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INFLUENCE OF REFRIGERANT R1234YF AS A SUBSTITUTE FOR R134A ON A PERFECT REFRIGERATION CYCLE AND EXCHANGER EFFICIENCY

WPŁYW CZYNNIKA CHŁODNICZEGO R1234YF JAKO ZAMIENNIKA R134A NA PRACĘ IDEALNEGO OBIEGU CHŁODNICZEGO ORAZ WYDAJNOŚĆ WYMIENNIKA

A b s t r a c t

This paper analyses the R1234yf refrigerant as a substitute of R134a with respect to its thermodynamic properties. For the assumed calculation parameters, identical evaporation and condensation temperature, ideal refrigeration cycles with R1234yf and R134a were compared. Moreover, for an actual car evaporator, thermal calculations were performed for the exchanger and the theoretical efficiency parameters of both refrigerants were provided.

Keywords: *refrigerant R134a*, *refrigerant R1234yf*

S t r e s z c z e n i e

W artykule dokonano analizy czynnika chłodniczego R1234yf jako zamiennika R134a pod względem termodynamicznym. Dla założonych parametrów obliczeniowych, identycznej temperatury odparowania i skraplania, porównano pracę idealnego obiegu, który współpracuje z czynnikiem R1234yf oraz R134a. Ponadto dla rzeczywistego parownika samochodowego wykonano obliczenia cieplne wymiennika i podano teoretyczne charakterystyki wydajnościowe obu czynników.

Słowa kluczowe: *czynnik chłodniczy R134a*, *czynnik chłodniczy R1234yf*

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Nomenclature

A – heat transfer surface area [m^2]
COP – coefficient of performance [–]
d_z – outer tube diameter [m]
i_1 – refrigerant enthalpy at the outlet from the evaporator, inlet of the compressor [kJ/kg]
i_2 – refrigerant enthalpy at the outlet from the compressor, inlet of the condenser [kJ/kg]
i_3 – refrigerant enthalpy at the outlet from the condenser, inlet of the expansion valve [kJ/kg]
i_4 – refrigerant enthalpy at the outlet from the expansion valve, inlet of the evaporator [kJ/kg]
k_A – heat transfer coefficient referring to surface area A [$W/(m^2 \cdot K)$]
$\dot{m}$ – mass flow rate of refrigerant [kg/s]
$\dot{N}$ – power of compressor [kW]
NTU – number of heat transfer units [–]
$\dot{Q}_o$ – capacity of evaporator [kW]
$\dot{Q}_k$ – capacity of condenser [kW]
RCJ – degree of process openness, calculated as 1/(Sensible Heat Ratio) [–]
T_{p1} – outside air temperature at the exchanger inlet [°C]
T_o – evaporation air temperature [°C]
$\dot{W}_p$ – air flux thermal capacity [W/K]
α_p – air-side heat transfer coefficient [$W/(m^2 \cdot K)$]
α_o – refrigerant-side heat transfer coefficient [$W/(m^2 \cdot K)$]
α_{kon} – heat transfer coefficient for single-phase vapour flow [$W/(m^2 \cdot K)$]
α_{os} – heat transfer coefficient for large-volume boiling [$W/(m^2 \cdot K)$]
ε – heat exchanger efficiency [–]

1. Introduction

The introduction of refrigerant R1234yf to the market raised certain concerns in the refrigeration and air-conditioning sector. The refrigerant was launched on the market as a substitute for R134a, which was widely used in small refrigeration and air-conditioning devices, its main use being within the automobile industry. The change resulted from legislation adopted for environmental protection reasons.

When comparing two substances, besides examining their physical and chemical properties, it is necessary to look at environmental indicators which help to assess the refrigerant's impact on the Earth's atmosphere – the GWP (Global Warming Potential) is one such coefficient. It describes the greenhouse effect potential of a particular refrigerant. Another important indicator is the ODP (Ozone Depletion Potential), which identifies the impact of a particular substance on the depletion of the ozone layer of the Earth's atmosphere.

In 2006, the European Union adopted Directive 2006/40/CE relating to emissions from air-conditioning systems of fluorinated gases. Pursuant to the aforementioned legal act, since 1 January 2011 it has been necessary to use refrigerants with a GWP value lower than 150 in automobiles. Due to technical problems related to the manufacturing of the new refrigerant, the directive has applied since 1 January 2013. From 1 January 2017, no new vehicles will be registered if their air-conditioning systems use refrigerants with a GWP value of > 150 [1]. Two global companies (Honeywell and DuPont) established a joint venture company and introduced R1234yf to the market in order to help the automobile industry to meet the stringent requirements of the EU directive. The parameters of the proposed refrigerant are similar to those of R134a and are coupled with low GWP coefficient values.

2. Comparison of refrigerants R134a and R1234yf

When introducing a new refrigerant as a substitute for an existing one, it needs to be ensured that it has better physical, chemical and thermo-dynamic properties, is safe to use, easily accessible, affordable and meets relevant legislative requirements [2].

