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Research article

Comparative analysis of water cooler for different working fluids: Energy and exergy approach

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Abstract

Enhancing the performance of traditional vapor compression cooling cycles is an important aspect in the quest to minimize global energy consumption, to own sustainable energy systems soon, and to preserve the environment. This study performed a comparative analysis of the performance of a water cooler with different working fluids to replace R143a and improve system performance. A mathematical model derived from energy and exergy analysis is developed for the evaluation of the effect of operating conditions on the system COP, exergetic losses, and exergetic efficiency. The evaluation has been conducted for evaporation and condensation temperatures ranging between -30°C to 15°C and 25°C to 55°C, respectively. Results showed that the cycle with R510A has the maximum COP. The average system COP with R510A, RE170, and R152a are 19.54%, 13.53%, and 9.36 % higher than that with R134a, respectively. The highest value of exergy loss takes place in the compressor. At different working fluids, exergy losses decrease as evaporation temperatures increase and condensation temperatures decrease. The system with R510A has the minimum exergy losses. The average exergy losses for systems with R510A, RE170, and R152a are 34.62%, 28.33%, and 18.64% lower than that of R134a, respectively. The system with R510A has higher exergy efficiency and R134a has the minimum values of exergy efficiency. Generally, the water cooler provided better performance with R510A and RE170 than with R152a and R134a. Therefore, R510A can be considered as the best replacement for R134a and R152a.

Nomenclature

Symbols		W	Work, Kw
h	Enthalpy, kJkg^{-1}	**Abbreviation**	
$\dot{m}$	Mass flow rate, kgs^{-1}	VCRC	vapor-compression refrigeration cycle
P	Pressure, Pa	COP	coefficient of performance
Q	Cooling capacity, kW	ODP	ozone depletion potential
P	Pressure, Pa	GWP	global warming potential
T	Temperature, °C		

1. INTRODUCTION

Energy savings and environmental impacts in residential and commercial sectors are becoming crucial factors on a global scale.[1,2] In hot climates such as the Gulf countries, cooling systems including air conditioning, refrigerators, and water coolers are frequently used. These systems are based on the vapor-compression refrigeration cycle (VCRC), because of the high coefficient of performance (COP). However, these systems expend a large quantity of electrical energy and use harmless working fluids which pollute the environment. In residential and commercial, around 30-60% of the total energy consumption is shared by VCRCs. This ratio may increase in hot climate conditions and due to refrigerant leakage.[3] Therefore, to save energy consumption in the cycles and protect the environment, thermal performance and working fluid utilization in this cycle should be improved. The system performance can be enhanced by minimizing compressor work, raising condenser heat rejection, and using refrigerants with desirable thermal properties and environment friendly.[4]

Different theoretical or experimental studies have proposed alternative environment-friendly working fluids include HC and HCFC as potential substitutes for CFCs and HFC. The HFCs working fluids have a considerable global warming potential (GWP) and recently have been substituted by HC working fluids in most of the VCRC.[5] The use of HC has thermodynamic and environmental advantages when compared with HFC refrigerants.[6] In evaluating the system performance and comparing the performance with different working fluids, the most common studies are based on energy and exergy analysis[7].

Energy analysis is built on the 1st law of thermodynamics. On the other hand, exergy analysis is built on the 2nd law of thermodynamics. Analysis of the energy balance provides the efficiency of energy utilization in certain parts of the cycle. In addition, it can compare the efficiency and the process factors with other achievable values in recent installations. Exergy is defined as the maximum amount of work that can be resulted by heat or work as it comes to equilibrium with surroundings. Exergy analysis is a powerful tool for the design, optimization, and performance assessment of energy cycles.[8] Exergy analysis of a cycle can be performed by analyzing each component of the cycle separately. In addition, is normally used to evaluate the optimum performance of the cycle and to the sites of exergy destruction show the direction for potential improvements.[9]

