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Energy, Exergy, Environmental and Economic Analysis of Heavy Duty Vapor Compression Chiller with Alternative Fluids in District Cooling

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A district cooling system (DCS) is superior to conventional air conditioning as it helps to reduce energy consumption and protect the environment by reducing carbon dioxide emissions. The investigation of the actual/existing vapour compression refrigeration (VCR) system used in the DCS has not been well documented. In this context, energy, exergy, environmental and economic (4E) analysis of the VCR chiller, operated with R134a, used in heavy duty existing DC plant has been systematically performed and compared with the ecofreindly refrigerant R717. The impact of the evaporation temperature on the total equivalent warming impact (TEWI), coefficient of performance, exergy efficiency and cost rate is assessed. It is observed that the COP and exergy efficiency of the VCR with R717 is around 3 % higher compared to a VCR with R134a. This is attributed to the significantly higher latent heat of evaporation, which ultimately requires a lower mass flow rate of R717. It is observed that the total global warming impact and Combined cost of R717 are lower by 1.6 % compared to the R134a. Lower TEWI is attributed to the zero global warming potential, lower compressor power and higher COP of the VCR system with R717 in comparison to R134a. However, further detailed parametric analysis considering the capital cost is required to claim the superiority of R717.

1. Introduction

The global cooling demand in diversified sectors has been increased rapidly, roughly consuming 15 % of global electricity and contributing to around 10 % of global greenhouse gas emissions (She et al., 2018). This unprecedented cooling demand has been fulfilled majorly using the vapor compression refrigeration (VCR) system and has a market share of 80 %. In most cases, such units are over-dimensioned compared to the actual cooling load that they serve and their electric consumption is not controlled or monitored and they often use environmentally harmful refrigerants (Čož et al., 2017). As a result, such plants are less efficient, less cost effective, and require large land space (Kadam et al., 2020). District cooling is a sustainable and energy efficient alternative over the conventional on-site air conditioning units at individual buildings as it offers reduced environmental impact, more reliable services, and space savings. Remotely operated chiller plants can facilitate in reducing the anthropogenic heat generation (released by plants installed at individual buildings) that contribute to reducing the intensity of the urban heat island effect. This is because of the damping heat from the densely constructed urban area to the nearer remote area where a chiller plant is often erected. A district cooling system that combines with renewable sources (Hui et al. 2017) or industrial waste heat utilization (Liew et al. 2015) can be a cost-effective option.
Belman-Flores et al. (2017) experimentally assessed and concluded that R1234yf has poor energy performance and more environmental impact compared to R134a. De Paula et al. (2020) concluded based on environmental, energy, and exergy analysis that at given operating conditions the overall performance of the R290 is relatively higher compared to R1234yf, R744, and R134a. Sun et al. (2020) observed that the energy and exergy

