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Trade-off working fluid selection for heat pumps

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Abstract. Nowadays heat pump systems are used to recover the heat from waste water from different sources and produce hot water for household and communal purposes. In this research comparative thermodynamic analysis of performance for a water-to-water single-stage vapor compression heat pump using several HCs, HCFCs and HFCs which belong to refrigerants of different generations is presented. A multi-criteria approach for optimal selection of refrigerants was used as scientific tool. Results of theoretical experiments of vapor compression heat pump system with the evaporator temperature range 0…25ºC and condenser temperature 60ºC and 83ºC showed that the COP of R1234ze was higher than that of R600a, R152b by about 6.7…17.3%, 8.25…20.5%, and 1.7…14.4%, respectively, at condenser temperature 60 ºC; however results are different if at condenser temperature is 83ºC: the average COP of R600a was higher than that of R1234ze and R152b by about 7.7…14.7%, 9.3…15.8%, and 7.5…15.6%, respectively. COP displays a positive correlation with the evaporator temperature as well as a negative correlation with the condenser temperature. The complete analysis of all factors, including environmental safety, indicates that R1234ze and R600a refrigerants should be preferred as the working fluids for using in the water-to-water single-stage vapor compression heat pump for the hot water supply and heating purposes in industrial applications.

1. Introduction

Refrigeration and climate technology in developed countries consume up to 15% or more of produced electricity per year. Today capacity refrigerating and climatic equipment market in the European Union is about 30 billion Euros, and only in Germany - 10 billion Euros. The growth rate of this market in individual countries is 20-30% per year. Russia has a steady growth rate of consumption (25% per year) [1-2].

Refrigerants, coolants and oils - have been and remain the objects of constant thermophysical research throughout the world. Despite the fact that the principle of obtaining artificial cooling based on changing phase state has not changed, the cooling and air-conditioning industry is invariably evolved and expanded, which directly affects the applicability of a particular refrigerant in a certain period of time. Refrigerants have changed over the years, mainly in response to safety and environmental issues (figure 1).

The standards and codes that guide the application of refrigerants in cooling and air-conditioning industryare getting more strict as well [3].

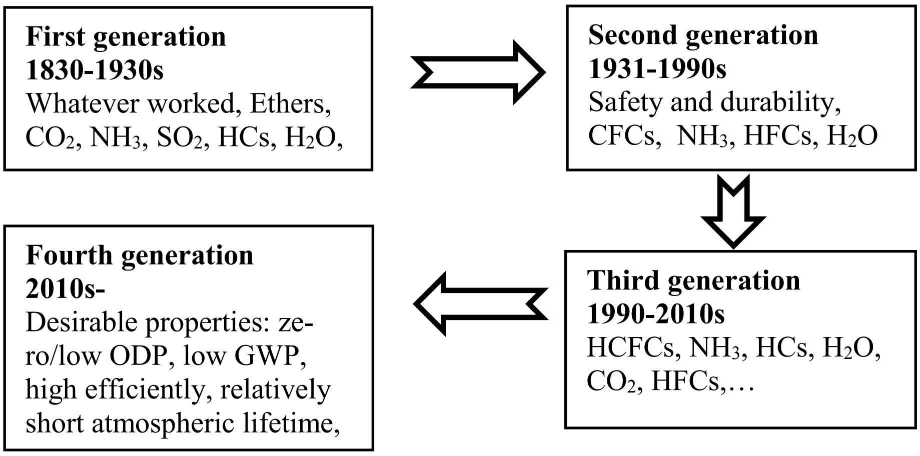

Figure 1.Generation of refrigerants.

Since January 1, 2020 the European Union has introduced a ban on the using of refrigerants with a global warming potential (GWP), greater than 2500, and since 01.01.2025 - a ban on refrigerants with GWP<150. D.Sc. Tsvetkov O.B. et al [1-2] have determined the following requirements for any refrigerants in modern conditions, they are:

- Ozone-Depleting Potential (ODP);
- Global Warming Potential (GWP);
- toxicity;
- fire and explosion hazard;
- ease in detecting leaks;
- critical parameters and thermodynamic properties;
- transfer properties;
- heat and mass transfer characteristics;
- freezing and thermal decomposition temperatures;
- solubility in lubricating oils;
- compatibility with the materials used in engineering and water;
- cost.

