient of Performance (COP) than R134a.The average COPs for R510A and R600a were 22,26 and 3,06 %, respectively, higher than that of R134a. Generally, R510A and R600a performed better than R134a and they can be used as retrofit substitute refrigerants for R134a in the existing domestic refrigerators. The best performance was obtained from the use of R510A in the retrofitted system.

KEY WORDS

domestic refrigerator
eco-friendly
performance
retrofitted
R510A and R600a

Sažetak

Halougljične radne tvari planiraju se potpuno izbaciti iz uporabe jer su znatno pridonijele dvama svjetskim ekološkim problemima – razaranju ozonskoga omotača i globalnome zatopljenju. U ovoj studiji eksperimentalno su ispitivana svojstva ekološki prihvatljivih radnih tvari R510A i R600a u modificiranome kućnome hladnjaku i uspoređena su sa svojstvima R134a. Dobiveni rezultati pokazali su da R510A ima najniži kondezatorski tlak s prosječno 13,4 % nižom vrijednošću od R134a. Prosječni kompresijski omjeri za R510A i R600 bili su 16,91 i 12,17 % niži nego za R134a. Volumetrijski rashladni kapacitet dobiven s R510A bio je 5,34 % viši nego s R134a. R510A i R600a postigli su viši rashladni učinak i COP nego R134a. Prosječne vrijednosti COP za R510A i R600a bile su 22,26 i 3,06 % više od onih za R134a. Općenito, R510A i R600 pokazali su se boljima nego R134a i mogu se koristiti kao zamjenske radne tvari za R134a u postojećim kućnim hladnjacima. Najbolja svojstva dobivena su uporabom radne tvari R510A u modificiranome sustavu.

KLJUČNE RIJEČI

kućni hladnjak
ekološki prihvatljiv
svojstvo
modificiran
R510A i R600a

1. INTRODUCTION / *Uvod*

Refrigeration and air-conditioning processes are extremely essential; they provide a wide-range of benefits to humanity. Their areas of applications include domestic and commercial refrigerating systems, comfort conditioning of living spaces and workplaces, hospitals, operation theatres, hotels, restaurants, automobiles and transportation. Large-scale industrial applications of refrigeration are found in the manufacture of ice, dehydration of gases, large scale warehouses for storage and preservation of foods and beverages and a host of other commercial and industrial services. Most of the refrigeration and air-conditioning system operate on vapour compression refrigeration cycle in which the refrigerant change phases from liquid to gas and gas to liquid in a closed cycle to generate cooling in the evaporator. The design of a cooling system generally depends on the properties of the refrigerants [1, 2].

All through the history of air conditioning and refrigeration, various substances have been employed as refrigerants. The first generation of refrigerants include substances such as hydrocarbons: propane (R290) and iso-butane (R600a), ammonia (R717), sulphur-dioxide (R764), methyl-chloride (R40) and carbon dioxide (CO_2), but these had shortcomings of being flammable, toxic, chemically not stable and not compatible with the various system components. The second generation of refrigerants include chlorofluorocarbons (CFCs) and hydro-chlorofluorocarbons (HCFCs), which became widely used because of their several appropriate properties such as non-toxicity, non-flammability, stability, good thermodynamic properties and good material compatibility. This led to their common wide spread use in various applications of vapour compression systems [3, 4].

However, these chlorine containing halogenated hydrocarbon refrigerants (CFCs and HCFCs) were found to diffuse up into the stratosphere where ultraviolent radiation from the sun releases their chlorine atoms. Chemical reactions in the atmosphere between chlorine atoms and ozone result in the formation of chlorine monoxide which reacts again with the ozone molecule to form oxygen and regenerates more chlorine atoms that carry on converting the ozone molecules. Thus, even a small amount of CFCs can cause a tremendous damage to the ozone layer which absorbs the sun's high energy ultraviolet rays and protects both humans and other living things from exposure to ultraviolet radiation. The hazard is represented by the refrigerant Ozone Depletion Potential (ODP) number[5]. The environmental impacts associated to ozone depletion have resulted in the scheduled phase out of the CFC and HCFC refrigerants under the Montreal Protocol in favour of the third generation of refrigerants: hydro-fluorocarbons (HFCs). HFCs have zero ozone depletion potential; however, when released to the atmosphere, they have significant Global Warming Potential (GWP). The growing international emphasis on global warming mitigation has stimulated interest in the fourth generation of low-GWP refrigerants [6].

