INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2016) 1–11

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

Energy and exergy investigation of R1234ze as R134a replacement in vapor compression chillers

Radhouane Ben Jemaa, Rami Mansouri, Ismail Boukholda, Ahmed Bellagi*

U.R. Thermique et thermodynamique des procédés industriels, Ecole Nationale d'Ingénieurs de Monastir, ENIM, Av. Ibn Jazzar, 5060, Monastir, University of Monastir, Tunisia

ARTICLE INFO

Article history:
Received 31 July 2016
Accepted 3 December 2016
Available online xxx

Keywords:
Exergy
Vapor compression
Refrigeration
Performance
R1234ze
R134a

ABSTRACT

Energy and exergy analyses are carried out for an air-cooled vapor compression chilled water (VCCW) using an alternative working fluid R1234ze to R134a. A thermodynamic model is developed using the Engineering Equation Solver (EES). A parametric study is conducted to investigate the effect of evaporating and ambient temperatures on the energy and exergy efficiencies, the total exergy destruction and the exergy losses in different components of the system. For both refrigerants, no important differences are observed between the energy and the exergy efficiencies. Among the components, the compressor presents the highest exergy destruction, followed by the condenser, the expansion valve and the evaporator. The irreversibility obtained in the unit using R1234ze is lower than the R134a. R1234ze is a good alternative to R134a in the VCCW systems.

Introduction

Centralized air-conditioning systems where the cooling production is provided by vapor compression chilled water occupy the majority of the tertiary air conditioning systems. Solutions based on absorption cycles exist but they are rare used.

Vapor compression refrigeration systems (VCR) consume electric energy and they use harmful refrigerants environment. Two important parameters are used to measure the impact of the working fluids on the environment. The ozone depletion potential (ODP) and the Global warming potential (GWP).

Several protocols and international agreements were signed: protocol of Montreal in 1987 to limit the use of the CFC and HCFC refrigerants, Kyoto protocol in 1998 for the CO_2 and the greenhouse gases, etc. These agreements have the objective to bring the signatory countries to reduce their greenhouse gas emissions by at least 5% compared with the level of 1990, during the period of commitment from 2008 to 2012. In 2015, the United Nations Climate Change Conference (COP21) was held in Paris, France. The objective of this conference was to achieve, for the first time in over 20 years of the United Nations negotiations, a binding and universal agreement on climate, from all the nations of the world, with the aim of keeping global warming below 2 °C. On April 2016, 174 countries signed the agreement and began adopting it within their own legal systems (through ratification, acceptance, approval, or accession).

Current researches deal with the modeling and the exergy analysis of VCR systems. Low GWP refrigerants are also the subject of many studies.

* *Corresponding author.*
E-mail address: r_bjemaa@yahoo.fr (R. Ben Jemaa).

http://dx.doi.org/10.1016/j.ijhydene.2016.12.010

Anand et al. [1] presented a review on refrigeration systems and different software used in their simulations. The effect of different parameters such as working fluids, effectiveness of heat exchangers and operating temperatures are studied. Browne et al. [2] predicted the performance of vapor compression liquid chillers using an NTU-ε model. Lee and Lu [3] predicted experimentally the energy performance of water chiller units. Researchers on VCR systems exergy analysis in various sectors are presented by Ahamed et al. [4]. They found that the compressor among the component of the system occurred the maximum exergy losses. Arora and Kaushik [5] presented a detailed exergy analysis of a VCRS to find the better alternate to the refrigerant R502. The working fluid R507A is the better alternate than R404A. Besbes et al. [6] presented a methodology based on exergy analyses to optimize vapor compression heat pumps used in industrial processes.

The Fluorinated propene isomer refrigerants recently introduced such as R1234yf and R1234ze, hold promise given their low GWP values.

Most relevant R1234ze researches are collected by Mota-Babiloni et al. [7]. Pressure drop, heat transfer characteristics, thermophysical properties and VCR system performance are presented. Fukuda et al. [8] assessed thermodynamically, numerically and experimentally the thermodynamic attributes of higher temperature heat pumps using R1234ze refrigerant. Özgür et al. [9] studied the use of the refrigerant HFO1234yf as an alternative to HFC-134a. Yotaganbaba et al. [10] analyzed the exergy of a VCR systems with two evaporators. The studied refrigerants are R1234yf, R1234ze and R134a. Five two stage VCR system configurations using low GWP working fluids are evaluated by Llopis et al. [11]. Mota-Babiloni et al. [12] carried out a comparative study of different VCR configurations using six low GWP refrigerants as R404A replacements.

Vapor compression chilled water systems using low GWP refrigerants are not enough well studied. The aim of this paper is to present in details a complete thermodynamic performance analyze of an air cooled vapor compression chillers and the exergy losses in different components of the system. Two working fluids are tested and compared, the HFC high GWP going to phased out, R134a and the low GWP, HFO refrigerant recently introduced R1234ze.

Table 1 – Safety and environment refrigerant properties.

	R134a	R1234ze
ODP	0	0
GWP	1430	4
ASHRAE safety group	A2L	A1
ASHRAE flammability	No	Yes (low)
ASHRAE toxity	No	No

Working fluids

For a given application, the working fluids are selected regarding some criteria such as thermo-physical properties, safety issues (toxicity and flammability), economic aspects, and environmental factors [13]. The parameters ODP and GWP are very important for the choice of refrigerants.

The HCFC (hydrochlorofluorocarbon) refrigerant R22 has been used in vapor compression chillers for many years. As a consequence of the Montreal protocol, this fluid is banned due to its ozone depletion potential (ODP). HFC (hydrofluorocarbon) such as R134a, R407C and R410A, having zero ODP, are proposed to substitute the R22. Theses refrigerants have high GWP, that's why they are eliminated by the Kyoto