Nowadays scientists try to understand if climate change causes from direct consequences or from indirect consequences such as energy-related emissions. There are thousand works showing advantages and disadvantages of the certain refrigerant [4-7].

Clearly, future discovery of ideal refrigerant that combines all the desirable properties is highly unlikely. However, algorithms for searching of a refrigerant with desirable combinations of properties have been described and founded application in ejector cooling cycle [8].

The aim of this study is to compare the thermodynamic performances of the high-temperature water-to-water vapor compression heat pump system using several HCs, HCFCs and HFCs which belong to refrigerants of different generations and to recommend more suitable substance based on theoretical calculation and analysis.

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2. Materials and Methods

In the work we consider the operation of refrigeration system which is simulated by the reverse Rankine cycle. The main processes in the single-stage vapor compression cycle include isentropic compression, isobaric cooling (condensation, subcooling), throttling, and isobaric cooling (evaporation, superheating). The following design specifications are chosen: evaporator and condenser temperatures, t_{ev}= 20°C, t_{cond} = 60°C and t_{cond} = 83°C; cold carrier temperature at the heat pump inlet/ outlet (temperature of the low potentional heat source), t_{low1}/ t_{low2} = 35/30 °C; hot carrier temperature at the heat pump inlet/ outlet, t_{high1}/ t_{high2} = 47/57 °C and 70/80°C; condenser/ evaporator pressure ratio - P_r<9.The temperature range of cold space is the most typical of the industrial cooling water system outlet.

The refrigerants used in this analysis are: natural refrigerants, such as R290A, R600a; third generation refrigerants R142b and R152a, and finally, fourth generation refrigerants, such as R1234yf, R1234ze (table 1). The results obtained from the theoretical calculation are presented and commented in this work from the energetic point of view.

Table 1. Main Characteristics of Refrigerants [9-12].

Refrigerant/ parameter	Natural refrigerants		Ethane Series fluids/ third generation refrigerants		Hydrofluoroolefins fluids/ fourth generation refrigerants	
	R290	R600a	R142b	R152a	R1234yf	R1234ze
Chemical formula	C_3H_8	C_4H_{10}	CH_3CClF_2*	CHF_2-CH_3	$CF_3CF{=}CH_2$	CF_3-$CH{=}CHF$
Molecular mass, kg/kmol	44.1	58.1	100.5	66.05	114.04	114.04
Normal Boiling Point at p=1atm, K	230.91	261.2	283.15	249.05	243.66	254.17
Critical Temperature, K	370	407.98	410.26	386.41	94.7	109.4
Critical Pressure (absolute), p_{cp}, bar	42.7	36.846	41.4	45.16	33.82	36.4
Critical Density, kg/m^3	220.48	225.5	446.0	368	475.55	470.0
Ozon Depletion Potential,ODP	0.0	0.0	0.065	0	0	0
Global Warming Potential, GWP	3	0.01	2000	140	4	7
Safety class[a]	A3	A3	A2	A2	A2L	A2L

[a]Classification: A2 – non-toxit, midly-flammable with higt velocity of flammability; A2L – non-toxit, midly-flammable with low velocity of flammability; A3 – non-toxit, flammable.

The temperature range of hot space is set basing on the most typical values for municipal and industrial high-temperature heating and hot water supply system inlet.

The heat pump thermodynamic cycles diagrams were prepared in the log(p)-h for each of the selected refrigerants. All calculations and diagrams were carried out with the help of freeware CoolPack ("CoolPack– IPU," n.d.) ver. 1.46, freeware REFPROF ver.8 (NIST Standard Reference Database 23) [11-12] and Microsoft Excel 2010.

The thermodynamic cycle for R600a is shown in the Log(p)-h diagramat t_{ev}= 20ºC, t_{cond} = 60ºC (figure 2) and at t_{ev}= 20ºC, t_{cond} = 83ºC (figure 3) as an example.The thermodynamic cycles for the other selected refrigerants have the same order except values of parameter for each state point.