Numerous researches have been conducted on performance and exergy analysis of refrigeration and heat pump cycles.[10,11] Kaygusuz and Ayhan[12] experimentally provided the exergy analysis on a heat pump cycle driven by solar energy. The effects of operating parameters on the cycle performance are provided. They concluded that the exergy efficiency is more stable than for the other system without energy storage at the same working conditions. Gang et al.[13] conducted an energy and exergy analysis on a modified VCRS operating working with zeotropic R290/R600a. A phase separator is created to improve the system performance. They showed that a good performance with energy and exergy was obtained. Saleh[14] conducted an energy and exergy analysis on the performance of an integrated organic Rankine cycle-VCRS with different working fluids. He showed that the R602 is proved to be the most suitable refrigerant for the proposed system based on the overall COP and environmental issues. Kanoglu[15] conducted a study for the exergy analysis of a multi-stage cascade cooling system.

Other studies are conducted on the substitute of R134a and R12 with other environmentally friendly working fluids through energy and exergy analysis.[16,17] Ahmad et al.[18] conducted a review study on the exergy destruction and efficiency of VCRCs. They concluded that the exergy of the VCRC depends on many parameters including evaporating and condensing temperatures, sub-cooling, compressor work, and dead state temperature. They also showed that the highest exergy loss in the cycle takes place in the compressor. Bolaji et al.[19] provided experimental investigation on the performance of VCRC. Three systems are provided and analyzed using three HFC working fluids with zero ODP (R32, R134a and R152a). The obtained results are compared. They showed that the COP of the system using R152a were 2.5% and 14.7% higher than that of R134a and R32, respectively. Wongwises and Chimres[20] conducted an experimental investigation on the replacement of R134a with mixtures of R290, R600, and R600a in a domestic VCRC. They concluded that a blend of R600 (60%) and R600a (40%) was the most suitable alternative working fluid. Wongwises et al.[21] also conducted an experimental investigation on the utilization of HC mixtures R290, R600, and R600a working fluids to substitute R134a in air conditioning systems.

Park and Jung[22] theoretically studied the performance assessment of a residential air conditioning system charged with two pure HCs working fluids and mixtures of R1270, R290, HFC152a and RE170 to replace R22 working fluid. They showed that the air conditioning COP of these working fluids is about 5.7% greater than that with R22working fluid. Ashwni et al.[23] utilized the exergy analysis to evaluate the performance of VCRC using different HC working fluids R290, R600, R600a and R1270 as an alternative to R134a and R22. They showed that R600 is the most appropriate refrigerant to replace R134a and R22 with high system COP. They found also, the exergy losses are higher for elevated condensing temperatures due to the high difference between ambient and cycle temperatures.

Kabul et al.[24] conducted an exergy analysis on the performance of VCRC with R600a and internal heat exchanger. They showed that the system COP and exergy efficiency were lowered with condenser temperatures, the total irreversibility was raised. Jabardo et al.[25] conducted experimental and exergy analysis on the performance assessment of an automotive air-conditioner. They concluded that the exergy losses increase with the rise in the condensing temperature. Kalaiselvam and Saravanan[26] conducted an exergy analysis on the performance of HVAC system working with R22, R407 and R717 refrigerants. They showed that, for all the working fluids, exergy efficiency lowered with the elevated condensing temperatures. In order to achieve perfect second law efficiency, the cycle should be worked within 35 °C and 40 °C condensing temperatures. Mahmoud[27] conducted theoretical analysis on the performance evaluation of an air conditioner using R152a and hydrocarbons working fluids R290, R600a, and R270 to replace R134a. They found that the cycle with R152a and R270 had the better thermal performance than that of R134a by 11% and 9% respectively.

The literature review showed that many studies have been conducted on domestic refrigeration cycle working with hydrocarbons or their mixtures to replace R134a and R22. However, the energy and exergy analysis on the possibility of utilizing R510A, RE170, HFC152 refrigerants as an alternative to HFC134a in water cooler systems is not investigated before and needs to be evaluated under different operating parameters. In addition, there are no studies found in the literature conducted on water cooler systems. In this study, energy and exergy analysis on the performances of 1 kW water cooler system is conducted under different operating parameters. Different working fluids including R510A, RE170, HFC152 are investigated and compared with the existing baseline refrigerant R134a. Exergy losses in each system elements were also evaluated at different operating parameters.