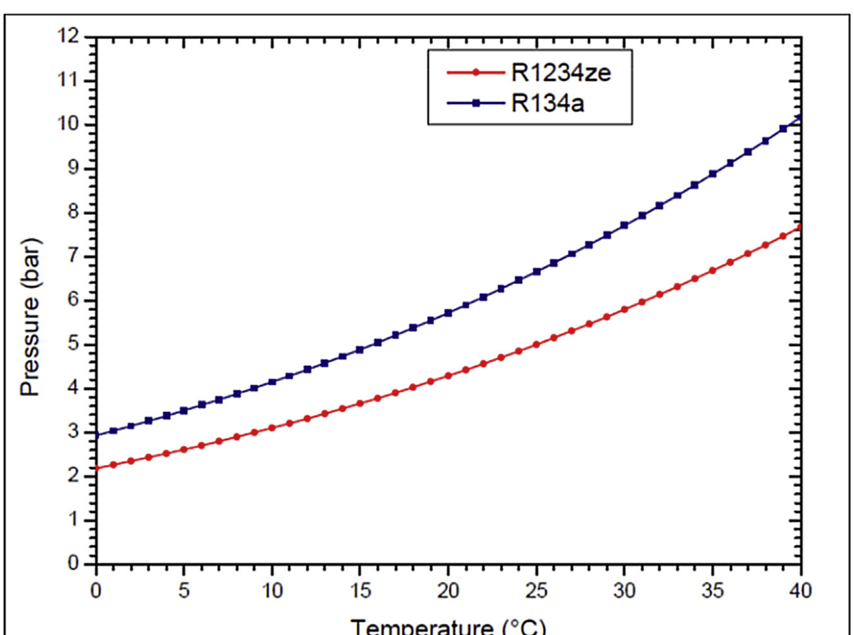

Fig. 1 – Saturation pressure *vs.* temperature.

Please cite this article in press as: Ben Jemaa R, et al., Energy and exergy investigation of R1234ze as R134a replacement in vapor compression chillers, International Journal of Hydrogen Energy (2016), http://dx.doi.org/10.1016/j.ijhydene.2016.12.010

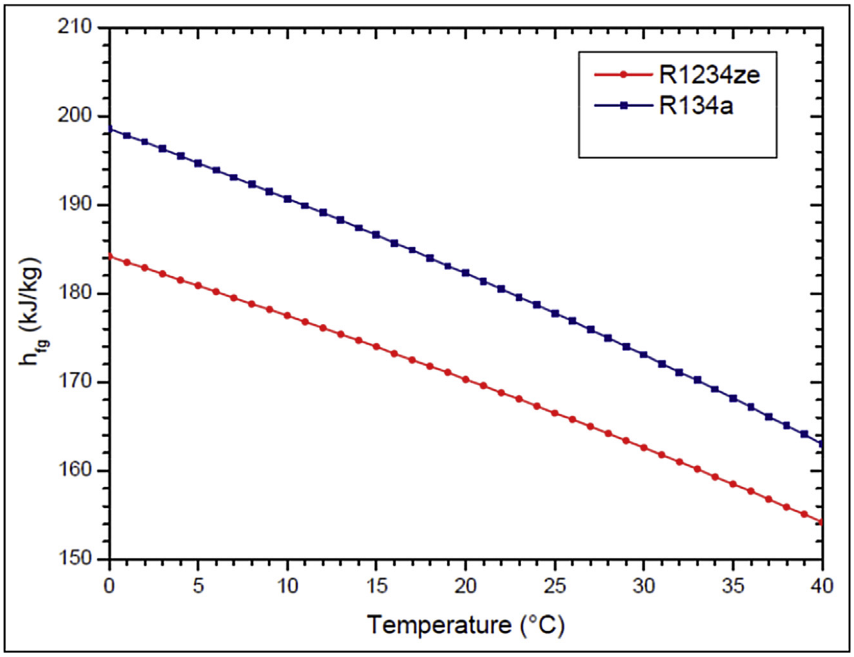

Fig. 2 – hfg *vs.* temperature.

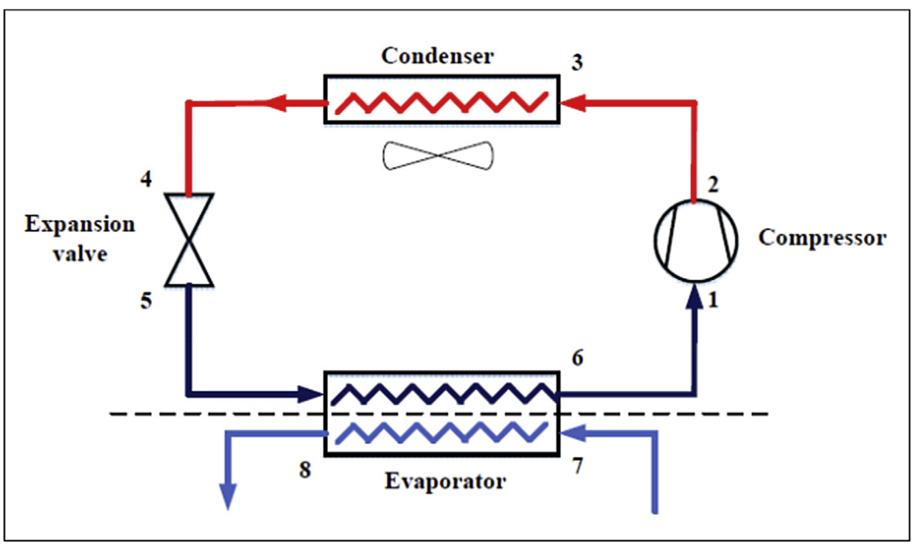

Fig. 3 – Schematic diagram of the VCCW.

Table 2 – Data inputs.

Parameter	Value
Ambient temperature	35 °C
Entering chilled water temperature	12 °C
Leaving chilled water temperature	7 °C
Condenser difference temperature	15 °C
Evaporator difference temperature	5 °C
Subcooling degree of liquid refrigerant	5 K
Superheating degree of vapor leaving the evaporator	5 K
Suction line superheating	5 K
Desuperheating in the discharge line	10 K
Isentropic efficiency of the compressor	75%
Mass flow rate	1 kg/s

protocol. Other refrigerants such as R1234ze characterized by a low GWP, is proposed.

Environment and safety properties of the R134a and R1234ze refrigerants are presented in Table 1. The two working fluids are non-toxic and have zero ODP. R1234ze have a low GWP value (7) compared to the R134a value which is 1430. R134a and R1234ze are classified A1 and A2L respectively. R134a is non-flammable but the R1234ze is low-flammable [14].

Fig. 1 presents the saturation pressure curves of the studied working fluids. It can be seen that, for a given temperature, the R1234ze saturation pressure is lower than the R134a pressure. The R134a systems require high pressure compressors and thicker walled tubing [15]. The

Table 3 – Energy flows, exergy destruction and relative irreversibility for R134a.