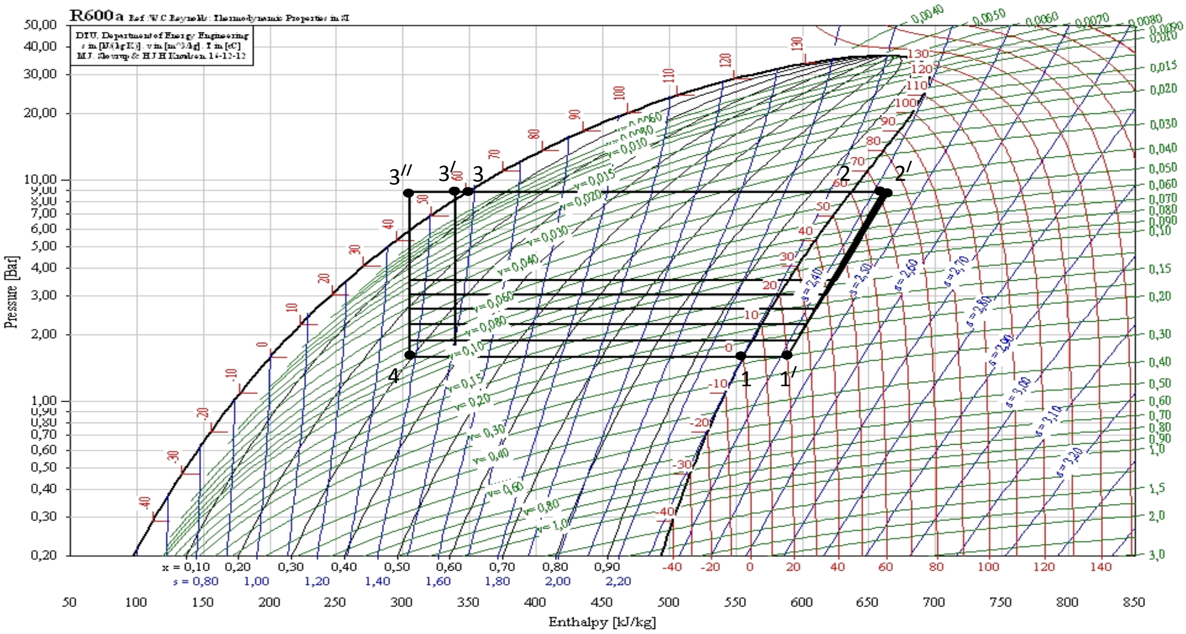


Figure 2.The log(p)-h diagram for R600a at variable evaporation temperature, including t_{ev}= 20ºC, t_{cond} = 60ºC.

