Original Research Article

Energy, environmental and enviroeconomic analysis of the use R134a/R1234yf (10/90) as replace to R134a in a vapor compression cooling system

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ABSTRACT

In this study, the use of R134a and R134a/R1234yf (10/90) refrigerants in a cooling system have been investigated theoretically. The energy, environmental and enviroeconomic analyzes of refrigerants have been performed for a cooling system. The energy performances of refrigerants have been made for different evaporator (between -10 °C and 5 °C) temperatures and a constant condenser (35 °C) temperature. The R134a/R1234yf (10/90) has a higher mass flow rate (26.50%) than R134a. Because R134a/R1234yf (10/90) has a lower refrigerating effect (evaporator enthalpy difference) than R134a. The R134a/R1234yf (10/90) has slightly higher compressor energy consumption (nearly 2.94%) than R134a, and so the COP of R134a has slightly (nearly 2.85%) higher than R134a/R1234yf (10/90). When compared to R134a, it is seen that the R134a/R1234yf (10/90) significantly reduces discharge temperature (about 16%). The environmental and enviroeconomic result values of R134a/R1234yf (10/90) are slightly higher than R134a. However, even the slight differences are significant to the evaluation of the environmental impact of refrigerants. It is seen that the wind energy source has the lowest environmental and enviroeconomic value and so the wind energy is the best environmentally friendly energy source according to the other energy sources.

Keywords: Energy; Environmental; Enviroeconomic; Global Warming; R134a/R1234yf mixture

1. Introduction

Many vapor compressing systems such as heating and cooling, domestic refrigeration, and hot water production used R134a as working fluid, in recent years. Even though ozone depletion potential (ODP) of R134a is zero, global warming potential (GWP) of this fluid is 1300. Therefore, R134a (hydrofluorocarbons (HFCs) was taken to the controlled greenhouse gas list with the Kyoto protocol (1997). The HFCs should be phased out according to the Kigali's amendment to the Montreal protocol (2016) [1].
There are some alternatives to replace R134a: (I) natural refrigerants (ammonia (NH_3), carbon dioxide (CO_2), etc.), (II) HFCs with low GWP (such as R32 and R152a), (III) hydrocarbons (HCs) and (IV) hydrofluorolefins (HFOs), R1234yf and R1234ze(E) [1,2]. Among all these options,

R1234yf is a good candidate for the alternative of R134a because the thermophysical properties of R1234yf and R134a are very similar. R1234yf has a low GWP ratio (less than 1) and zero ODP. However, it has low flammability [3]. R1234yf has some disadvantages when used in R134a systems, such as low flammability and insufficient cooling capacity[4,5]. To reduce those disadvantages of R1234yf and keep the GWP ratio low, refrigerants consisting of HFC/HFO binary mixtures have been developed recently (such as R513A and R450A). R513A refrigerant consists of mixing R134a/R1234yf by 44/56 percent by mass. R513A refrigerant is an azeotropic mixture. It has zero ODP and 573 GWP (about half of R134a) [6].
Meng et al. [7] experimentally examined both the heating and cooling performance of the refrigerant mixture