Component	Energy flow (kW)	Exergy destruction (kW)	Relative irreversibility (%)
Compressor	41.95	9.448	32.27
Condenser	175.6	8.412	28.73
Expansion valve	0	5.801	19.81
Evaporator	140.4	4.111	14.04
Discharge line	11.2	1.1	3.76
Suction line	4.484	0.4047	1.38
COP = 3.347		ECOP = 0.302	

Table 4 – Energy flows, exergy destruction and relative irreversibility for R1234ze.

Component	Energy flow (kW)	Exergy destruction (kW)	Relative irreversibility (%)
Compressor	37.93	8.757	33.12
Condenser	158.6	7.349	27.79
Expansion valve	0	5.481	20.73
Evaporator	127.2	3.626	13.71
Discharge line	11.09	0.827	3.13
Suction line	4.544	0.401	1.52
COP = 3.354		ECOP = 0.3027	

enthalpy of vaporization curves of the two refrigerants are illustrated in Fig. 2. For a given temperature the enthalpy of vaporization of the R134a is bigger than the R12234ze. The mass flow rate required for the R134a cycle is lower than the R1234ze one.

Thermodynamic analysis

The based cycle of the air cooled vapor compression chiller is shown in Fig. 3. It consists essentially of a water evaporator, a compressor, an air-cooled condenser and an expansion valve.

In order to simulate this system the principles of mass continuity, the first law, the second law and exergy analysis are applied to each component of the cycle taking into account the following assumptions: steady state operation, kinetic and potential energy are not considered and negligible pressure drops [16].

The general mass continuity equation is written as:

$$\sum_{in} \dot{m} = \sum_{out} \dot{m} \tag{1}$$

where $\dot{m}$ is the mass flow rate and the subscripts in and out stand for inlet and outlet, respectively.

The first law of thermodynamic can be written as [17]:

$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \dot{m}h = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \dot{m}h \tag{2}$$

where $\dot{W}$ is the work rate, $\dot{Q}$ is the heat transfer rate between the control volume and its surroundings, and h is the specific enthalpy.

The energy efficiency of the chiller is evaluated by its coefficient of performance (COP). This coefficient is the ratio of the refrigeration capacity $\dot{Q}_{evap}$ to the work rate required to compressor $\dot{W}_{comp}$:

$$COP = \frac{\dot{Q}_{evap}}{\dot{W}_{comp}} \tag{3}$$

The second law of thermodynamic can be written as [18]:

$$\sum_{in} \left(\frac{\dot{Q}_i}{T_i}\right) + \sum_{in} \dot{m}_i s_i + \dot{S}_{gen} = \sum_{out} \left(\frac{\dot{Q}_i}{T_i}\right) + \sum_{out} \dot{m}_i s_i \tag{4}$$

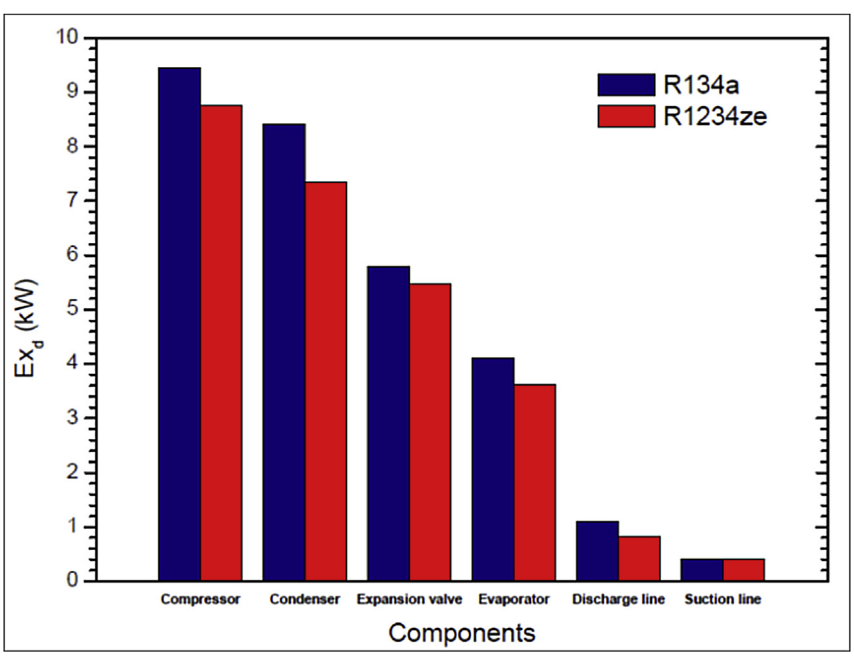

Fig. 4 – Exergy destruction of different components.

where $\left(\frac{\dot{Q}_i}{T_i}\right)$ is the entropy rate transfer by heat exchanged at a rate of $\dot{Q}_i$, s is the specific entropy and $\dot{S}_{gen}$ represents the entropy rate generation.

Exergy analysis is based on the first and second laws of thermodynamics. Exergy analysis describes the losses in the whole system and its components. Possibilities of thermodynamic improvement of the system can be indicated [19].

The specific exergy flow can be defined as:

$$ex = [(h - h_0) - T_0(s - s_0)] \tag{5}$$

where h_0 and s_0 are the specific enthalpy and entropy of the fluid, respectively at the environment conditions T_0 and P_0.

The general exergy balance in the rate form is written as [20]:

$$\sum_{in}\left(1-\frac{T_0}{T_i}\right)\dot{Q}_i + \dot{W}_{in} + \sum_{in}\dot{m}_i ex_i = \sum_{out}\left(1-\frac{T_0}{T_i}\right)\dot{Q}_i + \dot{W}_{out} + \sum_{out}\dot{m}_i ex_i + \dot{E}x_D \tag{6}$$