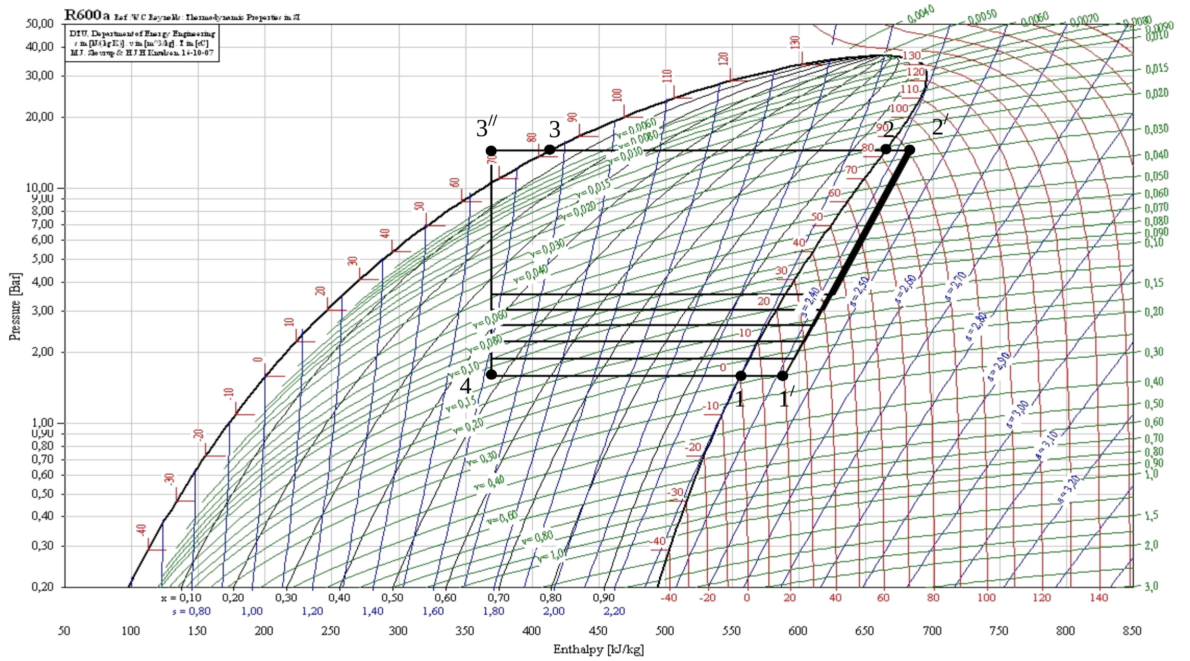


Figure 3.The log(p)-h diagram for R600aat variable evaporation temperature, including t_{ev}= 20ºC, t_{cond} = 83ºC.

The performance and efficiency of the water-to-water single-stage vapor compression heat pump were estimated as described in [13].

Basing on the parameters from diagrams all the necessary data were calculated for all refrigerants and presented in table 2**.**

In this work we have tried to adapt a multi-criteria optimization for making comparative analysis in order to choose "desirable" refrigerant for our heat pump system.For the multi-criteria problems the local criteria usually have a different physical meaning, and consequently, they have incomparable dimensions. It complicates the solution of a multi-criteria problem and makes it necessary to introduce the procedure of normalizing criteria or making these criteria dimensionless. There is no unique method for the criteria normalizing and choice of method depends on statement of problem having a subjective character [8]**.**

Table 2. Calculated parameters for using refrigerants at t_{ev}= 20°C, t_{cond} = 60°C.

Refrigerant/parameter	R290	R600a	R142b	R152a	R1234yf	R1234ze
Vaporizer specific heat load, q_{vap}, kJ/kg	269.5	279.0	176.0	251.29	100.0	120.0
Condenser specific heat load, q_{cond}, kJ/kg	316.1	315.0	200.0	283.27	116.0	136.0
Subcooler specific heat load, $q_{s\ cool}$, kJ/kg	8	8	8	8	8	8
Total heat pump specific heat load, q_{hp}, kJ/kg	324.1	323.0	208	291.27	124.4	144.0
Compressor specific work, l_{comp}, kJ/kg	48.2	44.0	32.0	45.83	20.4	18.0
Exergy efficiency ratio, η_e	0.45	0.48	0.4	0.43	0.42	0.52
Coefficient of perfomans COP, μ	6.72	7.34	6.5	6.36	6.1	8.0
Heat equivalent of the electric power, consumed by compressor, q_{cpower}, kJ/kg	53.41	48.75	44.44	50.78	22.6	19.94

Multi-criteria comparative analysis algorithm is realized in the following way.

- Thermodynamic properties and design characteristics of vapor compression cycle are calculated for specified external conditions.
- The "desirable" value of criterion D_i=D_{max} and D_i=D_{min} have been chosen for each of the criterion. The value of D_i depended on thermodynamic mean of each parameter, e.g. for "total heat pump specific heat load" D_{max}=q_{hp}=324.1kJ/kg and D_{min}=q_{hp} =124.41kJ/kg were chosen as data.

If the absolute value of parameter should strive for a minimum value, than $D^0{}_{absREF_i}$ can be obtained as (1)

$$D^0{}_{abs\,REF_i} = \frac{D_i - D_{\min}}{D_{\max} - D_{\min}}. \tag{1}$$

If the absolute value of parameter should strive for a maximum value, than $D^0{}_{absREF_i}$ can be obtained as (2)

$$D^0{}_{absREF_i} = \frac{D_{\max} - D_i}{D_{\max} - D_{\min}}. \tag{2}$$

- The best value of design characteristics D_{absREF} is chosen for each criterion among all concurrent refrigerants.
- Composite criterion D_{absREF} is defined by

$$D_{absREF} = \sum_{i=1}^{n} D^{0}{}_{absREF_i}. \tag{3}$$

- Minimum value of D_{absREF} – criterion corresponds to best refrigerant among concurrent working fluids.