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performance of the economized VCR system using R513a is lower compared to the R134a, however, R513a exhibits lower irreversibility at high ambient temperature and high space temperatures. Baakeem et al. (2018) performed a theoretical investigation of energy, exergy, and economic analysis of a multistage VCR system (1 kW) operated with different refrigerants (R717, R22, R134a, R1234yf, R1234ze(E), R410A, R404A, and R407C) and concluded that the R717 is the best refrigerant among other refrigerants. Wu et al. (2020) concluded that R290 has superior energy performance and environmental performance among various refrigerants (i.e., R134a, R152a, R1234yf, R290, R410a, R32, R744). Roy and Mandal (2019) performed the thermo-economic analysis of the VCR system of 10 kW cooling capacity and observed that the R152a shows better thermodynamic and economic performance compared to the R600a, R1234ze. Ande et al. (2018) observed that the use of copper oxides nanoparticle in R134a can increase the performance of the VCR system by 16.66 %.
The open literature related to district cooling is focused on the energy analysis of a hypothetical plant. To the best of the authors knowledge no efforts have been made to investigate and document together energy, exergy, environmental, and economic (4E) aspects of the VCR system used in the DC plant (Eveloy and Ayou, 2019). 4E analysis of a VCR unit has been reported considering different refrigerants, but for small capacities that are unsuitable for DC systems. However, the cooling requirement of the VCR-driven DC plant is very high, in the order of thousands of Tons of Refrigeration (TR). For instance, the DC plant at Pearl, Qatar is operated with VCR chillers to satisfy the cooling capacity of 130,000 TR (Kadam et al., 2020). The type of refrigerants used in the VCR could have a significant impact on the environment which eventually turn to be an environmental enemy. The release of refrigerants, due to slow leakage or during repair and maintenance of plant or accident, having high GWP could warm the earth by absorbing energy which supposed to escape to space. Thermophysical properties of the refrigerant can also affect the thermal performance, and hence associated capital, environmental and operational costs of the DC plant could change. Consequently, it is also important to conduct the 4E analysis using different refrigerants used in the VCR chiller of the DC plant. On the contrary, few analyses of hypothetical DC plants are available in the open literature that includes different configurations (Gang et al., 2016) and exergoeconomic optimization of the distribution network (Čož et al., 2017). In this context, this paper emphasizes the 4E comparison of the VCR system, operated with existing refrigerant R134a and alternative refrigerant R717, used for heavy duty district cooling applications. The refrigerant R134a is classified as a greenhouse gas (it has a high global warming potential) and the control and elimination of these gasses were proposed in the Kyoto protocol and restrictions were reaffirmed in the Kigali amendment in 2016 (de Paula et al., 2020). The developed economies like the USA, Japan, and EU countries are in the process of phasing out R134a shortly and are giving preference to alternative refrigerants (Du et al., 2016). Despite some handling and safety issues with R717, it remains one of the strong choices due to its energy efficiency and minimal environmental impact. In Jordon, the Abdali district cooling plant of 21,000 TR capacity is effectively and efficiently functioning using ammonia as a refrigerant (reported in Bara et al., 2021). Recently, Bara et al. (2021) identified that R717 exhibits better dynamic stability among R134a, R32, R1234yf, R1234ze(E), R600, R600a, R290, R410a and R22 for large capacity dual chillers. With this motivation, the R717 is considered and compared with the existing R134a.

2. Material and method

The data for the current study has been collected from the district cooling (DC) plant, situated at the Barwa City, Qatar, and used for the model development. The model of the VCR system as shown in Figure 1a is implemented using the ASPEN Plus^{TM} process simulator (V10), which has an inclusive databank of fluids (Al-Malah, 2016). The primary working fluid (i.e. refrigerant) is the R134a, whereas the secondary fluid is water. The REFPROP model is selected for the thermodynamic and transport properties, as it is most appropriate for the fluid under consideration (i.e., R134a and water), it implements three models for the thermodynamic properties of pure fluids: equations of state explicit in Helmholtz energy, the modified Benedict-Webb-Rubin equation of state, and an extended corresponding states (ECS) model. The heat exchanger, i.e., the condenser and the evaporator, are modeled using the HeatX model that has the capacity for rigorous fundamental analysis. Both heat exchangers are treated with the counter-flow arrangement. The compression and expansion process is considered as isentropic and isenthalpic.
Figure 1b represents the pressure-enthalpy diagram for the R134a and R717 using the REFPROP property method for the base case. The measurement accuracy of the flow meter (Siemens MAG 5000) is ± 0.5 %, pressure transducer (Daikin made) has accuracy of ± 1.5 %, and that for temperature sensors (Daikin made) is ± 0.5 °C. The current simulation approach is validated with the results of Ben Jemaa et al. (2017). The current model deviates by 2.69 % and 2.71 % relative to Ben Jemaa et al.'s data in the case of COP and ECOP as shown in Figure 2a and b. This indicates that a similar simulation approach can be effectively used for the analysis of the current heavy-duty VCR chiller.