The exergy efficiency or second law efficiency (ECOP) is defined as the ratio between the useful exergy gained from a system and that supplied to the system [21]:

$$ECOP = \frac{\dot{E}x_u}{\dot{E}x_{cons}} \tag{7}$$

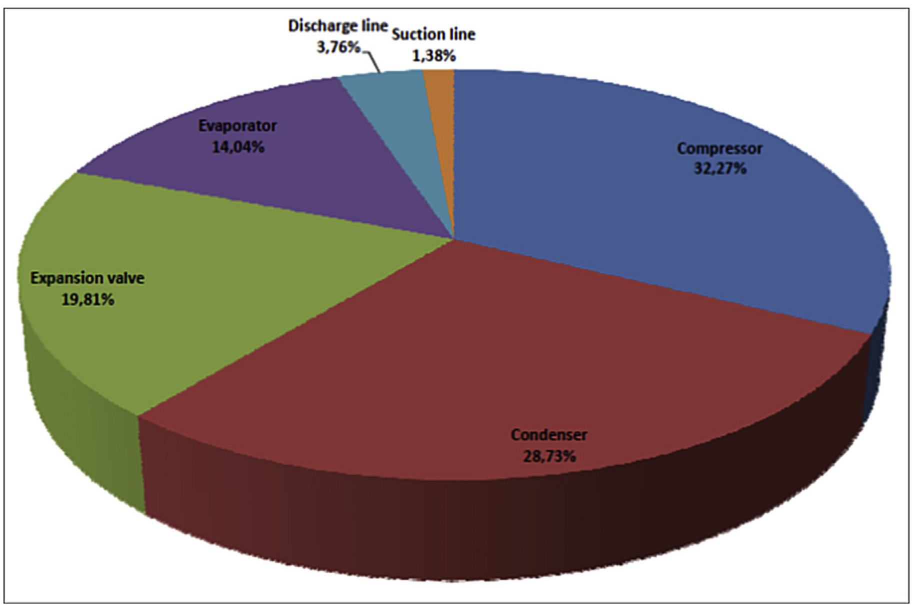

Fig. 5 – Relative irreversibility of different components (R134a).

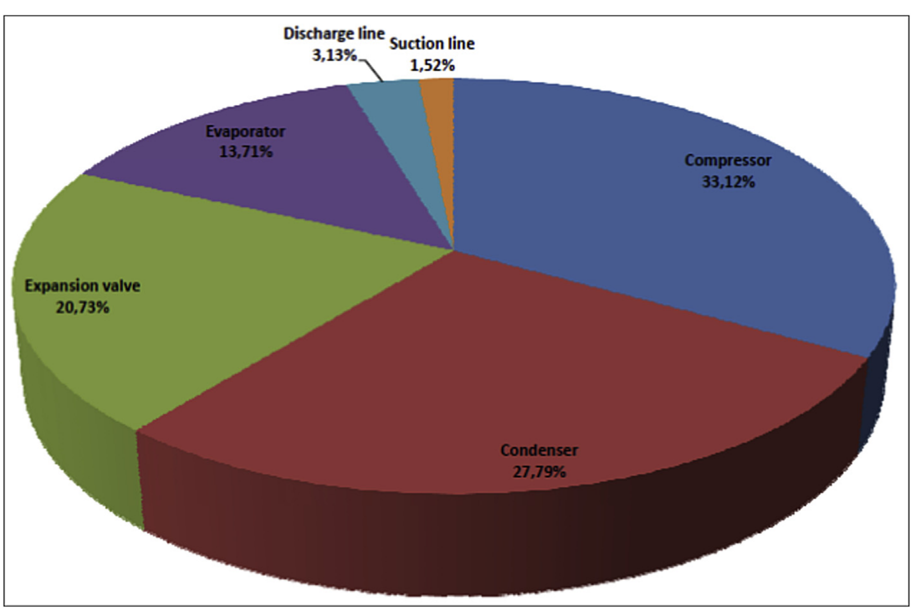

Fig. 6 – Relative irreversibility of different components (R134ze).

Please cite this article in press as: Ben Jemaa R, et al., Energy and exergy investigation of R1234ze as R134a replacement in vapor compression chillers, International Journal of Hydrogen Energy (2016), http://dx.doi.org/10.1016/j.ijhydene.2016.12.010

The relative irreversibility of each component k is defined by:

$$RI_k = \frac{\dot{I}_k}{\dot{I}_{tot}} = \frac{\dot{E}_{xD,k}}{\dot{E}_{xD,tot}} \tag{8}$$

where $\dot{I}_k$ is the irreversibility of component k and $\dot{I}_{tot}$ is the sum of the component irreversibility.

Energy and exergy analyses of the overall VCRCW and its components are provided:

- Compressor

$$\dot{W}_{comp} + \dot{m}h_1 = \dot{m}h_2 \tag{9}$$

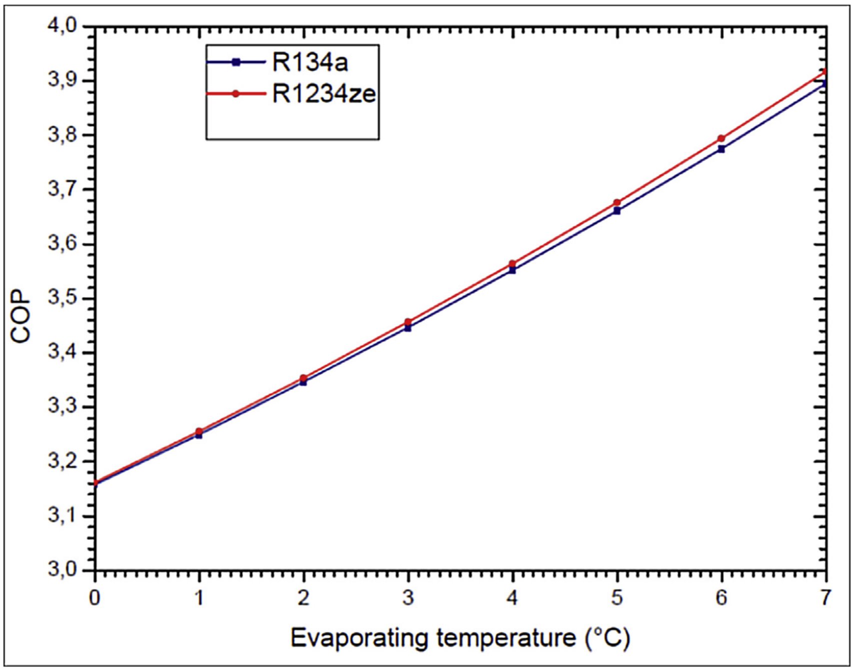

Fig. 7 – COP *vs.* evaporating temperature.