R134a/R1234yf (11/89 by mass) in the air conditioning systems of cars. They stated that R134a/R1234yf refrigerant mixture had 4% to 9% lower cooling COP than R134a. In the case of heating, they stated that the COP value of the R134a/R1234yf refrigerant mixture compared to R134a, this ratio varied between 4% and 16%. This refrigerant mixture can be used as an alternative fluid to R134a in the vehicle cooling system. Aprea et al. [8] experimentally examined and compared the performance of refrigerants R134a, R1234yf and R134a/R1234yf (10/90 by mass) in the household refrigerator. They stated that the R134a/R1234yf mixture has similar thermophysical properties with R134a and consumes 16% less energy than R134a and 14% less energy than R1234yf. They also stated that adding 10% of HFC134a to HFO1234yf, the mixture becomes non-flammable. In another study, Aprea et al. experimentally investigated energy and environmental analysis of refrigerants with low GWP ratios such as R134a, R1234yf, R1234ze (E), R134a/R1234yf (10/90 by mass), R134a/R1234ze (E) (10/90 by mass). They stated that R134a/R1234yf (10/90) reduced the emission value by 17% compared to R134a [8]. Lee et al. [9] examined the effects of R1234yf and R134a/R1234yf mixtures (5/95, 10/90, 15/85 mixing rates in mass) on COP, heating and cooling capacity, discharge temperatures, and stated that the R134a/R1234yf mixtures gave close results with R134a refrigerant. They also emphasized that R1234yf and R134a/R1234yf mixtures need to charge more refrigerant (approximately 11%) than R134a.
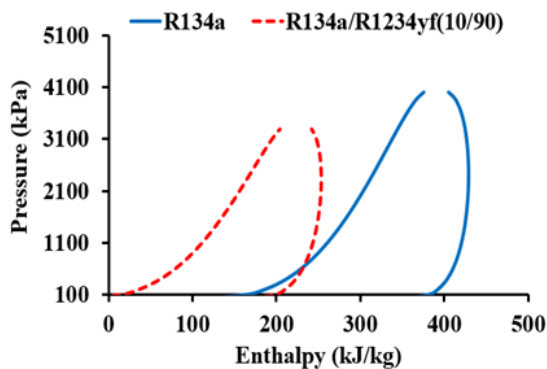

Fig. 1. Pressure - enthalpy diagram of refrigerants

Refrigerants with a low GWP are required to reduce the impact of vapor compressing systems on climate change. R134a/R1234yf mixtures are thought to replace R134a in systems operating according to the vapor compressing cycle. R134a/R1234yf mixtures can overcome particular of the drawbacks of pure refrigerants and improve thermophysical properties. In this study, investigated that the energy, environmental, and enviroeconomic analyses of a vapor compression refrigeration system for R134a and R134a/R1234yf (10/90). The pressure-enthalpy and pressure-temperature diagrams of refrigerants are given in Fig. 1 and Fig. 2, respectively. It is important to investigate

environmentally friendly new generation refrigerants with low GWP and zero ODP. Therefore, this study could be made important contributions to the literature.
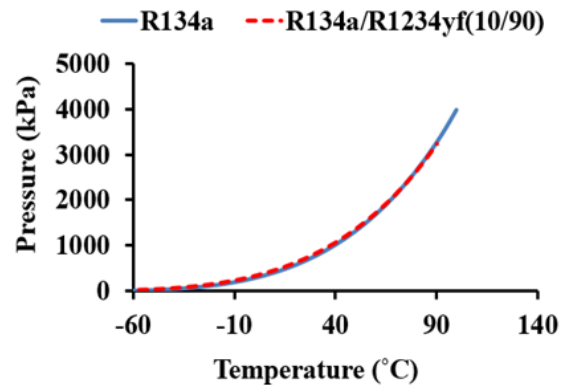

Fig. 2. Pressure – temperature diagram of refrigerants

2. Materials and Methods

In this study, a single-stage steam compression cooling system was used to compare the performances of R134a and R134a/R1234yf (10/90 by mass) refrigerants (Fig. 3). Acceptances made for the cooling system are shown in Table 1. Also, it is assumed that there is no pressure loss in the pipes and all elements of the system are steady-state flow.
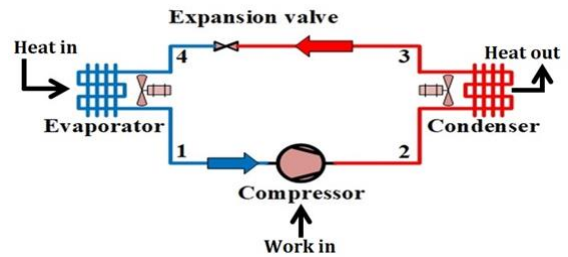

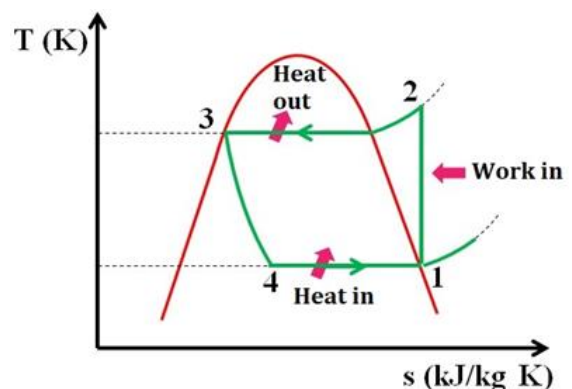**Fig. 3.** The schematic diagram of the cooling system

Fig. 4. T-s diagram of the cooling system

Table 1. Assumptions made for the system

Cooling capacity	1 kW
Condenser temperature	35 ºC
Evaporator temperature	-10 ºC, -5 ºC, 0 ºC and 5 ºC
Compressor isentropic efficiency	0.70
Superheating temperature	5 ºC
Sub-cooling temperature	5 ºC
The expansion valve is isenthalpic.	