Trade-off search of working fluid control variables X is formulated as a fuzzy nonlinear programming problem with n non-compatible criteria (economic, environmental, and thermodynamic), m decision variables, and k nonlinear constraints:

$$\mathrm{O_{ptimize}}\ K\ [K_{th}(X), K_{ec}(X), K_{en}(X)] \tag{4}$$

subject to

$$G_{Li} \pounds G_i\,(X) \pounds G_{Ui},\ I = 1,2,\ldots, k \tag{5}$$

$$X_{Li} \pounds X_i \pounds X_{Ui},\ i = 1,2,\ldots, m \tag{6}$$

where $K_{th}(X)$, $K_{ec}(X)$, $K_{en}(X)$ represent the fuzzy local criteria of thermodynamic, economic, and environmental efficiency; X $(X_1, X_2, \ldots, X_m)$ is a vector of control variables; G_{Li}, G_{Ui}, are respectively the lower and upper limits for the constraints $G_i(X)$ and X_{Li}, X_{Ui} are respectively the lower and upper bounds for the control variables.

There are several methods of finding “good” solutions to the above problem in thermoeconomic analysis based on scalar optimization. However, as example, the attempts to resolve the CGAM problem [14, 15] via single objective paradigm illustrate a conflict among different approaches and lack of compromise decision [8]. Multicriteria approach is based on synergetic combination of formal and informal making-decision procedures to select a trade-off solution of problem. There are no entirely formal mathematical tools to resolve a multicriteria problem and additional exogenous information is needed.

In the present study, a next sequence of decision-making steps in fuzzy thermoeconomic analysis of refrigeration system is applied [8, 16].

- Determination of the Pareto optimal (or compromise, or trade-off) set X_P as the formal solution of multicriteria problem to minimize a conflict source of uncertainty;
- Fuzzification of goals as well as constraints to represent an ill-structured situation;
- Informal selection of convolution scheme to switch over a vector criterion $K[K_{th}(X)\ K_{ec}(X), K_{en}(X);]$ into scalar combination of the $K_{th}(X)$, $K_{ec}(X)$, and $K_{en}(X)$;

Evaluation of the final decision vector X_{opt}Î X_P to minimize a vagueness source of uncertainty.

3. Results

The complete set of design criteria is considered in table 3 where calculation results for R290A, R600a; R142b, R152a, R1234yf, R1234ze are given.

Results of comparison are shown in figure 4(column a) where thermodynamic advantages of such refrigerants as R600a, R152a and R1234ze are demonstrated obviously. R142b has the worst value of the Global Warming Potential; it was taken into account during the calculation procedure.

The similar calculation stages were made for the same groups of the refrigerants at another condition, videlicet t_{ev}= 20 °C, t_{cond} = 83 °C. Diagram with multi-criteria selection of refrigerants for water-to-water single-stage vapor compression heat pump is shown in figure 4 (column b). In facttheoreticalresults indicate the preservation of the trend in refrigeration choice. Both natural refrigerant R600a and new fourth generation’s refrigerant R1234ze have obvious advantages.

In order to obtain the results in the theoretical assessment of a water-to-water single-stage vapor compression heat pump using three chosen refrigerants, two different condenser temperatures were set as 60 °C and 83 °C versus a wide range of evaporator temperatures (range between 0 °C and 25 °C).

Table 3. Assessment of design criteria for using refrigerants.

Refrigerant/ parameter	K	R290A	R600a	R142b	R152a	R1234yf	R1234ze	Dmax	Dmin	ΔD
Total heat pump specific heat load, q_{hp}, kJ/kg	K1	324.1	323.0	208	291.27	124.4	144.0	324.1	124.4	199.7
Exergy efficiency ratio, η_e	K2	0.45	0.48	0.4	0.43	0.42	0.52	0.52	0.4	0.12
Coefficient of perfomans COP, μ	K3	6.72	7.34	6.5	6.36	6.1	8.0	8.0	6.1	1.9
Ozon Depletion Potential, ODP	K4	0.0	0.0	0.065	0	0	0	0.065	0.0	0.065
Global Warming Potential, GWP	K5	3	0.01	2000	140	4	7	2000	0.01	1999.99
Flammability index[a]	K6	1.0	1.0	0.5	0.5	0.0	0.0	1.0	0.0	1.0