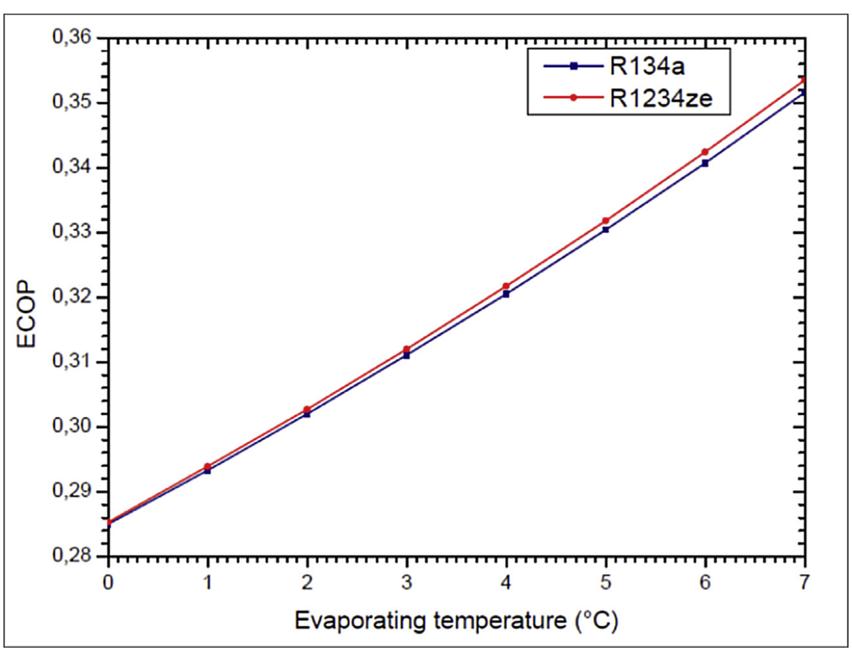

Fig. 8 – ECOP *vs.* evaporating temperature.

$$\dot{W}_{comp} + \dot{m}ex_1 = \dot{m}ex_2 + \dot{E}x_{D,comp} \quad (10)$$

- Discharge line

$$\dot{m}h_2 = \dot{m}h_3 + \dot{Q}_{dis} \quad (11)$$

$$\dot{m}ex_2 = \dot{m}ex_3 + \dot{E}x_{D,dis} \quad (12)$$

- Condenser

$$\dot{m}h_3 = \dot{m}h_4 + \dot{Q}_{cond} \quad (13)$$

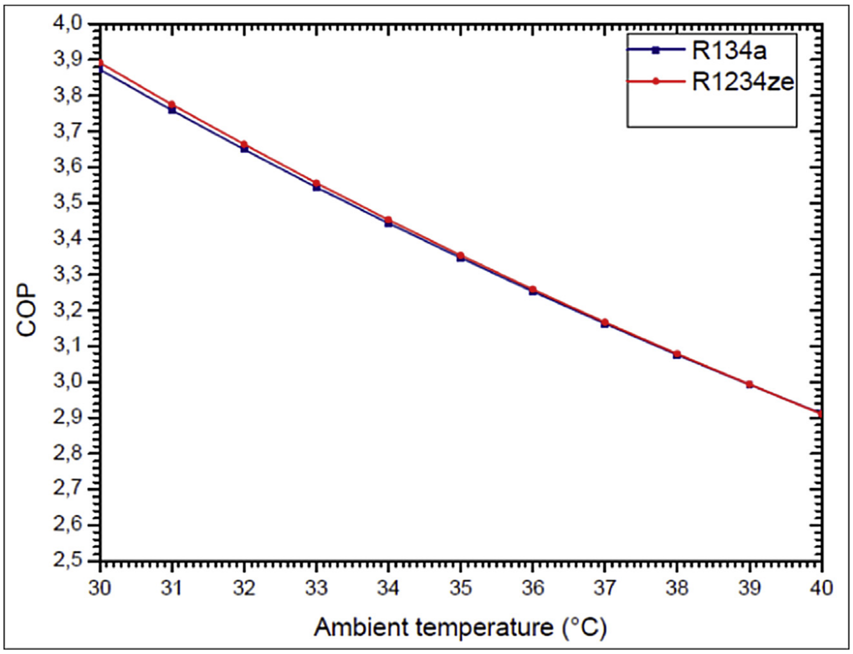

Fig. 9 – *COP vs.* ambient temperature.

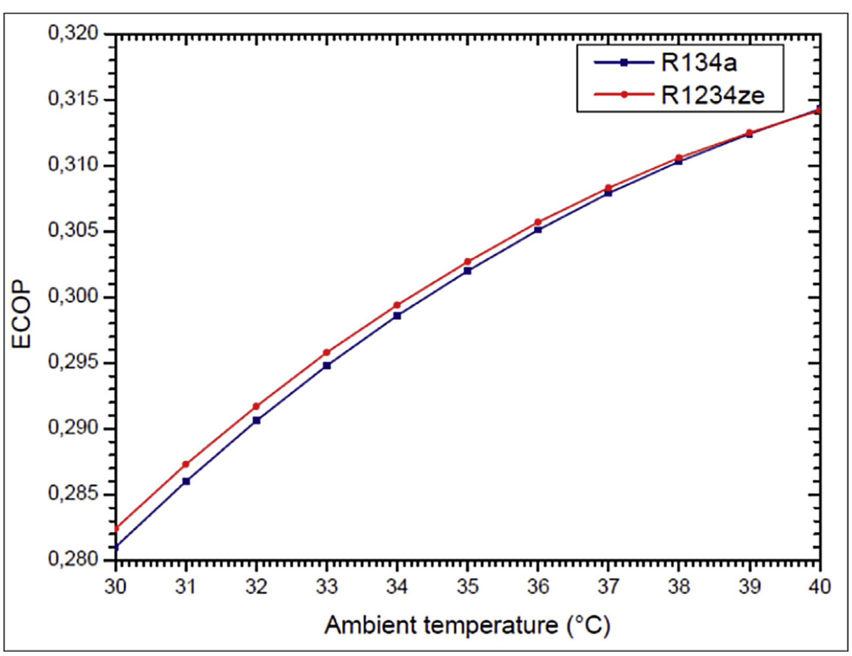

Fig. 10 – *ECOP vs.* ambient temperature.