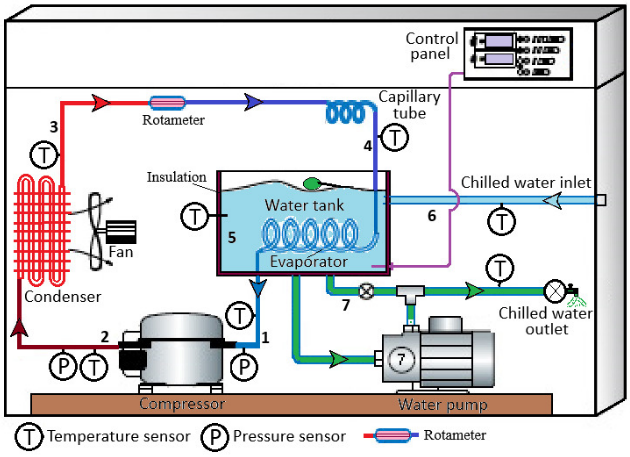

Figure 1. Schematic diagram of the components of water cooler cycle.

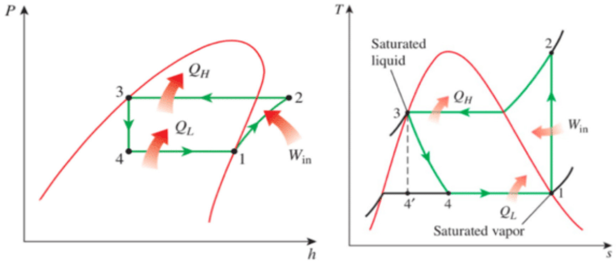

Figure 2. P-h and T-s diagram for the ideal water cooler cycle.

2. METHODOLOGY

A schematic layout of a typical water cooler is shown in Fig. 1. The system is used to supply sufficient drinking water for hot climates regions such as the Gulf countries. The system works on the principle of vapor compression cooling system. The system components include compressor, condenser, capillary tube, water tank containing the evaporator, dryer, control panel, and water pump. The system is also associated with measuring instruments like temperature sensors (thermocouples), pressure transducers, rotameter with flow control valve, and Avometer. The chilled water temperatures are changed by using an electric water heater. Fig. 2 shows a schematic diagram of both P-h and T-s for the ideal water cooler cycle.

Energy and exergy analyses were carried out for the proposed water cooler cycle with four different working fluids R510A, RE170, HFC152, and HFC134a. The different working fluids are used as an alternative to chlorofluorocarbons R143a. The R152a working fluid is used to substitute R143a. R152a has zero ozone depletion potential (ODP) and low global warming potential (GWP) of about 124 and a short atmospheric lifetime of about 1.4 years. RE170-Dimethyl ether (C_2H_6O) is a hydrocarbon working fluid with zero ODP and exceptionally low GWP. It is used in very low temperature industrial refrigeration applications and is a replacement for R23 and R5088. R510A is an azeotropic working fluid mixture containing RE170 (88%) and R600a (12%). The possibility of utilizing RE170 and R510A to substitute R134a in water coolers requires more investigation under different operating parameters. The environmental and thermophysical characteristics of investigated working fluids are presented in Table 1.

3. THEORETICAL ANALYSIS

In system analysis the mass, energy balance, and exergy balance equations are applied for the water cooler components. The mathematical equations for energy and exergy analysis in different water cooler elements can be arranged.