Currently, many researches on hydro-fluorocarbon (HFC) refrigerants are devoted on the retrofitting processes appropriate for the refrigerants which have high global warming potential (GWP). The European Union has approved a regulation which prohibits the use of refrigerants with GWP above 150 in household refrigerators and freezers since January 1, 2015 and in new automobile air-conditioning systems by January 1, 2017[7]. R134a, a zero ODP refrigerant but with a relatively high GWP, is used worldwide in most of the domestic refrigerators because of its good thermodynamics and thermo-physical properties. The sale of R134a has considerably increased during the past two decades. The growing usage of this refrigerant and its subsequent emissions to the atmosphere are steadily increasing the concentration of greenhouse gases, resulting in adverse climate problems [8]. R134a was originally estimated as having a GWP of 1300 [9], but later estimated to have a GWP of 1430 [10] as compared to that of carbon dioxide (CO_2).

A number of studies have recommended R600a and R510A as alternative refrigerants to R134a in domestic refrigeration systems. Kabul *et al*. [11] studied the performance analysis of a vapour compression refrigerating system with an internal heat exchanger using an iso-butane (R600a) for a refrigeration capacity of 1 kW and cold chamber temperature of 0°C. The results showed that the compressor has the highest irreversibility rate, and the heat exchanger has the lowest. Also, it was found that condenser and evaporator temperatures have strong effects on the Coefficient of Performance (COP) of the system. Bayrakci and Ozgur[12] conducted a theoretical comparative performance of a vapour compression refrigerating system using four pure hydrocarbon (HC) refrigerants (R290, R600, R600a and R1270). The results showed that the differences of coefficient of cooling performance values of these refrigerants are quite small. Energetic and exergetic efficiency values obtained with R1270 and R600 are higher than R600a and R290. Joybari*et al*. [13] investigated the performance of R600a refrigerant in domestic refrigerating system originally manufactured to use R134a refrigerant. The results showed that the amount of charge required for R600a was 50 g, 66% lower than R134a one, which not only brings economic advantages, but also significantly reduces the risk of flammability of the hydrocarbon refrigerant.

Park *et al*. [14] numerically and experimentally examined the cooling performance of R510A as a replacement for R134a in the refrigeration system of domestic water purifiers. Test results showed that, due to the small internal volume of the domestic water purifier's refrigeration system, the system performance with R510A is greatly influenced by the amount of charge. With the optimum charge of 21 g, just about 50% that of R134a, the discharge temperature of R510A is 3,7 °C lower than that of R134a and the compressor energy consumption of R510A is 22,3% lower than that of R134a. Also, Bolaji and Huan[15] investigated theoretically, the energy performance of two eco-friendly hydrocarbon refrigerants (RE170 and R510A) in vapour compression refrigeration system under different operating conditions. The results showed that the energy performances of both R510A and RE170 were better than that of R134a. Thermophysical properties and saturation vapour pressure characteristics of RE170 and R510A refrigerants are also similar to those of R134a.

The main objective of the present study is to examine experimentally the performance of a retrofitted existing refrigerating system using R600a and R510A as compare to the performance of original system working with R134a. R600a and R510A have many advantages like zero ODP, negligible GWP, low critical pressures and high enthalpy difference during evaporation process. They are also compatible with common materials found in refrigerating systems and are soluble in conventional mineral oils. These refrigerants contain no chlorine or fluorine atoms, therefore, they cannot react with water and do not form strong acids that can result to untimely system failure which are notable problems with R134a systems.

2. MATERIALS AND METHODS / *Materijali i metode*

2.1. Vapour Compression Refrigeration System / *Parni kompresorski rashladni sustav*

A standard vapour compression refrigeration system uses circulating refrigerant as a medium which absorbs and takes away heat from the space to be cooled and then rejects that heat elsewhere. Figure 1 shows vapour compression refrigeration cycle on the p-h diagram. It is made up of four major processes: evaporation, compression, condensation and expansion. Evaporation takes place in the evaporator where the liquid refrigerant vaporizes by absorbing latent heat from the material being cooled and the resulting low pressure vapour refrigerant then passes from the evaporator to the compressor.