Please cite this article in press as: Ben Jemaa R, et al., Energy and exergy investigation of R1234ze as R134a replacement in vapor compression chillers, International Journal of Hydrogen Energy (2016), http://dx.doi.org/10.1016/j.ijhydene.2016.12.010

$$\dot{m}ex_3 = \dot{m}ex_4 + \dot{E}x_{D,cond} \tag{14}$$

- Expansion valve

$$\dot{m}h_4 = \dot{m}h_5 \tag{15}$$

$$\dot{m}ex_4 = \dot{m}ex_5 + \dot{E}x_{D,\ \exp v} \tag{16}$$

- Evaporator

$$\dot{m}h_5 + \dot{Q}_{evap} = \dot{m}h_6 \tag{17}$$

$$\dot{m}_w h_7 = \dot{m}_w h_8 + \dot{Q}_{evap} \tag{18}$$

$$\dot{m}ex_5 + \dot{m}_w ex_7 = \dot{m}ex_6 + \dot{m}_w ex_8 + \dot{E}x_{D,evap} \tag{19}$$

- Suction line

$$\dot{m}h_6 + \dot{Q}_{suc} = \dot{m}h_1 \tag{20}$$

$$\dot{m}ex_6 = \dot{m}ex_1 + \dot{E}x_{D,suc} \tag{21}$$

- Energy efficiency:

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

- Exergy efficiency:

$$ECOP = \frac{\dot{E}x_u}{\dot{E}x_{cons}} = \frac{\dot{m}_7(ex_7 - ex_8)}{\dot{W}_{comp}} \tag{23}$$

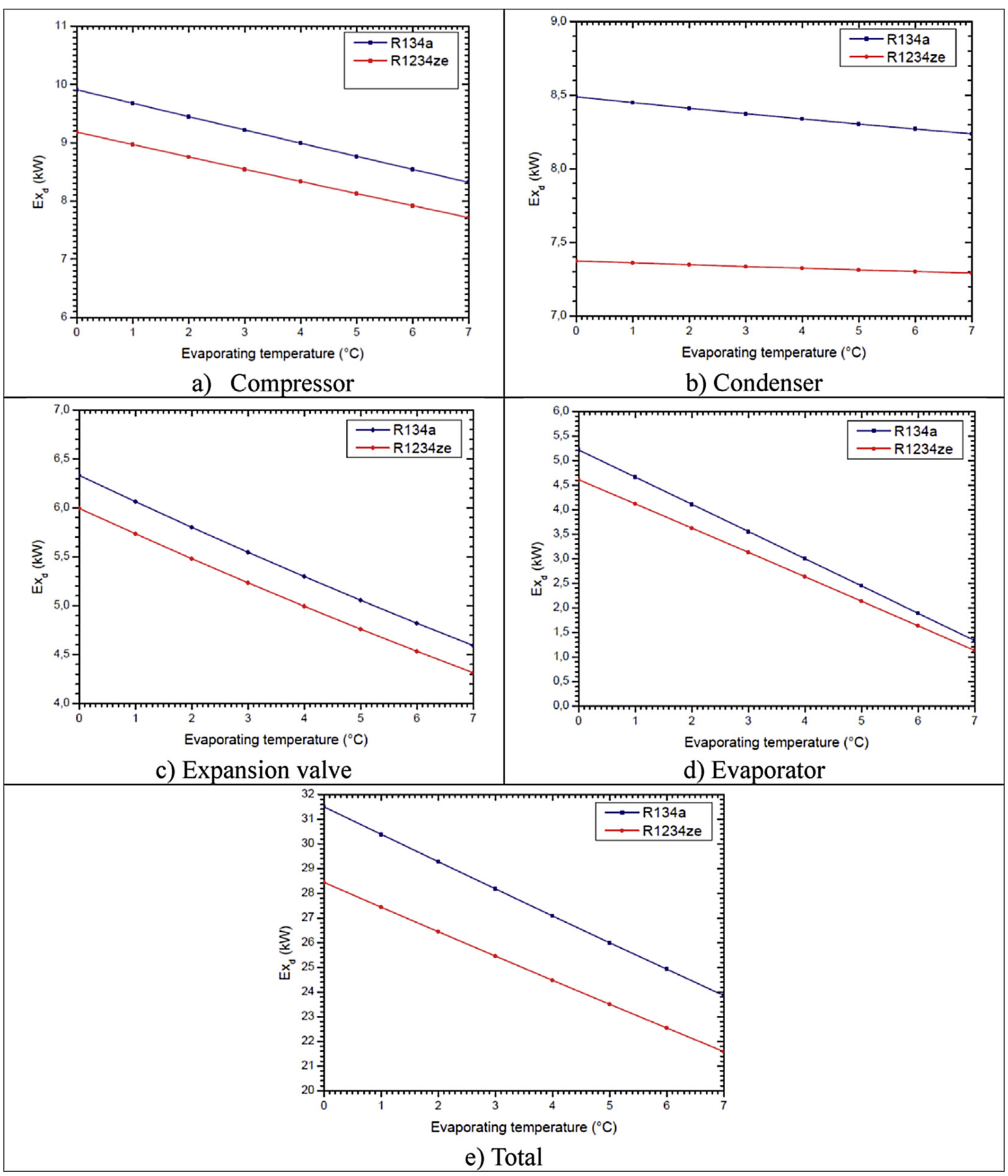

Fig. 11 – Effect of the evaporating temperature on the exergy destruction.

Please cite this article in press as: Ben Jemaa R, et al., Energy and exergy investigation of R1234ze as R134a replacement in vapor compression chillers, International Journal of Hydrogen Energy (2016), http://dx.doi.org/10.1016/j.ijhydene.2016.12.010

Results and discussions

A computer program developed in Engineering Equation Solver [22] was used to solve the obtained equations.

The input data were the nominal functioning conditions of the unit such as chilled water supply and return temperature, ambient temperature, condenser and evaporator difference temperatures, subcooling degree of liquid refrigerant, superheating degree of vapor leaving the evaporator, suction line superheating, desuperheating in the discharge line and isentropic efficiency of the compressor. The values of theses input parameters are summarized in Table 2. With the given parameters, the program calculates all thermodynamic properties of different points of the cycle, energy and exergy efficiencies, irreversibility and exergy destruction of the system and its components. The results are presented in Tables 3 and 4 for the refrigerants R134a and R1234ze, respectively.