3.1. ENERGY ANALYSIS

The energy analysis model for each system components are based on the 1st law of thermodynamics, the changes in kinetic and potential energies were not considered.:

$$\sum \dot{E}_{in} - \sum \dot{E}_{out} + \sum \dot{Q}_k - \dot{W} = 0 \qquad (1)$$

3.2. EXERGY ANALYSIS

The exergy destruction of the system is the difference between the in and out flowing exergy. The general exergy balance can be presented as:

$$\sum \dot{E}x_{in} - \sum \dot{E}x_{out} = \dot{E}x_{loss} \qquad (2)$$

$$\sum \dot{m}_{in} \Psi_{in} - \sum \dot{m}_{out} \Psi_{out} + \dot{W}_{comp} = \dot{E}x_{loss} \qquad (3)$$

Where, Ex_{in} and Ex_{out} are the exergy rates entering and exiting the control volume, respectively and Ex_{loss} is the exergy losses.

The net exergy ($\sum E_{Q}^{\&}$) of heat transfer $\dot{Q}$ at temperature T_k by the maximum rate of conversion of thermal energy. For a heat Q_k and constant temperature T_k, exergy can be given by:

$$\dot{E}_Q = \sum_k (1 - \frac{T_0}{T_k}) \dot{Q}_k \qquad (4)$$

where T_0 is the reference (surrounding) temperature is often the surrounding of system.

$$\dot{E}_w = \dot{W} \qquad (5)$$

The specific exergy is given by:

$$\Psi = (\mathrm{h} - \mathrm{h}_0) - \mathrm{T}_0 \, (\mathrm{S} - \mathrm{S}_0) \qquad (6)$$

Where, h_o is the enthalpy and S_o is the entropy values of the dead case of the working fluid at pressure and temperature P_o and T_o, respectively.

The general exergy balance from Equation (2) given by:

$$\sum \dot{m}_{in} \Psi_{in} - \sum \dot{m}_{out} \Psi_{out} + \sum_k (1 - \frac{T_o}{T_H}) Q_k - E\dot{W} = \dot{E}x_{loss} \qquad (7)$$

The total exergy destruction rate is obtained by summing the exergy destruction rates in all water cooler components.

$$\dot{E}x_{loss,tot} = \sum \dot{X}_{cond} + \sum \dot{X}_{comp} + \sum \dot{X}_{evap} + \sum \dot{X}_{Ex.valve} \qquad (8)$$

The exergy efficiency can be given by the ratio of useful output exergy to the input supplied exergy:

$$\eta_{ex} = \frac{\text{exergy output}}{\text{exergy input}} = \frac{\dot{E}x_{in} - \dot{E}x_{out}}{\dot{E}x_{in}} = \frac{\Psi_1 - \Psi_4}{W_{tot}} \qquad (9)$$

Table 1. Thermodynamic and environmental characteristics of investigated working fluids .[28]

Properties	Working fluids			
	HFC134a	HFC152	RE170	R510A
Molar mass, kgkmol^{-1}	102.03	66.051	46.07	47.24
Normal boiling point, °C	-26.07	-24.7	-24.78	-23.21
Critical Temperature, °C	101.06	113.15	127.23	125.67
Critical Density, kgm^{-3}	512	368	271	268.56
ODP	0	0	0	0
GWP	1300	124	3	3

The total power supplied to the system ($\dot{W}$) in the compressor:

$$\dot{\mathrm{W}}_{\mathrm{tot}} = \dot{\mathrm{W}}_{\mathrm{com}} + \dot{\mathrm{W}}_{\mathrm{fan}} + \dot{\mathrm{W}}_{\mathrm{pump}} \tag{10}$$

$$\dot{\mathrm{W}}_{\mathrm{com}} = \frac{\dot{\mathrm{m}}_{\mathrm{r}}\left(\mathrm{h}_{2\,\mathrm{s}} - \mathrm{h}_{1}\right)}{\eta_{\mathrm{s}} \times \eta_{\mathrm{m}} \times \eta_{\mathrm{e}}} \tag{11}$$

Where, η~2s~, η_m, and η_e are the isotropic, mechanical, and electrical efficiencies, respectively. The values are given in Table 2.