The compressor (heart of refrigeration system) pumps and circulates refrigerant through the system and then supplies the necessary force to keep the system running. This compression process increases the refrigerant pressure and temperature simultaneously to allow heat rejection at a higher temperature in the condenser. The vapour refrigerant with high pressure and temperature which enters the condenser has heat removed from it and as a result, it condenses back to liquid. Finally, high pressure liquid refrigerant from the condenser is expanded through the expansion valve (also called a throttle valve), allowing its pressure to drop to that of the evaporator.

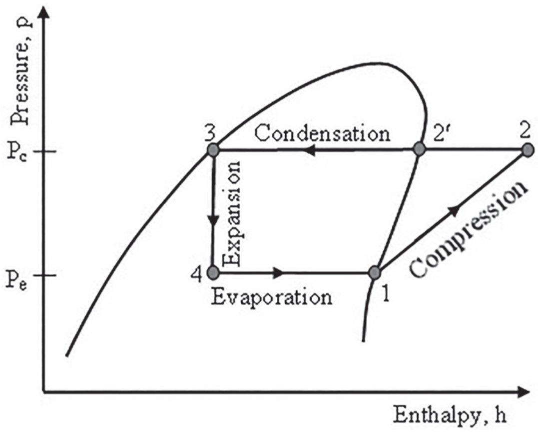

Figure 1 Vapour compression refrigeration cycle on p-h diagram

Slika 1. Parni kompresorski rashladni ciklus u p-h dijagramu

2.2. Properties and Environmental Impacts of the Studied Refrigerants / *Svojstva i ekološki učinci ispitivanih radnih tvari*

The two refrigerants investigated (R600a and R510A) are natural, chlorine and fluorine free refrigerants, therefore, they are not harmful to the environment. Some of the properties and environmental impacts of the refrigerants in comparison with baseline refrigerant (R134a) are shown in Table 1.

3. EXPERIMENTAL ANALYSIS / *Experimentalna analiza*

3.1. Baseline Test / *Osnovni test*

The Schematic diagram of the vapour compression refrigerator is shown in Figure 2. Service ports were installed at the inlet of the compressor and expansion device for recovering and charging the refrigerant.

Table 1 Some properties and environmental impacts of the studied refrigerants [16, 17]

Tablica 1 Neka svojstva i ekološki učinci ispitivanih radnih tvari [16, 17]

Properties	R134a	R600a	R510A
Molecular weight (kg/kmol)	102,03	58,122	47,244
Critical temperature (°C)	101,06	134,66	125,67
Critical pressure (MPa)	4,0593	3,629	5,1185
Liquid density at -25°C (kg/m^3)	1373,4	608,27	722,34
Vapour density at -25°C (kg/m^3)	5,5059	1,6931	2,4002
Normal boiling point (°C)	-26,074	-11,749	-34,40
ODP	0	0	0
GWP	1300	3	3

The system was evacuated through the service port with the help of a Blue-VAC vacuum pump to remove moisture and non-condensable particle. It was flushed with nitrogen gas to eliminate impurities and other materials inside the system which may affect its performance. The system was incorporated with two pressure gauges with accuracy of ± 0,1 kPa at the inlet and outlet of the compressor for measuring the suction and discharge pressures. The temperature of the refrigerant at four different points was measured with digital thermocouples with accuracy of ±0,1 °C. The energy consumption of the refrigeration system was measured using energy meter with accuracy of ±0,2 kWh. The refrigeration system was charged with 160 g of R134a to study the baseline performance. After completing the baseline test with R134a, the refrigerant was recovered from the system prior to retrofit.