The COP of the chiller using R134a and R1234ze are 3.347 and 3.354, respectively. The ECOP is 0.302 for the R134a cycle and 0.3027 for the R1234ze. No important differences are observed between the COP and the ECOP for the two working fluids.

The exergy destructions of the four main components are compared in Figs. 4–6 present the relative irreversibility of each component using R134a and R1234ze, respectively. The compressor is responsible for the highest exergy destruction, followed by the condenser, the expansion valve and the evaporator. The irreversibility of the cycle using R1234ze is 29.277 kW. The contribution of the different components are 8.757 kW (33.12%) for the compressor, 7.349 kW (27.79%) for

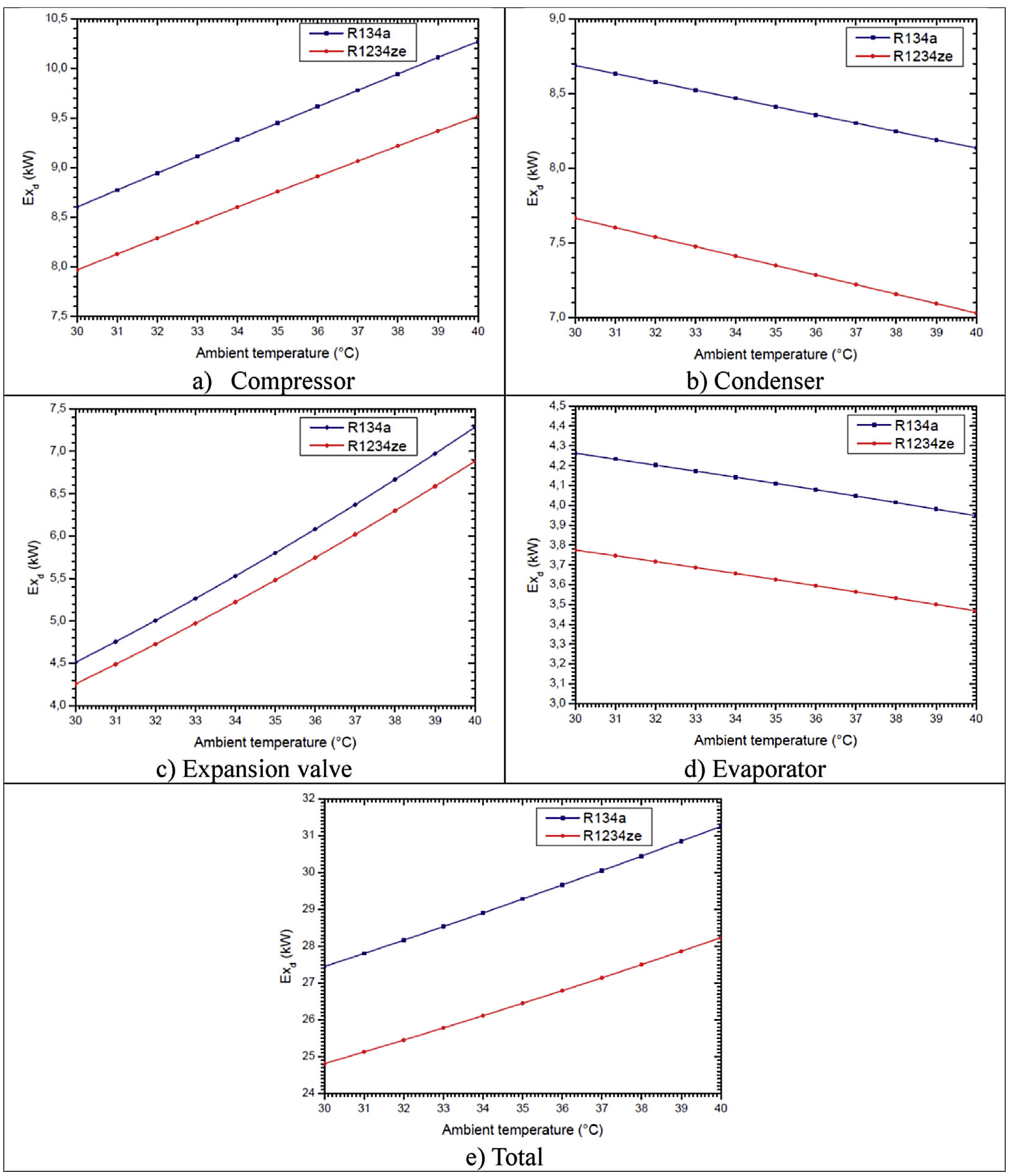

Fig. 12 – Effect of the ambient temperature on the exergy destruction.

the condenser, 5.481 kW (20.73%) for the expansion valve and 3.6256 kW (13.71%) for the evaporator. The irreversibility corresponding to the R134a is 9.448 kW (32.27%) for the compressor, 8.412 kW (28.73%) for the condenser, 5.801 kW (19.81%) for the expansion valve and 4.111 kW (14.04%) for the evaporator. The total exergy destruction is 26.441 kW.

The irreversibility of all components and the whole R1234ze chiller is lower than the R134a one. The improvements are 7.3% for the compressor, 12.6% for the condenser, 5.5% for the expansion valve, 11.8% for the evaporator and 9.7% for the entire unit.

A parametric study was done to ascertain the impact of ambient temperature and evaporating temperature on the energy and exergy efficiencies, exergy destruction of the unit components and the total irreversibility. The effect of the evaporating temperature on the *COP* and the *ECOP* are presented in Figs. 7 and 8, respectively. Figs. 9 and 10 describe the evolution of the *COP* and the *ECOP* verses the ambient temperature, respectively. For both refrigerants, the energy and exergy efficiencies increase when the evaporating temperature increases. The *COP* of the system decreases and the *ECOP* increases with the ambient temperature.

With the increase in the evaporating temperature, the low pressure increases causing the augmentation of the cooling capacity, the reduce of the compressor pressure ratio and the compressor work. Thus *COP* and *ECOP* increase.

The increase in the ambient temperature is accompanied with the augmentation of the high pressure which causes the increase of the pressure ratio across the compressor and its required work. The *COP* is than decreased and the *ECOP* is increased.

Regardless of the evaporating and the ambient temperatures, the *COP* and the *ECOP* of the chiller using the R1234ze refrigerant are at least equal to those using R134a. The maximum of the *COP* increase is in the average of 0.5–0.6%. The difference in the *ECOP* is about 0.1–0.5%.