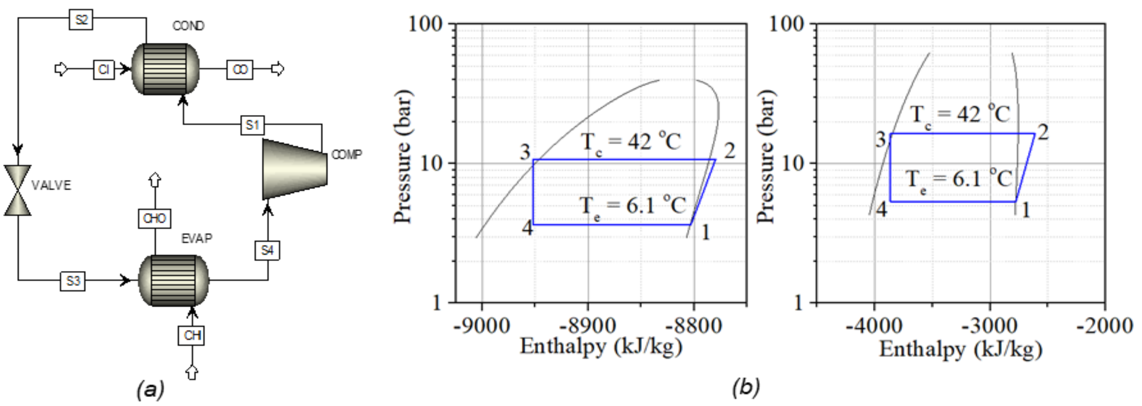

Figure 1: (a) The VCR simulation flowsheet. S1, S2, S3, and S4 are streams of the VCR cycle. CI, CO, CHO, and CHI are streams of cooling water inlet and outlet and chilled water inlet and outlet; (b) Pressure-enthalpy diagram for R134a and R717 at base case (evaporator temperature (T_e) = 6.1 °C, condenser temperature (T_c) = 42 °C)

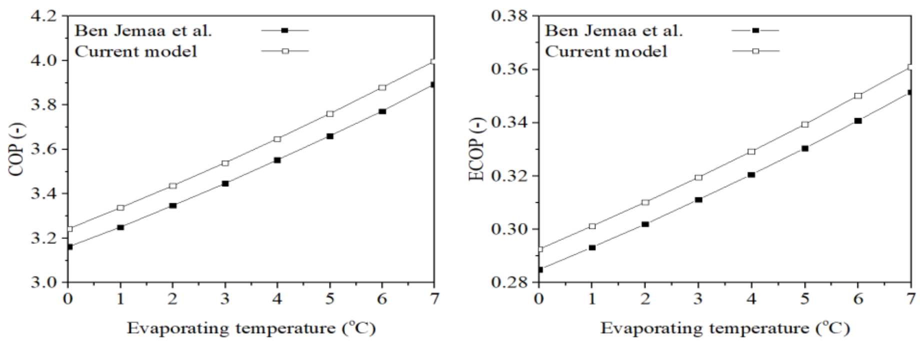

Figure 2: Comparison of the current model with results of Ben Jemaa et al. (2017); (a) COP, (b) ECOP

3. Performance indicators

The coefficient of the performance (COP) is used as an energy indicator as presented by Eq(1).

$$COP = \frac{\dot{Q}_{evap}}{\dot{W}_{comp}} \tag{1}$$

Where $\dot{Q}_{evap}$ and $\dot{W}_{comp}$ are the refrigerating effect and the compressor work in kW. The exergy analysis is carried out in terms of the exergetic efficiency (η_{exergy}), as given by Eq(2) (de Paula et al., 2020).

$$\eta_{exergy} = 1 - \frac{\dot{E}_{des,total}}{\dot{W}_{comp}} = 1 - \frac{\left(\dot{E}_{des,comp} + \dot{E}_{des,cond} + \dot{E}_{des,valve} + \dot{E}_{des,evap}\right)}{\dot{W}_{comp}} \tag{2}$$

where $\dot{E}_{des,total}$ is total exergy destruction associated with the VCR system in kW, which is the summation of exergy destruction of the system components, namely the compressor, the condenser, the expansion valve, and the evaporator, as presented below Eq(3)-(6) (Morosuk and Tsatsaronis, 2009).

$$\dot{E}_{des,comp} = \dot{W}_{comp} - \left(\dot{E}_{s1} - \dot{E}_{s4}\right) \tag{3}$$

$$\dot{E}_{des,cond} = \left(\dot{E}_{s1} - \dot{E}_{s2}\right) - \left(\dot{E}_{CO} - \dot{E}_{CI}\right) \tag{4}$$

$$\dot{E}_{valve} = \dot{E}_{s2} - \dot{E}_{s3} \tag{5}$$

$$\dot{E}_{evap} = \left(\dot{E}_{s3} - \dot{E}_{s4}\right) - \left(\dot{E}_{CHO} - \dot{E}_{CHI}\right) \quad (6)$$

The environmental impact of the refrigerant usage and the VCR system can be measured using the concept of total equivalent warming impact (TEWI) (Fischer, 1993). The TEWI accounts for the direct emissions due to refrigerant leakage and the indirect emissions due to electricity consumption of the compressor, as given by Eq(7).