Table 1 shows some properties of refrigerants R134a and R1234yf. When the data is compared, it becomes clear that the refrigerants are quite similar. The only major difference concerns the GWP indicator. For R1234yf, the GWP value is 357 times lower than that of R134a and significantly below the requirements set forth in the EU Directive. Another key unfavorable factor is the low self-ignition temperature and low flammability threshold of R1234yf when compared to R134a, which is non-flammable.

Table 1

Selected properties of refrigerants R134a and R1234yf [2, 4, 5, 6]

Name	1,1,1,2-Tetrafluoroethane (R134a) or HFC 134a	2,3,3,3-Tetrafluoropropane or HFO 1234yf
Molar mass	102.03 [kg/kmol]	114.04 [kg/kmol]
Density (for t = 25°C)	1206 [kg/m^3]	1100 [kg/m^3]
Boiling point	–26.07 [°C]	–29.45 [°C]
Critical temperature	101.06 [°C]	94.70 [°C]
Critical pressure	40.59 [bar]	33.82 [bar]
Self-ignition temperature	non-flammable	405 [°C]
Flammability limits	non-flammable	6.2% (vol) to 12.3% (vol)
GWP	1430	4
ODP	0	0

3. Comparison of theoretical refrigeration cycles fed with refrigerants R134a and R1234yf

The following parameters, listed in Table 2, have been adopted for the purposes of conducting a comparison of ideal refrigeration cycles with refrigerants R134a and R1234yf. The relevant points of the compared refrigeration cycles were then plotted on log p – i graphs for the compared refrigerants. The graph was then used to identify the values of enthalpy at particular points and the efficiency of other elements of the installation was calculated along with the COP value using equations (1)–(4).

Table 2

Parameters of the air-conditioning installation

Evaporator capa city [W]	Overheating of refrigerant vapour [K]	Subcooling of refrigerant liquid [K]	Evaporation temperature [°C]	Condensation temperature [°C]
4000	5	5	0	50

$$\dot{m} = \frac{\dot{Q}_o}{i_1 - i_4} \tag{1}$$

$$\dot{Q}_k = \dot{m} \cdot (i_2 - i_3) \tag{2}$$

$$\dot{N} = \dot{m} \cdot (i_2 - i_1) \tag{3}$$

$$\text{COP} = \frac{\dot{Q}_o}{\dot{N}} \tag{4}$$

Figure 1 shows the comparison cycles for the examined refrigerants with the assumed operating parameters of the installation.

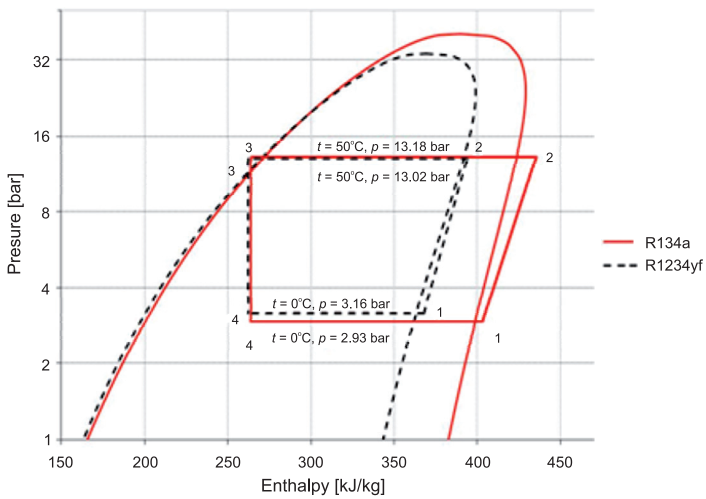

Fig. 1. Refrigeration cycles for refrigerants R134a and R1234yf

Table 3 shows a comparison of the mass flux of the refrigerant $\dot{m}$, the capacity of the condenser $\dot{Q}_k$, the compressor engine power $\dot{N}$ and the COP calculated on the basis of equations (1)–(4).

Table 3

Results of calculations

Refrigerant	$\dot{m}$ [kg/s]	$\dot{Q}_k$ [kW]	$\dot{N}$ [kW]	COP
R134a	0.0287	4.93	0.93	4.31
R1234yf	0.0378	4.91	0.91	4.39
%	31.67	–0.36	–1.93	1.97

An analysis of the obtained results clearly indicates that the parameters of installations operating with both refrigerants are similar. Refrigerant R1234yf and R134a have almost identical condensation pressures, while the evaporation pressure is slightly higher in the former compared to the latter. As regards the other parameters included in Table 3, when using a new refrigerant in the air-conditioning installation, it is necessary to account for a greater mass flux of the refrigerant, which increases by almost 32%. This results from the fact that the refrigerant vapours leaving the evaporator are less dense and therefore they have lower volumetric efficiency and, as shown in Fig. 1, lower values of latent heat.

4. Comparison of the efficiency of an actual automobile evaporator fed with refrigerants R134a and R1234yf

Besides comparing the performance of a theoretical refrigeration cycle, the study also looked at how the efficiency of an actual automobile evaporator changed when fed with each of the analysed refrigerants. The refrigerant evaporation temperature, the surrounding temperature and various air flow velocities in the exchanger were assumed for calculation purposes. A passenger car evaporator made of brass tubes and aluminum lamellas was used as a sample exchanger for the purposes of performing the calculations. The geometrical parameters are included in Table 4.