2.1. Energy analysis

The energy analysis of the cooling system has made according to the first law of thermodynamics. The energy consumed of compressor ($\dot{W}_{comp.}$), the heat rejected from the condenser ($\dot{Q}_{cond.}$), the heat taken from the evaporator ($\dot{Q}_{evap.}$) and the coefficient of performance (COP) for cooling mode are given in Eq.1- Eq.4, respectively. Where h shows the enthalpy value of the related reference point (kJ/kg) and $\dot{m}_R$ is the mass flow rate of refrigerant (kg/s).

$$\dot{W}_{comp.} = \dot{m}_R(h_2 - h_1) \qquad (1)$$

$$\dot{Q}_{cond.} = \dot{m}_R(h_2 - h_3) \qquad (2)$$

$$\dot{Q}_{evap.} = \dot{m}_R(h_1 - h_4) \qquad (3)$$

$$COP = \frac{\dot{Q}_{evap.}}{\dot{W}_{comp.}} \qquad (4)$$

2.2. Environmental analysis

The environmental analysis is calculated by Equation 5 [10].

$$x_{CO_2} = y_{CO_2} \dot{E}_{in} t_{working} \qquad (5)$$

x_{CO_2} is the greenhouse releasing (CO_2) in a period of time (kgCO_2 / time), y_{CO_2} is the emission value for the energy option (kgCO_2 / kWh), $\dot{E}_{in}$ is the energy rate of the energy option (kW) and $t_{working}$ is the working time of the system (h / time).

2.3. Enviroeconomic analysis

The enviroeconomic analysis can be calculated by Equation 6 [10].

$$C_{CO_2} = c_{CO_2} x_{CO_2} \qquad (6)$$

x_{CO_2} is the result of environmental analysis (kgCO_2 / time), c_{CO_2} is the CO_2 emission price ($ / kgCO_2) and C_{CO_2} is enviroeconomic analysis ($ / time). The CO_2 emission price was taken as 0.0145 ($ / kgCO_2) [10].

Table 2. CO_2 emission value of the energy sources used for electricity generations [11]

Electricity generation source	CO_2 Emission value (kgCO_2 / kWh)
Hydro	0.0037 – 0.237
Wind	0.0097- 0.1237
Solar thermal	0.0136 – 0.202
Nuclear	0.0242
Biomass	0.035 – 0.178
Solar PV	0.0534 – 0.250
Coal	0.9753
Oil	0.7421

Required electricity for the cooling systems can be provided from many energy sources. There are some of the CO_2 emission values for electricity generation sources in the literature (Table 2). In this study, hydro, wind, solar PV, coal, oil, and nuclear were selected as energy options. The CO_2 emission values of the hydro, wind, solar PV, coal, oil

and nuclear are 0.1204 kgCO_2/kWh, 0.0667 kgCO_2/kWh, 0.3034 kgCO_2/kWh, 0.9753 kgCO_2/kWh, 0.7421 kgCO_2/kWh and 0.1078 kgCO_2/kWh, respectively. It is assumed that the working period of the cooling system is 360 hours /month.