The exergy balance for the compressor:

$$I_{comp} = \dot{m}_r[(\Psi_1 - \Psi_2) + \dot{W}_{tot} \tag{12}$$

$$I_{comp} = \dot{m}_r[(h_1 - h_2) - T_o(S_1 - S_2)] + \dot{W}_{tot} \tag{13}$$

The condenser heat rejection:

$$\dot{Q}_{cond} = \dot{m}_r(h_2 - h_3) \tag{14}$$

The condenser exergy balance is gives:

$$I_{cond} = \dot{m}_r[\Psi_2 - \Psi_3) - \dot{Q}_{con}(1 - \frac{T_o}{T_{con}}) + \dot{W}_{fan,con} \tag{15}$$

$$\begin{aligned} I_{cond} =& \dot{m}_r[h_2 - h_3) - T_o(S_2 - S_3)] \\ & - \dot{Q}_{con}(1 - \frac{T_o}{T_{con}}) + \dot{W}_{fan,con} \end{aligned} \tag{16}$$

For throttling process (h_3=h_4). The exergy balance for the capillary tube is given by:

$$I_{cap} = \dot{m}_r(\Psi_3 - \Psi_4) \tag{17}$$

$$\mathrm{I}_{\mathrm{cap}} = \mathrm{T}_{\mathrm{o}}\left(\mathrm{S}_{4} - \mathrm{S}_{3}\right) \tag{18}$$

The heat addition in the evaporator:

$$\dot{Q}_{evap} = \dot{m}_r(h_1 - h_4) = \dot{m}_{chw}Cp(T_{chw,in} - T_{chw,out}) \tag{19}$$

The exergy balance for the evaporator is given by:

$$I_{evap} = \dot{m}_r[\Psi_4 - \Psi_1) + \dot{Q}(1 - \frac{T_o}{T_{evap}}) \tag{20}$$

$$I_{evap} = \dot{m}_r[h_4 - h_1) - T_o(S_4 - S_1)] + \dot{Q}_{eva}(1 - \frac{T_o}{T_{evap}}) \tag{21}$$

The water cooler coefficient of performance given by:

$$\mathrm{COP} = \frac{\dot{\mathrm{Q}}_{\mathrm{evap}}}{\dot{\mathrm{W}}_{\mathrm{tot}}} \tag{22}$$

The total exergy destruction in the water cooler system elements:

$$\mathrm{I}_{\mathrm{tot}} = \mathrm{I}_{\mathrm{evap}} + \mathrm{I}_{\mathrm{cond}} + \mathrm{I}_{\mathrm{cap}} + \mathrm{I}_{\mathrm{comp}} \tag{23}$$

The thermodynamic equations model (Equations 11 - 23) of the water cooler system runs with the selected working fluids R134, R152, R170, and R510A and with operating conditions shown in Table 2. The system produces a cooling capacity of 1 kW. Evaporator temperatures varied between -30 and 15 °C and condensing temperatures varied between 25 and 55 °C. There is no pressure drop in the evaporator or the condenser. Thermodynamic properties of the used working fluids were obtained with a simulation computer program (EES).

4. RESULTS

The effect of evaporation and condensing temperatures on system COP, energy analysis, exergy losses, and exergy efficiency of the proposed water cooler with R510A, R170, R152, and R134 are presented here.

4.1. SYSTEM PERFORMANCE

4.1.1. EFFECT OF EVAPORATION TEMPERATURE ON WATER COOLER COP

Fig. 3 presents the COP of the water cooler as a function of the evaporation temperatures at different working fluids with constant condenser temperature at 30° C. As can be shown, the COP increases as the evaporation temperatures increase for all the working fluids. The trend is the same for the different working fluids over the tested operating conditions. However, the system with R510A has the highest COP followed by R152a, RE170, and R134a respectively. The difference in COP values was quite small. The minimum COP is obtained with R134a. The average system COP for the system with R510A, RE170, and R152a are higher than that of R134a by 19.54%, 13.53%, and 9.36%, respectively. Therefore, R510A can be considered as the best replacement working fluid for HFC134a and HFC152a.