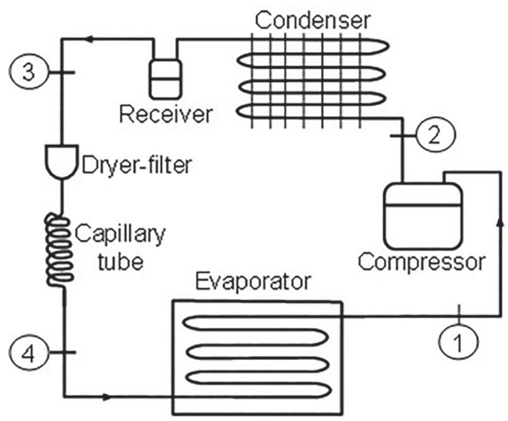

Figure 2 Schematic diagram of the vapour compression refrigerator

Slika 2. Shema parnog kompresorskog hladnjaka

3.2. Retrofitting Existing Refrigerator / *Prilagodba postojećeg hladnjaka*

The existing refrigerating system which was originally designed to work with R134a was modified to use the alternative refrigerants (R600a andR510A) as working fluids. This will enable the existing system to operate safely and effectively beyond the phase-out date of its original environmentally offensive refrigerant until the end of its economic life. The specification of the existing refrigerator is shown in Table 2. R600a andR510A refrigerants require higher volumetric displacement than R134a for the same refrigerator capacity. Hence, in order to retain performance or increase the efficiency, changes are necessary in the system design especially in the required compressor since only compressor specially designed for these refrigerants can be used [18]. R600a compressor of the same capacity with the existing one was used for the retrofit. Although, the polyol-ester oil used in the R134a refrigeration system is compatible with R600a and R510A, it will not be used because it requires special care in handling due to its high moisture absorption capacity. The alternative refrigerants are also compatible with mineral and alkyl-benzenes oils. The mineral oil recommended for R600a compressor was used for the experiments [19].

The condenser and the evaporator in the existing system are retained since they are designed together with the compressor for the same capacity. It has been experimentally verified that no alteration is necessary to the capillary tube of refrigeration systems originally designed for R134a when R600a is used as alternative refrigerant except that a slightly longer length will improve performance [19]. Capillary tube length of 3950 mm with internal diameter of 0,8 mm was used as against the 3550 mm length of the existing refrigerator. The filter-drier was replaced by a solid core filter-drier type 4A-XH5. The system was evacuated through the service port with the help of a Blue-VAC vacuum pump to remove moisture and non-condensable particle. It was flushed with nitrogen gas to eliminate impurities and other materials inside the system which may affect its performance. Figure 3 shows the test rig used for the experiment.

Table 2 The Specification of the existing refrigerator
Tablica 2 Specifikacija postojećeg hladnjaka

Specifications	Value
Freezer capacity (litres)	120
Fresh food compartment capacity (litres)	320
Power rating (W)	60
Current rating (A)	0,60
Voltage (V)	220-240
Frequency (Hz)	50
No of door	1
Refrigerant type	R 134a
Refrigerant charged	160 g
Capillary tube length	3550 mm

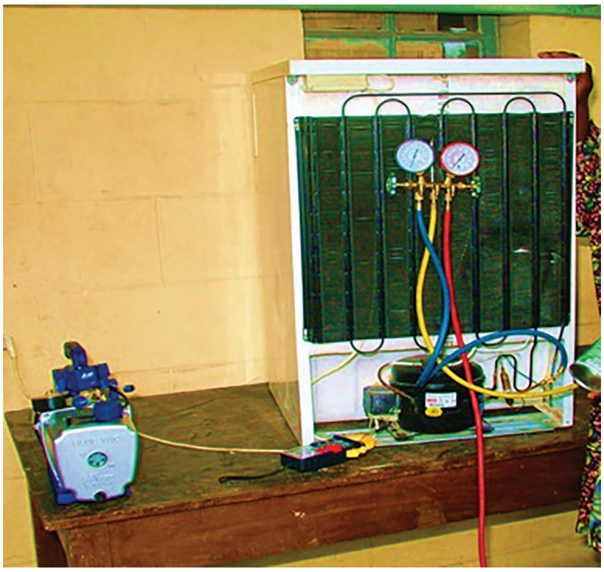

Figure 3 Experimental refrigerator
Slika 3. Pokusni hladnjak

The hydrocarbon system required 40 - 45 % by mass of the initial 160 g of R134a charged. Undercharging will result in higher energy consumption; hence, 70 g of refrigerant charge was used for each of the alternative refrigerants. Using the charging system, R600a and R510A were charged into the retrofitted system and tested one after the other following the same experimental procedure used for the baseline test.

3.3. Analysis of the Heat Transfer in the Refrigeration System / *Analiza transfera topline u rashladnom sustavu*

The data collected at different evaporating temperatures and the corresponding properties of refrigerants obtained using refrigerant database software known as REFPROP [20] were used to compute the following performance parameters (Eqs. 1 to 7): refrigerating effect (Q_{evap}), compressor work input (W_{comp}), condenser heat load (Q_{cond}), Coefficient of Performance (COP), Volumetric Cooling Capacity (VCC) and Pressure Ratio (PR).