3. Results and Discussion

In this study, the performances of R134a and R134a/R1234yf (10/90) mixture for the cooling system have been investigated. The mass flow rate of refrigerant, refrigerating effect, compressor energy consumption, COP value, and discharge temperature, have analyzed and compared for the cooling system. Also, the environmental and enviroeconomic analyzes of both refrigerant were made.
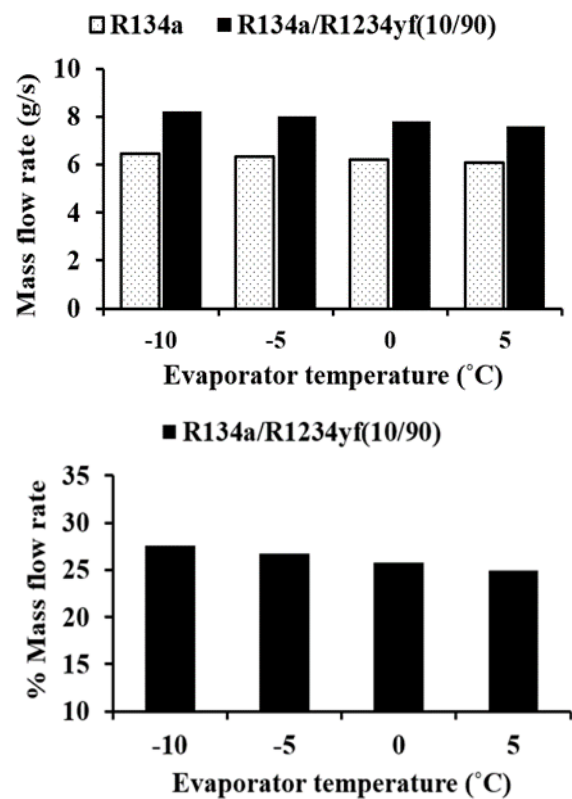

Fig. 5. Mass flow rate and comparison of mass flow rate relative to R134a

The mass flow rate of refrigerants is given in Fig. 5 for different evaporator temperatures. At the evaporator temperatures of -10 °C, -5 °C, 0 °C and 5 °C, the mass flow rate of R134a are 6.44, 6.32, 6.20 and 6.08 g/s respectively, while the flow rate of R134a/R1234yf (10/90) are 8.22, 8.00, 7.80 and 7.60 g/s. As seen Fig. 5, the R134a/R1234yf (10/90) has higher mass flow rate (25%- 28%) than R134a. This is because R134a/R1234yf (10/90) has lower refrigerating effect (evaporator enthalpy difference) (20% - 22%) than R134a (Fig. 6).

The compressor energy consumption of R134a and R134a/R1234yf (10/90) is given in Fig. 7 for different evaporator temperatures. R134a/R1234yf (10/90) has slight

higher compressor energy consumption (2.18% - 3.69%) than R134a. Though R134a/R1234yf (10/90) has a higher mass flow rate than R134a, compressor energy consumption of it is almost the same as R134a. This situation is related to the thermophysical properties of refrigerants.

The COP of R134a and R134a/R1234yf (10/90) is given in Fig. 8. At the evaporator temperatures of -10 ºC, -5 ºC, 0 ºC and 5 ºC, the COP of R134a are 3.42, 4.02, 4.78 and 5.79 respectively, while the COP of R134a/R1234yf (10/90) are 3.30, 3.89, 4.65 and 5.67. As seen in Fig. 8, when Compared COP of refrigerants R134a has slightly higher (2.13% - 3.56%) COP than R134a/R1234yf (10/90).
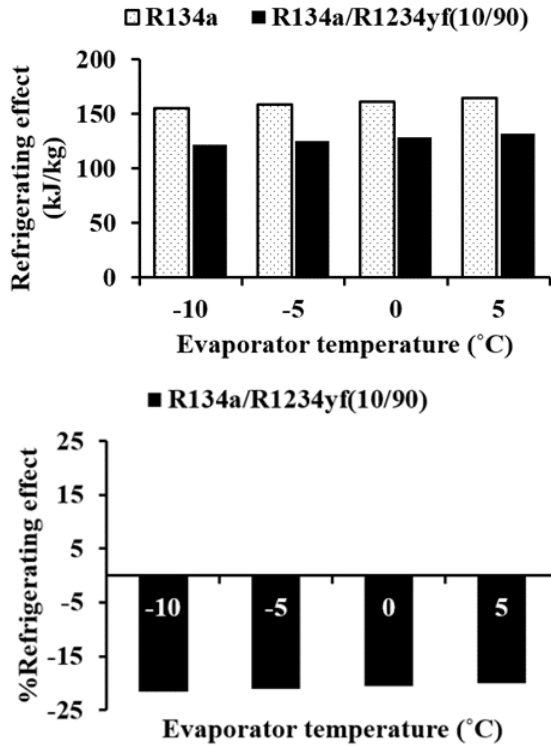