$$TEWI = GWP \cdot m_{ref} \cdot L_{rate} \cdot L_{time} + GWP \cdot m_{ref} \cdot \left(1-\alpha\right) + E_n \cdot \beta \cdot L_{time} \quad (7)$$

where m_{ref} is the refrigerant charge quantity of the VCR chiller in kg, L_{rate} is an annual rate refrigerant leakage from the VCR chiller in %, L_{time} is the life of the VCR chiller in (y), α is the refrigerant life recovery rate in %, E_n is the annual electricity consumption of the VCR chiller in kWh/y as given by Eq(8), and β is the CO_2 emission factor for producing electricity (equal to 0.469 $kgCO_2/kWh$ for natural gas) (Edenhofer et al., 2011).

$$E_n = 365 \cdot T_{oper} \cdot \left[\dot{Q}_{evap} / COP\right] \quad (8)$$

In the cost analysis, combined costs associated with operational and penalty cost rates due to CO_2 emissions are considered as given by Eq(9)

$$\dot{C} = \dot{C}_{op} + \dot{C}_{env} \quad (9)$$

The operational and environmental cost is estimated as shown by Eq(10) and Eq(11).

$$\dot{C}_{op} = \dot{W}_{comp} 365 \cdot T_{oper} \cdot \dot{C}_{ele} \quad (10)$$

$$\dot{C}_{env} = \beta \cdot E_n \cdot C_{CO_2} \quad (11)$$

where, $\dot{C}_{ele}$ is the electricity unit cost for Qatar (1 kWh = 0.03562 USD) and C_{CO_2} is the unit damage cost of CO_2 emission (equal to 0.09 $USD/kgCO_2$) (Roy and Mandal, 2019).

4. Results and discussion

In this paper, a 4E analysis of the VCR system used in the existing district cooling plant has been carried out. The performance of the existing VCR system using R134a as a refrigerant is compared with that of the eco-friendly refrigerant R717. The operating parameters of the VCR with R717 are the same as those of the VCR with R134a, except for the mass flow rate of the refrigerants. The mass flow rate of the R717 is adjusted to obtain the same outlet temperature of the chilled water as that of R134a. With an increase in the evaporation temperature, the refrigerating effect increases, and the compressor work decreases. The COP of the system is increasing with an increase of the evaporation temperature in the case of both refrigerants. The corresponding data is presented in Table 1.

Table 1: Thermodynamic, environmental, and economic comparison R134a and R717

T_e	T_c	COP		Exergy Efficiency (%)		TEWI (Kg CO_2)		Cost (USD)	
(°C)	(°C)	R134a	R717	R134a	R717	R134a	R717	R134a	R717
2.1	42	5.5	5.6	53.4	55.2	5.36E+07	5.16E+07	5.77E+05	5.70E+05
3.1	42	5.7	5.8	55.3	57.1	5.20E+07	4.99E+07	5.59E+05	5.52E+05
4.1	42	5.9	6.0	57.2	59.0	5.05E+07	4.83E+07	5.42E+05	5.35E+05
5.1	42	6.1	6.2	59.2	61.0	4.91E+07	4.67E+07	5.26E+05	5.17E+05
6.1	42	6.3	6.5	61.4	63.2	4.76E+07	4.52E+07	5.10E+05	5.00E+05

From Figures 3a and b, it is observed that the COP and exergy efficiency of the VCR with R717 is around 3 % higher compared to a VCR with R134a. Although the difference between condenser and evaporator pressures for the R717 is high in comparison to the R134a at the same condensation and evaporation temperature (see Figure 1b, the compressor work requirement is slightly lower for R717. This is because of the requirement of the significantly lower mass flow rate of the R717 compared to R134a. The mass flow rate of the R134a case is 31.5 kg/s. In the case of the R717, it is 4.35 kg/s. The flow rate of the R717 is lower to achieve the same refrigerating effect; the latent heat of evaporation for R717 is considerably high at the same evaporation temperature. The COP of the R717 based VCR chiller is slightly higher than that of the R134a-based, VCR chiller. On the contrary, environmental performance and the cost are reduced with an increase in the evaporation temperature as shown in Figures 4a and b. The corresponding data is also presented in the Table 1.