4.1.2. EFFECTS OF EVAPORATION TEMPERATURE ON EXERGY LOSS OF THE SYSTEM COMPONENTS

Fig. 4 illustrates the variation of exergy losses with the evaporation temperatures in the different water cooler components (compressor, evaporator, capillary tube, and condenser) when using R510A as working fluid. The exergy losses in the water cooler elements lowered with the rise in the evaporation temperature. The greater the temperature differences in any element with the surrounding environment, the greater the energy loss. The trends of exergy losses in the different system elements are found to be similar. The highest value of exergy loss in the system takes place in the compressor followed by expansion valve, condenser, and evaporator components. Vincent and Heun[29] concluded that, the higher exergy destruction happened

Table 2. Operating parameters of the water cooler cycle.

Conditions	Values
Reference temperature [K]	293
Reference pressure [kPa]	100
Cooling capacity [kW]	1
Evaporation temperatures [^oC]	-30:15
Condensing temperatures [^oC]	25:55
Sub-cooling temperature [K]	0
Superheating temperature [K]	3
Superheating temperature [K]	3
Isentropic efficiency of compressor [%]	80
Mechanical efficiency of compressor [%]	90
Electric motor efficiency [%]	90

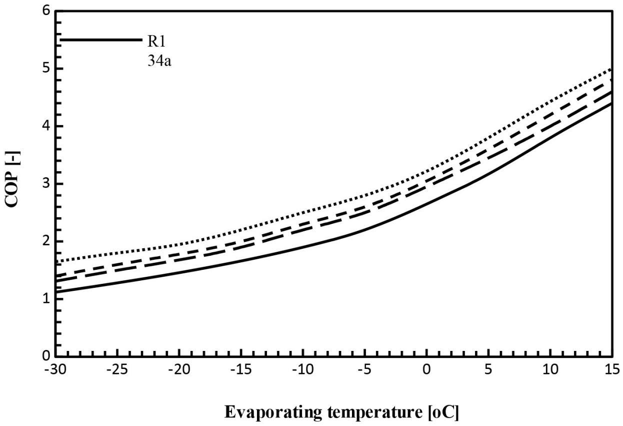

Figure 3. Effect of evaporation temperature on water cooler COP for different working fluids.

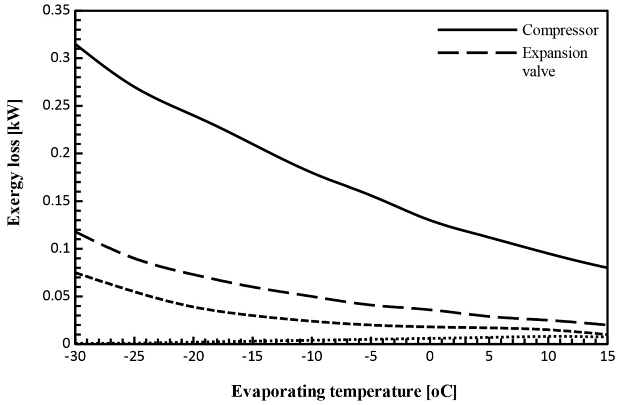

Figure 4. Effect of evaporation temperature on exergy losses for different system elements.

in the compressor element compared with other cycle elements. Compared to the system components, evaporator has minimum exergy losses compared to the other cycle elements.[18] At high evaporating temperatures, exergy losses are decreased for all working fluids.

4.2. EFFECT OF EVAPORATION TEMPERATURES

The exergy losses and exergy efficiency for the water cooler as a function of the evaporation temperature for different working fluids is shown.

4.2.1. EFFECT OF EVAPORATION TEMPERATURE ON WATER COOLER EXERGY LOSSES

Fig. 5 presents the effect of evaporation temperatures on the system exergy losses at different working fluids. As shown, the exergy losses decrease with the rise in evaporation temperatures. This is the same trend obtained by Khan.[30] This may be due to, when the evaporating temperature rises, the amount of heat transfer between the working fluid entered the evaporator element and the working fluid being cooled also rises, which finally rise the cooling capacity thus the exergy loss minimized. Along with the tested values, R510A has the minimum exergy losses and R134a has the higher values of exergy losses. The average exergy losses for R510A, RE170, and R152a are lower than that of R134a by 34.62 %, 28.33%, and 18.64%, respectively. At high evaporating temperatures, exergy loss values are decreased for all working fluids. At high values evaporating temperatures, exergy loss is minimum compared to that of at low values evaporating temperature. Kalaiselvam and Saravanan[26] reported that exergy losses decreased with the increase in evaporating temperature.