Fig. 6. Refrigerating effect and comparison of refrigerating effect relative to R134a
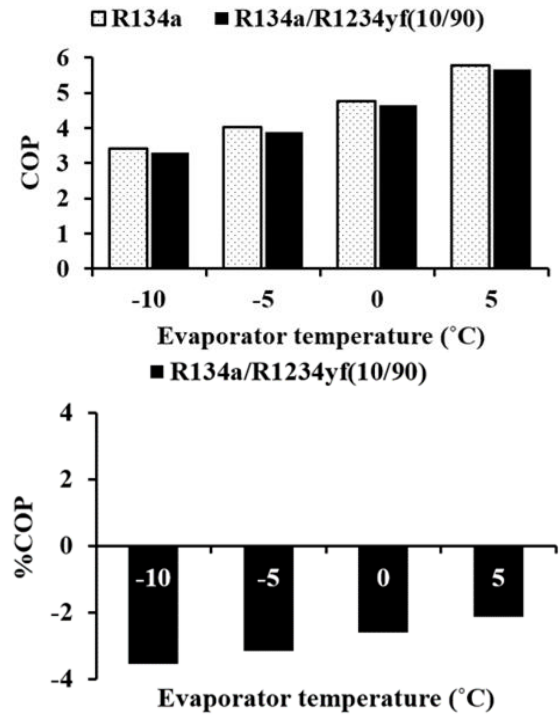

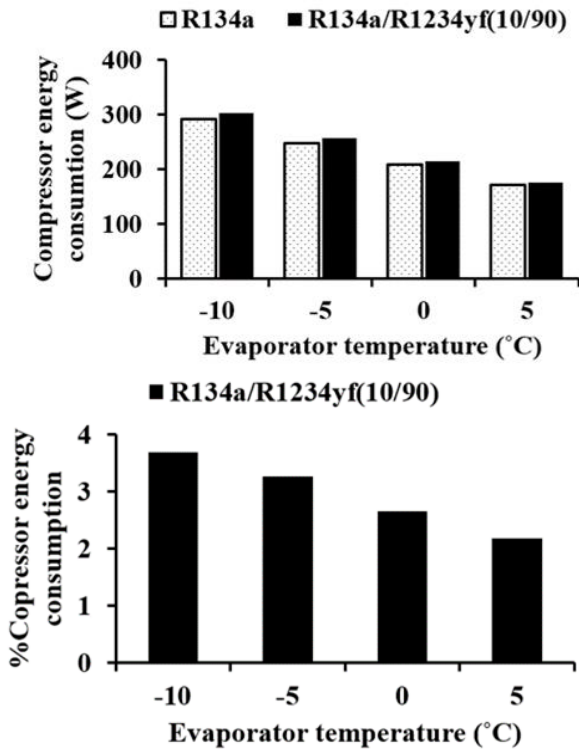**Fig. 8.** COP and comparison of COP relative to R134a

Fig. 7. Compressor energy consumption and comparison of compressor energy consumption relative to R134a
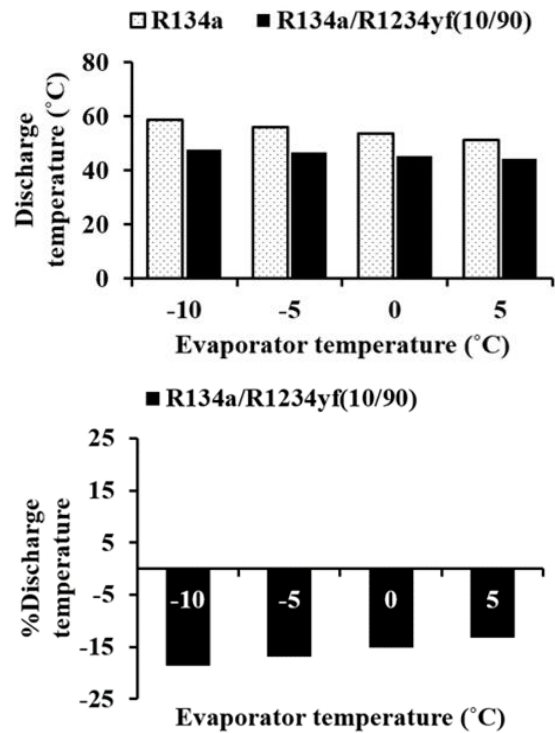