[a]Flammability index based on the refrigerant's safety class

It was obtained that the average COP of R 1234ze was higher than that of R600a, R152b by about 6.7-17.3%, 8.25-20.5%, and 1.7-14.4%, respectively, at condenser temperature 60 °C (figure 5a). However results are different if at condenser temperature is 83 °C: the average COP of R600a was higher than that of R1234ze and R152b by about 7.7-14.7%, 9.3-15.8%, and 7.5-15.6%, respectively (figure 5b). COP displays a positive correlation with the evaporator temperature as well as a negative correlation with the condenser temperature.

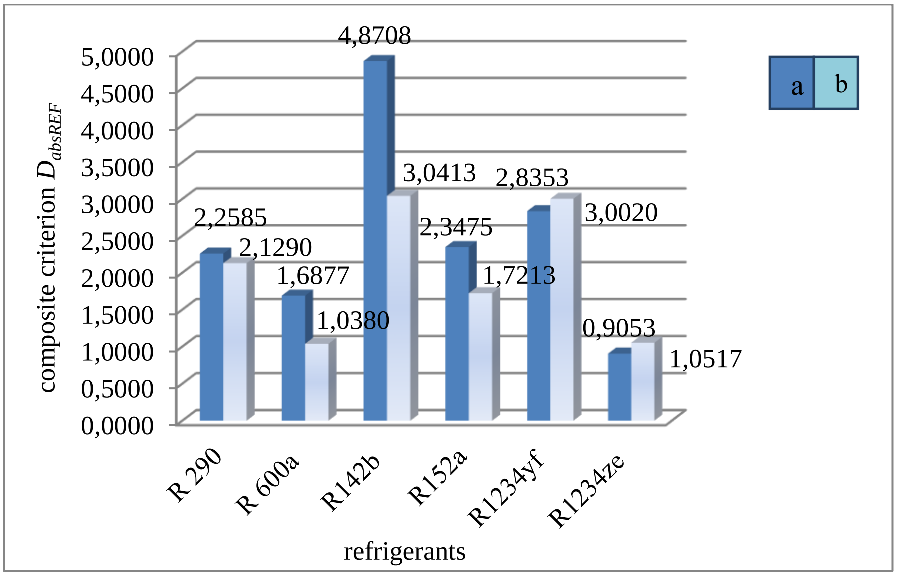
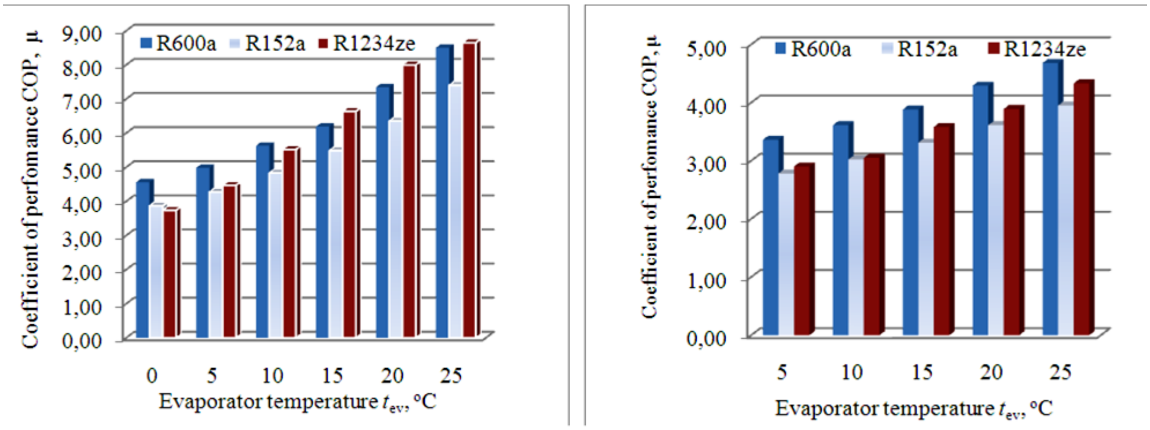


Figure 4. Multi-criteria selection of refrigerants for water-to-water single-stage vapor compression heat pump: a) at t_{ev}= 20°C, t_{cond} =60°C; b) t_{ev}= 20°C, t_{cond} = 83°C.