Table 4

Geometrical parameters of the evaporator

width	$G = 357$ mm	**transversal pitch**	$S_q = 25$ mm
height	$H = 202$ mm	**longitudinal pitch**	$S_l = 12$ mm
depth	$L = 89$ mm	**lamella pitch**	$t = 1{,}5$ mm
number of tubes	$n_r = 8$	**lamella thickness**	$g = 0{,}1$ mm
number of tube rows	$n_{rr} = 8$	**number of lamellas**	230
number of feeds	$n_z = 6$	**tube arrangement**	staggered
outer tube diameter	$d_z = 8$mm		

The assumed evaporation temperature for both refrigerants was 0°C, while the outer air temperature was assumed as 30°C and the external air flow velocities amounted to respectively: 1; 2; 3; 3.5; 4 m/s.

The NTU method was used to calculate the efficiency of the lamella heat exchanger, according to equations (5)–(8) [3].

$$\dot{Q}_o = \varepsilon \dot{W}_p (T_{p1} - T_o) \tag{5}$$

$$\varepsilon = 1 - e^{-\mathrm{NTU}} \tag{6}$$

$$\dot{W}_p = \dot{m} c_{pp} \mathrm{RCJ} \tag{7}$$

$$\mathrm{NTU} = \frac{k_A A}{\dot{W}_p} \tag{8}$$

The air-side heat transfer coefficient was calculated on the basis of the Schmidt equation [3].

$$\alpha_p = \mathrm{RCJ} \frac{Nu_p \lambda_p}{d_z} \tag{9}$$

The heat transfer coefficient on the side of the boiling agent was calculated using the Mikielewicz equation [3].

$$\alpha_o = \alpha_{kon} \sqrt{R_1^{0.8} + \omega \left(\frac{\alpha_{os}}{\alpha_{kon}} \right)^2} \tag{10}$$

Figure 2 presents the results of calculations of the efficiency of the exchanger as a function of the amount of flowing air. It is clear that the graphs are quite similar with only minor differences. For a limited mass flux of air of up to 0.1 m³/s, which corresponds

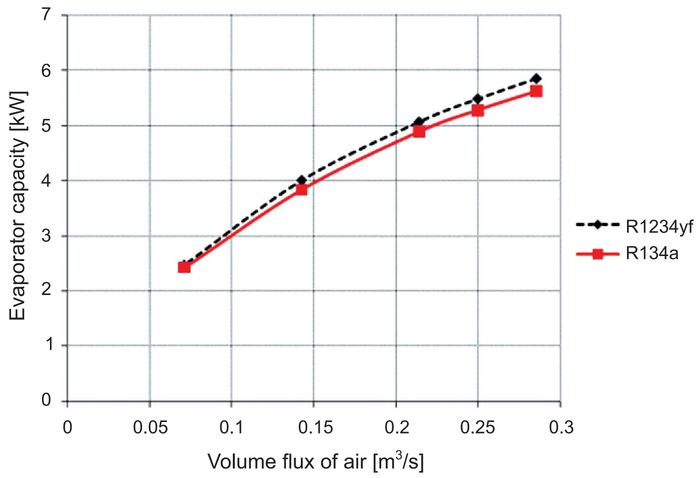

Fig. 2. Evaporator capacity depending on the volume flux of air

to the airflow velocity through the exchanger of ca. 1.5 m/s, the graphs virtually overlap. In the case of a larger mass flux, the graphs are similar, but the efficiencies differ. The capacity of the exchanger fed with R1234yf is slightly higher than the capacity of that fed with R134a at airflow velocities inside the exchanger between 2 m/s and 4 m/s. The increase amounts to ca. 4% for an exchanger operating with R1234yf.

5. Conclusions

A cooling installation operating with R1234yf has a 2% higher COP coefficient than an installation filled with R134a. The evaporation and condensation pressures are at similar levels for the same operating conditions. Depending on the operating conditions, the capacity of a heat exchanger with R1234yf is almost identical or slightly higher (by 4%) than the capacity achieved when R134a is being evaporated.

Just as R134a was introduced as a substitute for R12 in the early 1990s, the time has come for R1234yf to be introduced as a substitute for R134a. When the advantages and disadvantages of R1234yf are analysed, it becomes clear that as far as cooling installations are concerned, the refrigerant seems to be an appropriate substitute for R134a. It slightly improves the efficiency and COP of the cooling installation and operates with similar parameters. Flammability and explosiveness are a concern among car users, but it needs to be stressed that other flammable substances besides the refrigerant are commonly found in automobiles. They may also cause a threat to the user and the environment. As far as environmental protection is concerned, the refrigerant is a desirable substitute and should be used in air-conditioning installations. Currently, studies on the application of natural refrigerants in air cooling and air-conditioning installations are becoming readily available. Let us hope that a natural refrigerant, such as CO_2, can be used in cars in the near future. It would be both safe for the user and environmentally neutral.

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