Evaporator: The liquid refrigerant at low pressure side enters the evaporator. As the liquid refrigerant passes through the evaporator coil, it continually absorbs latent heat of vaporization at constant temperature through the coil walls from the medium being cooled and turn to vapour refrigerant. The refrigerating effect is the difference between the enthalpies of the refrigerant at the inlet and the outlet of the evaporator. The heat absorbed by the refrigerant in the evaporator or refrigerating effect (Q_{evap}, kJ/kg) is expressed as:

$$Q_{evap} = (h_1 - h_4) \tag{1}$$

where h_1 and h_4 are the specific enthalpies of refrigerant at the outlet and inlet of evaporator respectively.

Compressor: The compressor work input (W_{comp}, kJ/kg) is expressed as:

$$W_{comp} = (h_2 - h_1) \tag{2}$$

where h_2 is the enthalpy of refrigerant at the outlet of compressor.

Condenser: The heat rejected by the condenser (Q_{cond}, kJ/kg) to the atmosphere is given as:

$$Q_{cond} = (h_2 - h_3) \tag{3}$$

where h_3 is the enthalpy of refrigerant at the outlet of condenser (kJ/kg).

Capillary tube: The enthalpy remains constant (isenthalpy process)in the capillary tube,therefore,

$$h_3 = h_4 \tag{4}$$

The Coefficient of Performance (COP) is the refrigerating effect produced per unit of work required. It is a major parameter use in refrigeration system to determine the performance of the system. It indicates the overall energy consumption for a desired load. The lower the energy consumption, the higher the COP. It is expressed as:

$$COP = \frac{Q_{evap}}{W_{comp}} \tag{5}$$

The Volumetric Cooling Capacity (VCC, kJ/m^3) is the refrigerating effect per unit volume of refrigerant at the inlet of the compressor. It is a value calculated from the vapour density at the compressor's inlet and the enthalpy difference of the evaporation [20]:

$$VCC = \rho_1 \cdot (h_1 - h_4) = \rho_1 \cdot Q_{evap} \tag{6}$$

where, ρ_1 = density of the refrigerant at the inlet of the compressor (kg/m^3). The Pressure Ratio (PR) of the compressor is the ratio between the discharge pressure (P_{dis}, MN/m^2) and the suction pressure (P_{suc}, MN/m^2) of compressor which is expressed as:

$$COP = \frac{P_{dis}}{P_{suc}} \tag{7}$$

4. RESULTS AND DISCUSSION / *Rezultati i diskusija*

Similar vapour volume is required for any refrigerant to be suitable as drop-in replacement for another. Figure 4 shows thecurves of the specific volume of the vapour refrigerant at the compressor inlet versus saturation temperature for R134a and its two potential alternative refrigerants (R600a and R510A). The specific volume decreases as the saturation temperature increases. The specific volume and temperature characteristics of R510Aare very close tothose of R600awith an average value of 9,09% lower in the temperature range of -30 to 50°C which shows that it can use the same compressor size with R600a since the swept volumes of their compressorsare similar.Thevapour volumeof R134a is significantly lower than those of R600a and R510A, which shows that they cannot perfectly work with R134a compressor.

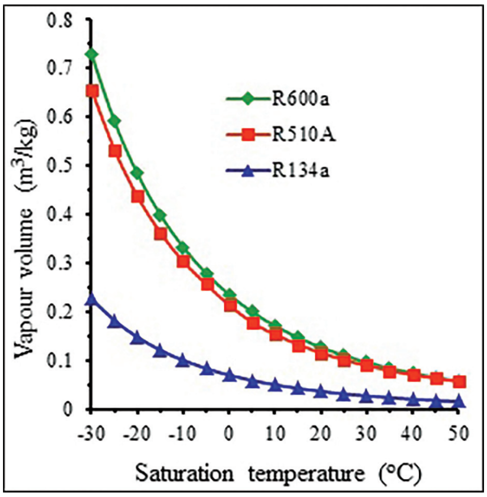

Figure 4 Vapour volume of the refrigerants versus saturation temperatures

Slika 4. Volumen pare radnih tvari u ovisnosti o temperaturi zasićenja

Refrigerating effect is the main purpose of the refrigeration system. The variation of refrigerating effect with the evaporating temperature is shown in Figure 5. From the figure, it clearly shown that the refrigerating effect gradually increases as the evaporating temperature increases. The average refrigerating effect obtained for R134a in the initial system was far lower than those obtained for R510A and R600a in the retrofitted system. Figure 6 shows the discharge pressures at the different evaporating temperatures for the three refrigerants. As shown in the figure, the discharge pressure reduces as the evaporating temperature increases. R134a exhibited high pressure when compared to R510A and R600a. R510A has the lowest pressure with an average discharge pressure of 13,4 % lower than that of R134a but the pressure of R510A was very close to that of R600a. Refrigerants with low pressure are desirable in the system because high pressure will have negative effects on the equipment accessories and parts.