When the evaporating temperature and the condensing temperature are 20°C and 60°C, COP_h of R600a and R1234ze are 7.37 and 8.0 respectively, so this theoretical cycle is becoming more closer to ideal Karnot cycle. When the evaporating temperature and the condensing temperature are 20°C and 83°C, COP_h of R600a and R1234ze are 4.3 and 3.89 respectively.

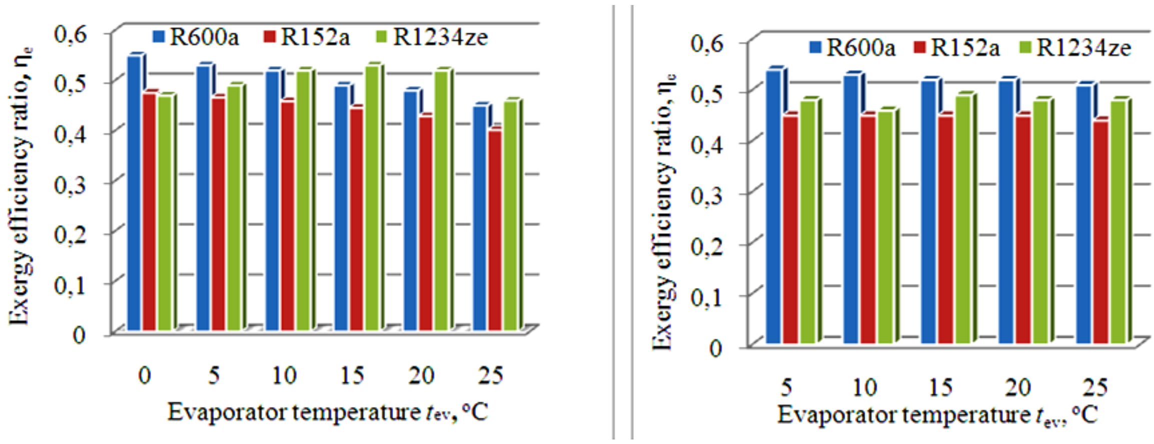
The change in exergy efficiency ratio η_e as a function of evaporator temperature for R600a, R152a and R1234ze is demonstrated in figure 6.



a) b)

Figure 5. Variation of coefficient of performance with evaporator temperature: a) for t_{cond} = 60°C b) for t_{cond} = 83°C.

It was obtained that exergy efficiency ratio η_e doesn't change a lot for each temperature value and η_e difference between R600a, R152a and R1234ze is 7.7-13.5% . η_e of R600a and R1234ze were higher than that of R152a for a range of condenser and evaporator temperatures. It also slightly decreases with the evaporator temperature increase (2-5%).



a) b)

Figure 6. Variation of exergy efficiency ratio η_e with evaporator temperature: a) for t_{cond} = 60°C b) for t_{cond} = 83°C.

4. Conclusion

To find balance between high performance and environmental safety of working fluids for HPS is an extremely important goal for heating and cooling industries. In fact, a refrigerant that combines all the desirable properties and has no undesirable properties does not exist.

Thermodynamic analysis based on a multi-criteria approach to optimum selection of refrigerants is useful tool for engineering calculations.

Theoretical results indicate that both the natural working fluid R600a and new fourth generation’s refrigerant R1234ze have good cycle performances in a water-to-water single-stage vapor compression heat pump cycle. Therefore the complete analysis of all factors, including environmental safety, allows us to draw a conclusion that the R-1234ze and R600a refrigerants should be preferred as the working fluids for using in the water-to-water single-stage vapor compression heat pump for the hot water supply and heating purposes in industrial applications.

Nomenclature

HFC: Hydrofluorocarbon;
HFO: Hydrofluoroolefin;
ODP: Ozone Depletion Potential;
GWP: Global Warming Potential,
COP: Coefficient of Performance;
p: Pressure (kPa);
t: Temperature (°C);

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