4.2.2. EFFECT OF EVAPORATION TEMPERATURE ON WATER COOLER EXERGY EFFICIENCY

Fig. 6 presents the effect of evaporation temperatures on the exergetic efficiency (η_{ex}) at different working fluids. The exergetic efficiency decreases with the increase in evaporation temperatures from -30 ^oC to -15 ^oC. The maximum exergy efficiency is obtained at -15 ^oC evaporation temperatures for the different working fluids. However, the degradation in the exergetic efficiency drops very quickly with evaporation temperatures below -10 ^oC. The electrical work needed by compressor (W) minimized with the rise in evaporator temperatures. The exergy in work needed by

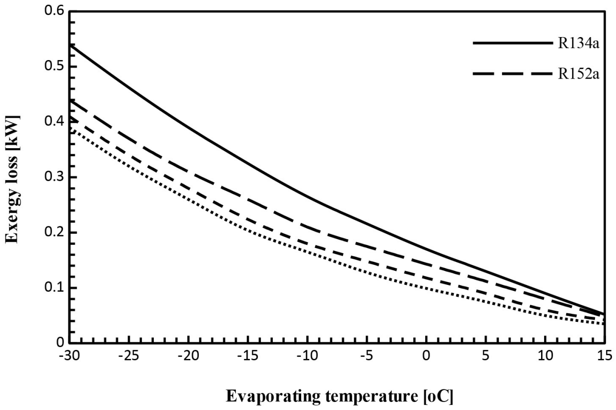

Figure 5. Effect of evaporation temperature on exergy loss for different working fluids.

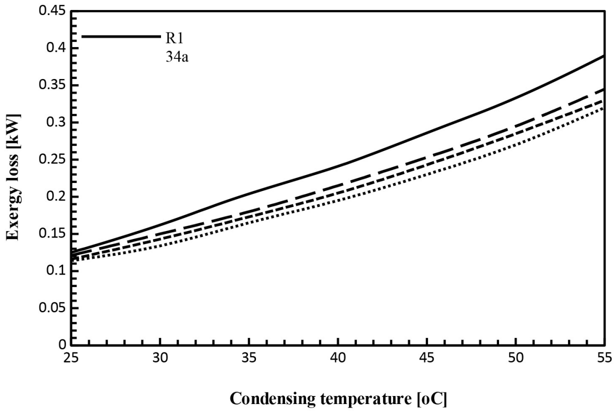

Figure 7. Effect of condensing temperature on exergy losses for working fluids.

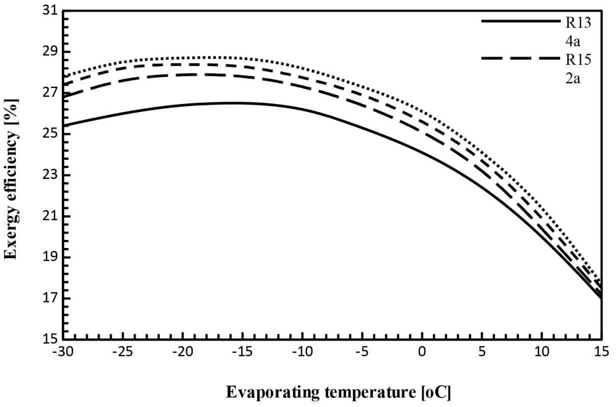

Figure 6. Evaporation temperatures vs. exergy efficiency for different working fluids.