The curves of the pressure ratio versus evaporating temperature for the investigated refrigerants are shown in Figure 7. As reflected in the figure, the pressure ratio decreases as the evaporating temperature increases. This trend is similar for all the three refrigerants; however, the pressure ratio of R134a is higher than those of R510A and R600a. The average pressure ratios obtained using R510A and R600a in the retrofitted system were 16,91 and 12,17 %, respectively, lower than the value obtained for R134a during the baseline test. Therefore, same compressor is usable for both R510A and R600a, while a slightly heavier compressor for the same capacity is required for R134a.

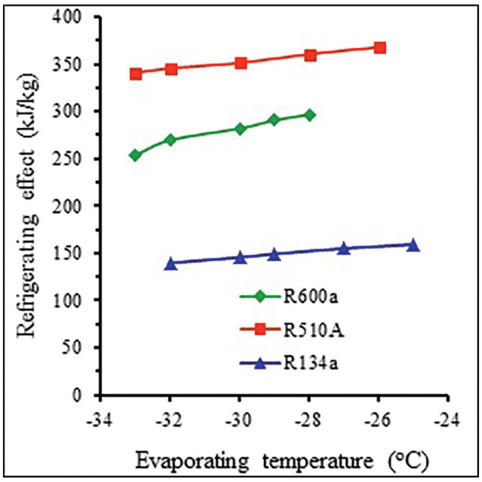

Figure 5 Variation of refrigerating effect with the evaporating temperature

Slika 5. Promjena rashladnog učinka u ovisnosti o temperaturi isparavanja

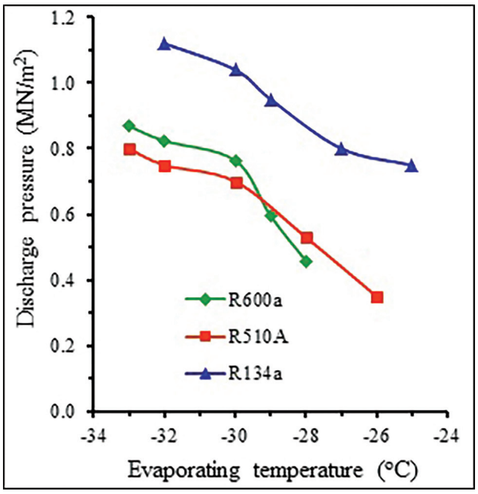

Figure 6 Influence of the evaporating temperature on the discharge pressure

Slika 6. Utjecaj temperature isparavanja na kondezatorski tlak

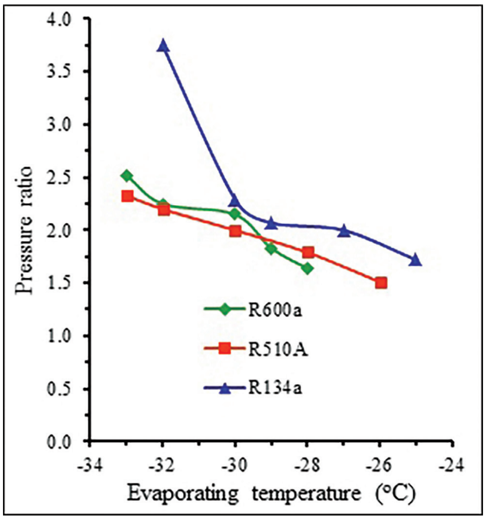

Figure 7 Pressure ratio versus evaporating temperatures.

Slika 7. Kompresijski omjer u ovisnosti o temperaturi isparavanja

The effect of the evaporating temperature on the Volumetric Cooling Capacity (VCC) for the three refrigerants is shown in

Figure 8. Refrigerants with high volumetric capacities for a given swept volume in the compressor are desirable because they will produce systems with high cooling capacity. The figure shows that the VCC increases with increase in the evaporating temperature. This is due to decrease in the specific volume and increase in the cooling effect. The VCC curve of R134a is close to those of the other refrigerants and the average VCCs obtained for R134a was 5,34 % lower than the value of R510A and 8,82 % higher that of R600a.