Fig. 9. Discharge temperature and comparison of discharge temperature relative to R134a

The compressor discharge temperature is one of the significant parameters to select refrigerants as a working fluid. When it is too high, it may cause lubricant degradation and so compressor breakdown. The discharge temperature of refrigerants is given in Fig. 9. The R134a has higher (13.30% - 18.71%) discharge temperature than R134a/R1234yf (10/90).

Fig. 10. Environmental results for different evaporator temperatures and energy sources

The environmental analysis of the R134a and R134a/R1234yf (10/90) for the different energy sources is given in Fig. 10. For evaporator temperature -10 ºC and hydro, wind, solar PV, coal, oil, and nuclear energy sources: the environmental analysis of R134a is 12.66, 7.01, 31.90, 102.54, 78.02 and 11.33 kgCO$_2$/month, respectively. Under same conditions the environmental analysis of

R134a/R1234yf(10/90) is 13.13, 7.27, 33.07, 106.32, 80.90 and 11.75 kgCO$_2$/month. The environmental result values of R134a/R1234yf(10/90) are slightly higher than R134a. However, even the slight differences are significant to perform the environmental evaluation effectively. Also, it is seen that the wind energy source has the lowest environmental value and so, the wind energy is the best environmental energy source according to the other energy sources.
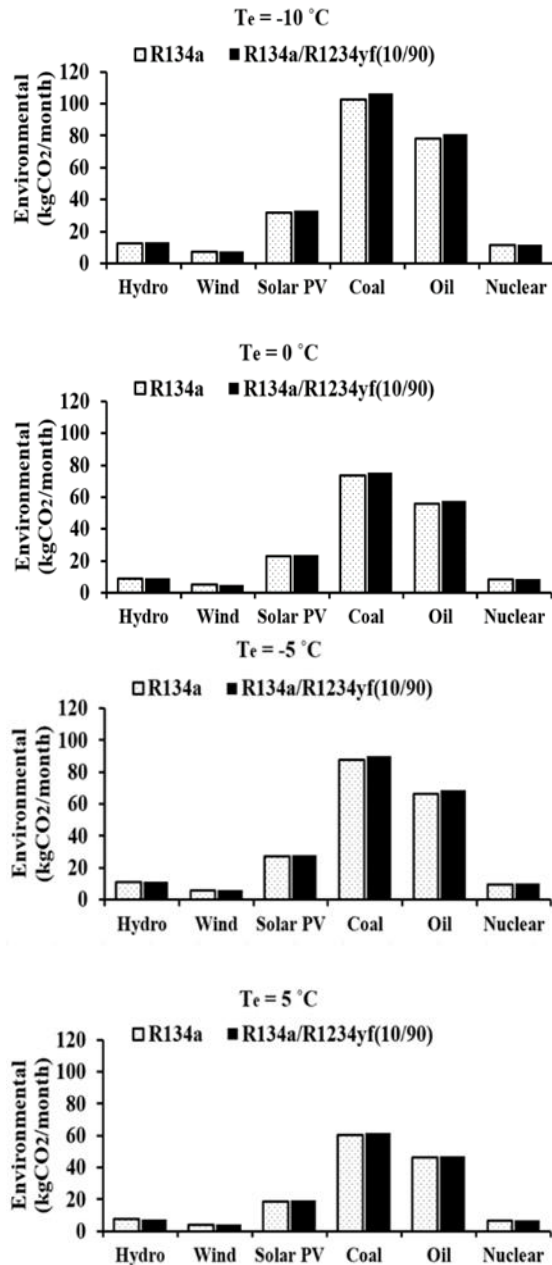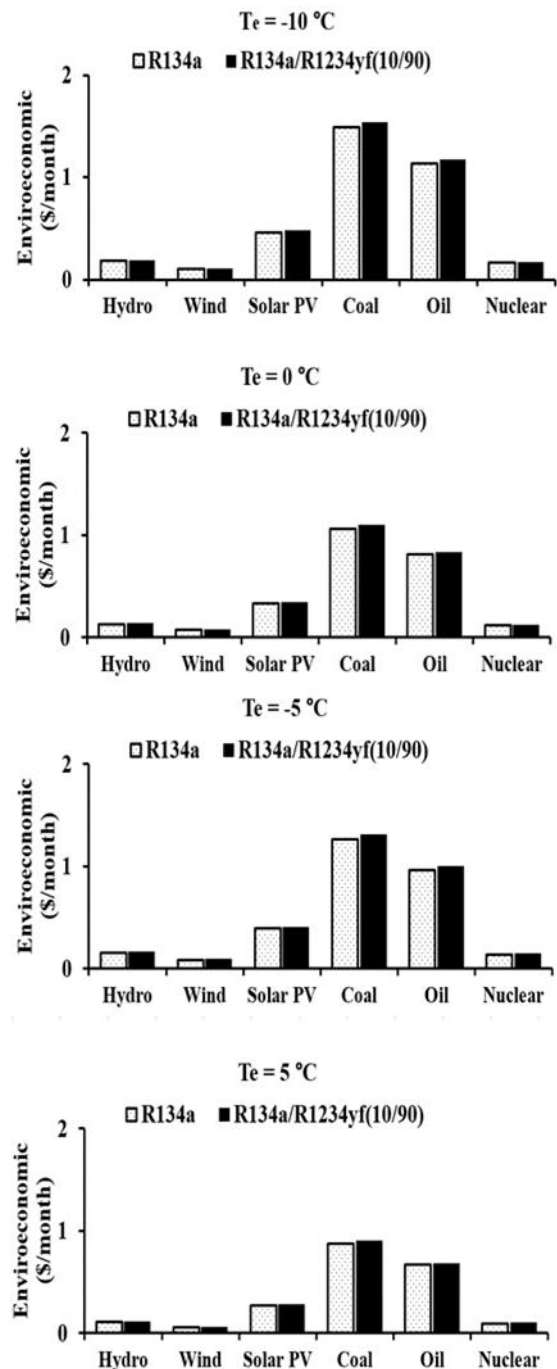