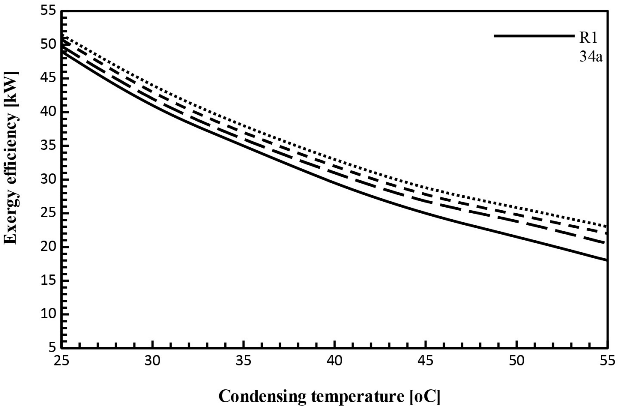

Figure 8. Effect of condensing temperature on exergy efficiency for different working fluids.

compressor (W) decreases with an increase in evaporator temperature. The exergy of cooling capacity (Q_{evap}) reduces with the evaporation temperatures. The effect of compressor work and cooling capacity affect the system exergetic efficiency. R510A has the highest exergy efficiency.

4.3. EFFECT OF CONDENSING TEMPERATURES

Condensing temperature has a significant effect on the exergy losses and efficiency of the water cooler.

4.3.1. EFFECT OF CONDENSING TEMPERATURE ON WATER COOLER EXERGY LOSSES

Fig. 7 illustrates the effect of condensing temperatures on the exergy losses at different working fluids. for all the refrigerants, the exergy losses increase with the increase in condensing temperature. The increment of the ambient temperature increases the condensing temperature, reduces the amount of heat rejected to the ambient. Increasing the condensing temperature decreases the difference between the surrounding and condenser, leading to a reduction in the amount of heat rejected to the ambient. This causes the refrigerant pressure inside the condenser to be increased to reject heat to the ambient, leading to an increase in the compressor work. This effect causes the drop of the COP and increases the system's exergy losses. The greater the temperature differences between the surrounding and cycle elements, the greater the energy losses. Along with the tested values, R510A has the minimum exergy losses and R134a has the higher values of exergy losses. The average exergy losses for R510A, RE170, and R152a are 17.98%, 14.13%, and 10.45% lower than that of R134a, respectively.

4.3.2. EFFECT OF CONDENSING TEMPERATURE ON WATER COOLER EXERGY EFFICIENCY

Fig. 8 illustrates the effect of condensing temperatures on the exergy efficiency of the cycle at different working fluids. As shown, the exergy efficiency drops off by increasing the condensing temperatures at different working fluids. The system with R510A has higher exergy efficiency and R134a has the minimum values of exergy efficiency. Increasing condensing temperatures increase the exergy losses as shown in Fig. 8. This causes a decrease in the exergy efficiency with condensing temperatures. This explains the benefits of reducing the exergy destroyed in the water cooler elements.

5. CONCLUSION

The energetic and exergetic performance analysis of 1 kW water cooler system is evaluated using four working fluid R510A, RE170, R152a, and R134a. The following conclusions can be given:

- The average COP of the investigated water cooler system with R510A, RE170, and R152a are 19.54 %, 13.53, and 9.36 % higher than that with R134a, respectively.
- The highest value of exergy loss in the system takes place in the compressor followed by expansion valve, condenser, and evaporator components.
- Along with the tested values, R510A has the minimum exergy losses and R134a has the higher values of exergy losses.
- The average exergy losses for R510A, RE170, and R152a are 34.62 %, 28.33%, and 18.64% lower than that of R134a, respectively along with evaporation temperatures between -30 and -15 ^{o}C.
- The exergy efficiency decreases with the increase in evaporation temperatures for all system components. However, the decrease is not significant in the range between -30 ^{o}C and -10 ^{o}C evaporation temperatures.
- The exergy efficiency drops off by increasing the condensing temperatures at different working fluids.
- R510A has higher exergy efficiency and R134a has the minimum values of exergy efficiency.
- The water cooler system provided better performance using R510A and RE170 than using HFC152a and HFC134a as working fluids. Therefore, R510A can be considered as the best replacement working fluid for HFC134a and HFC152a.

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