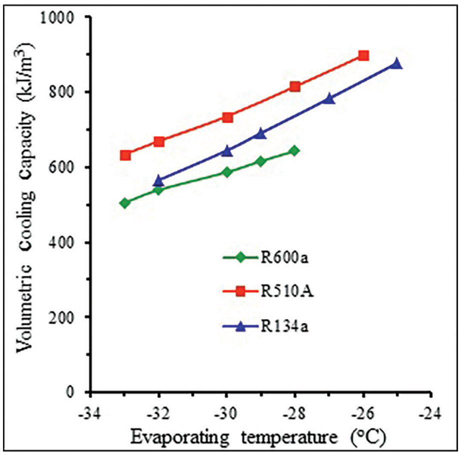

Figure 8 Effect of the evaporating temperature on the volumetric cooling capacity

Slika 8. Utjecaj temperature isparavanja na volumetrijski rashladni kapacitet

Figure 9 shows the influence of the evaporating temperature on the Coefficient of Performance (COP) for the three investigated refrigerants. As shown in this figure, the COP increases as evaporating temperature decreases. The COP is the ratio of the refrigerating effect to the compressor work. The increase in evaporating temperature increases the refrigerating effect and decreases the compressor work input thereby increasing the COP of the refrigeration system. The retrofitted system operating with R510A and R600a yielded higher COPs than the existing system operating with baseline refrigerant (R134a). The average COPs for R510A and R600a were 22,26 and 3,06 %, respectively, higher than that of R134a.

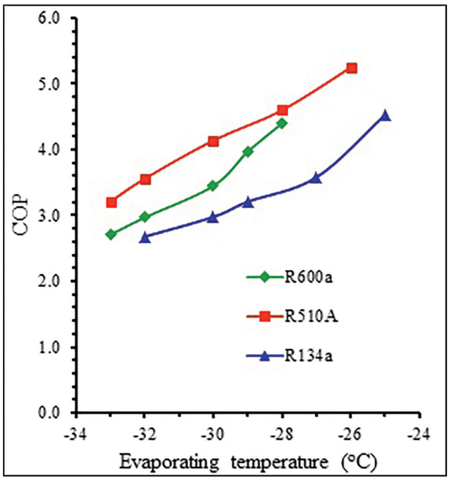

Figure 9 Influence of the evaporating temperature on the Coefficient of Performance (COP)

Slika 9. Utjecaj temperature isparavanja na COP

5. CONCLUSION / *Zaključak*

R510A and R600a are environmentally friendly. They have zero ozone depletion potential and negligible global warming potential. They arepossible alternatives to R134a which is currently the most widely used refrigerant in the domestic refrigerators. In this study, the performances of R510A and R600a in a retrofitted domesticrefrigerating system were investigated experimentally and compared with the performance of baseline refrigerant (R134a). The following conclusions can be drawn from the analysis and discussion of the results:

(i) R510A refrigerant showed very close vapour volume and temperature characteristics with R600a in the temperature range of -30 to 50 °C which indicates that both refrigerants can use the same compressor size for domestic refrigeration application. However, the vapour volume of R134a is significantly lower than those of R600a and R510A which shows that they cannot perfectly work with the same compressor.

(ii) R510A and R600a produced higher refrigerating effect than R134a.

(iii) The two alternative refrigerants exhibited better discharge pressure and pressure ratio than R134a. R510A has the lowest pressure with an average discharge pressure of 13,4 % lower than that of R134a. The average pressure ratios of R510A and R600a in the retrofitted system were 16,91 and 12,17 %, respectively, lower than that of R134a.

(iv) Thevolumetric cooling capacityof R134a is close to those of the alternative refrigerants and the average valueobtained for R510A was 5,34 % higher than that of R134a.

(v) The retrofitted system operating with R510A and R600a yielded higher COPs than the existing system operating with baseline refrigerant (R134a). The average COPs for R510A and R600a were 22,26 and 3,06 %, respectively, higher than that of R134a.

Generally, R510A and R600a performed better than R134a and they can be used as retrofit substitute refrigerants for R134a in the existing domestic refrigerators. The best performance was obtained from the use of R510A in the retrofitted system.

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