Fig. 11. Enviroeconomic results for different evaporator temperatures and energy sources

The enviroeconomic analysis of the R134a and R134a/R1234yf (10/90) for the different energy sources is

given in Fig. 11. For evaporator temperature -10 ℃ and hydro, wind, solar PV, coal, oil, and nuclear energy sources: the envieconomic analysis of R134a are 0.18, 0.10, 0.46, 1.49, 1.13, and 0.16 \$/month, respectively. Under same conditions the enviroeconomic analysis of R134a/R1234yf (10/90) are 0.19, 0.11, 0.48, 1.54, 1.17 and 0.17 \$/month. The enviroeconomic results of both refrigerants are very small due to both of are used in the small scale cooling system. The wind energy has the lowest envireconomic values for both of refrigerants.

4. Conclusions

The energy, environmental, and enviroeconomic analysis of the using R134a/R1234yf (10/90) as replace to R134a in a vapor compression cooling system have been presented and discussed. The following main conclusions can be drawn from this study:

- The R134a/R1234yf (10/90) has a higher mass flow rate than R134a, Because of the R134a/R1234yf (10/90) has lower refrigerating effect than R134a.
- The R134a/R1234yf (10/90) has slightly higher compressor energy consumption (nearly 2.94%) than R134a.
- The R134a has slightly higher (2.85%) COP than R134a/R1234yf (10/90).
- The R134a/R1234yf (10/90) has lower (about 16%) discharge temperature than R134a.
- The conventional energy sources (coal and oil) are the worst options among the energy sources according to the environmental and eviroeconomic analyzes. But, the oil would be a better choice, if there was an obligation to choose between oil and coal. In general, renewable energy sources and nuclear energy are better options than conventional energy sources. The wind energy, which is a renewable energy source, is the best choice among all energy sources.
- The environmental and enviroeconomic analyzes give helpful information related to CO_2 emission and CO_2 prices in a certain period of time. So, it can succeed in that reduction and economic management of greenhouse gases owing to the environmental and enviroeconomic analyzes.

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