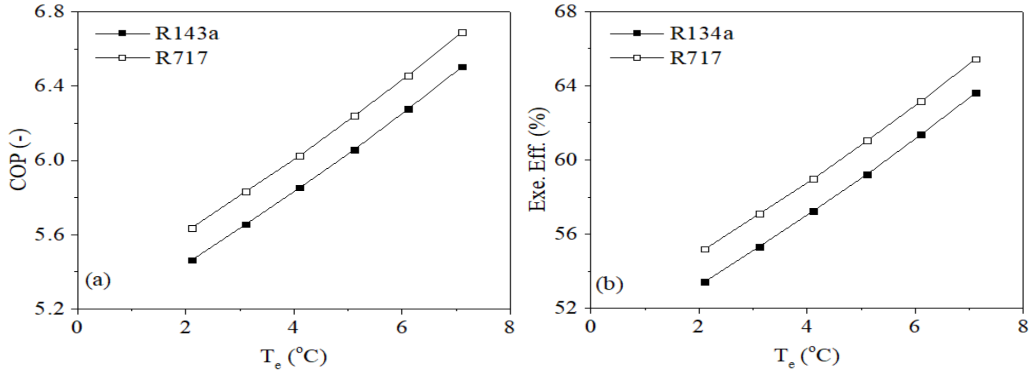

Figure 3: Comparison of the performance indicators between R134a and R717 at constant condenser temperature (T_c = 42 °C), (a) COP, (b) Exergy efficiency

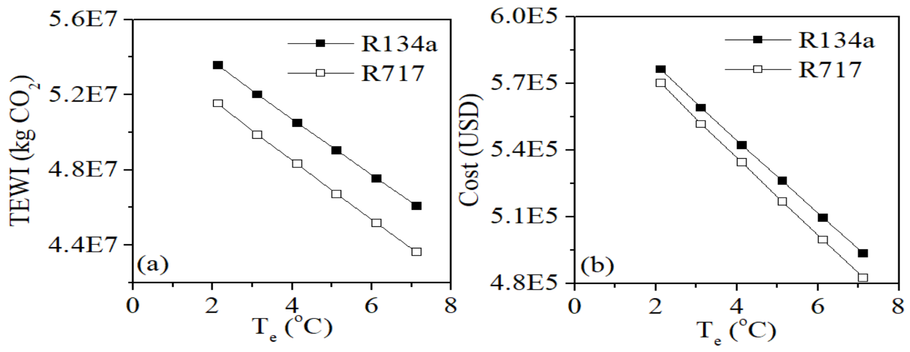

Figure 4: Comparison of the performance indicators between R134a and R717 at constant condenser temperature (T_c = 42 °C), (a) TEWI, (b) Cost

The TEWI decreases due to a reduction in the refrigerating effect with an increase in the condensation effect. The reduction in the cost is due to the decreasing trend of the compressor work and the refrigerating effect with an increase in the evaporation temperature. The environmental impact of the R717 is relatively lower compared to the R134a. It is observed from Figure 4a that the total global warming impact (TEWI) is lower by 1.6 % compared to the R134a. The major reason for this lower impact is the zero value of the global warming potential of the R717, and the higher COP value. Similarly, the summation of the operating and environmental cost of the R717-based VCR system is 1.6 % lower than the R134a as shown in Figure 4b, due to lower compressor work and higher COP. Based on the current comparison under the given operating conditions, it is concluded that the performance of the R717-based VCR chiller is better than that of the R134a-based VCR chiller.

5. Conclusions

The energy, exergy, environmental and economic (4E) analysis of the VCR chiller, operated with R134a, used in a heavy duty, existing DC plant has been systematically performed and compared with the ecofrendly refrigerant R717. It is observed that the COP and the exergy efficiency of the VCR with R717 are around 3 % higher compared to a VCR with R134a. This is attributed to the significantly higher latent heat of evaporation, which ultimately requires a lower mass flow rate of R717. It is observed that the total global warming impact (TEWI) and the combined cost of R717 are lower by 1.6 % compared to the R134a. Lower TEWI is attributed to the zero global warming potential, lower compressor power and higher COP of the VCR system with R717 in comparison to R134a. However, further detailed parametric analysis considering the capital cost is required to claim the superiority of the R717. The 4E analysis conducted and results obtained in this study have noteworthy practical importance. The system designer can adopt a similar approach to quantify the benefits offered by the other eco-friendly refrigerants as done for R717, before performing experimental testing. This is of great practical value because a similar analysis could result in a significant reduction in associated capital and operational costs, at the early stage of planning of the DC plant.

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