The exergy destruction variations with evaporating temperature of the compressor, the condenser, the expansion valve, the evaporator and the total irreversibility are presented in Fig. 11. The total and the different exergy destruction components decrease with the evaporating temperature. The irreversibility in the R1234ze cycle are lower than the R134a. For the various studied evaporating temperatures, the differences are 7.3% for the compressor, between 11.5 and 13.1% for the condenser, from 5.3 to 6.1% for the expansion valve, between 11.6 and 15.1% for the evaporator and from 9.5 to 9.7% for the total irreversibility.

Fig. 12 depicts the effect of the ambient temperature on the irreversibility of the main components and the total exergy destruction. The condenser and the evaporator irreversibility decrease with the increase of the ambient temperature. The total exergy destruction, the irreversibility in the compressor and the expansion valve increase with the ambient temperature. For the various ambient temperatures the irreversibility using R1234ze are lower than the R134a. The differences are 7.3% for the compressor, from 11.8 to 13.6% for the condenser, 5.5% of the expansion valve and 9.6% for the total exergy destruction.

According to the obtained results and discussions, the working fluid R1234ze is assumed as more favorable environmentally and thermodynamically than the R134a.

Conclusion

First and second law of thermodynamics have been combined to perform an exergy analysis to evaluate the irreversibility or the exergy destruction of the whole and each component of the air cooled vapor compression chilled water. Two working fluids are compared. A high GWP refrigerant R134a and its candidate of replacement the R1234ze. A parametric study was performed to analyze the effect of the ambient and the evaporating temperatures on the performance of the vapor compression chiller. The energy and the exergy efficiencies of the both refrigerant cycles have almost the same values. The largest irreversibility was recorded in the compressor followed by the condenser, the expansion valve and the evaporator. The R1234ze cycle presents the lowest irreversibility.

Environmentally problems caused by the working fluid R134a will be solved using the refrigerant R1234ze in vapor compression chilled water systems.

REFERENCES

[1] Anand S, Gupta A, Tyagi SK. Simulation studies of refrigeration cycles: a review. Renew Sustain Energy Rev 2013;17:260–77.
[2] Browne MW, Bansal PK. An elemental NTU-ε model for vapor compression liquid chillers. Int J Refrig 2001;24:612–27.
[3] Lee TS, Lu WC. An evaluation of empirically-based models for predicting energy performance of vapor-compression water chillers. Appl Energy 2010;87:3486–93.
[4] Ahamed JU, Saidur R, Masjuki HH. A review on exergy analysis of vapor compression refrigeration system. Renew Sustain Energy Rev 2011;15:1593–600.
[5] Arora A, Kaushik SC. Theoretical analysis of a vapour compression refrigeration system with R502, R404A and R507A. Int J Refrig 2008;31:998–1005.
[6] Besbes K, Zoughaïb A, De Carlan F, Peureux JL. Exergy based methodology for optimized integration of vapor compression heat pumps in industrial processes. In: 15th International refrigeration and air conditioning conference at Perdue; 2014.
[7] Mota-Babiloni A, Navarro-Esbri J, Molès F, Barragan-Cervera A, Peris B, Verdu GA. Review of refrigerant R1234ze recent investigations. Appl Therm Eng 2016;95:211–22.
[8] Fukuda S, Kondou C, Takata N, Koyama S. Low GWP refrigerant R1234ze for high temperature heat pumps. Int J Refrig 2014;40:161–73.
[9] Özgür AE, Kabul A, Kizilkan Ö. Exergy analysis of refrigeration systems using an alternative refrigerant (hfo-1234yf) to R134a. Int J Low Carbon Technol Adv 2013;28.
[10] Yotaganbaba A, Kilicarslan A, Kurtbas I. Exergy analysis of R1234yf and R1234ze as R134a replacements in a two evaporator vapour compression refrigeration system. Int J Refrig 2015;60:26–37.
[11] Llopis R, Sanchez D, Sanz-Kock C, Cabello R, Torrela E. Energy and environmental comparison of two-stage solutions for commercial refrigeration at low temperature: fluids and systems. Appl Energy 2015;138:133–42.
[12] Mota-Babiloni A, Navarro-Esbri J, Barragan-Cervera A, Molès F, Peris B. Theoretical comparison of low GWP alternatives for different refrigeration configurations taking R404A as baseline. Int J Refrig 2015;44:81–90.
[13] Moles F, Navarro-Esbri J, Peris B, Mota-Babiloni A, Barragan-Cervera A. Theoretical energy performance evaluation of different single stage vapor compression refrigeration

Please cite this article in press as: Ben Jemaa R, et al., Energy and exergy investigation of R1234ze as R134a replacement in vapor compression chillers, International Journal of Hydrogen Energy (2016), http://dx.doi.org/10.1016/j.ijhydene.2016.12.010

configurations using R1234yf and R1234ze as working fluids. Int J Refrig 2014;44:141–50.
[14] Ben Jemaa R, Mansouri R, Boukholda I, Bellagi A. Second law analysis of a vapor compression chilled water using a friendly environment refrigerant (R1234ze) as a substitute of R134a. In: 7th International renewable energy congress (IREC); 2016.
[15] Emerson Network Power. Technical note: comparing R407C and R410A as alternatives for R22. www.emersonnetworkpower.com.
[16] Ben Jemaa R, Ben Issa N, Ben Issa S, Bellagi A. Exergy analysis of a diffusion absorption refrigeration system. Int J Exergy 2008;5(5/6).
[17] Ben Jemaa R, Mansouri R, Boukholda I, Bellagi A. Experimental investigation and exergy analysis of a triple fluid vapor absorption refrigerator. Energy Convers Manag 2016;124:84–91.
[18] Dincer I, Kanoglu M. Refrigeration systems and applications. 2nd ed. John Willey and Sons, Ltd Publication; 2010.
[19] Dincer I, Rosen MA. Exergy, energy and environment sustainable development. 2nd ed. Elseiver Ltd Publication; 2013.
[20] Bouaziz N, Lounissi D. Energy and exergy investigation of a novel double effect hybrid absorption refrigeration system for solar cooling. Int J Hydrogen Energy 2015;40(39):13849–56.
[21] Terzi R, Tükenmez İ, Kurt E. Energy and exergy analyses of a VVER type nuclear power plant. Int J Hydrogen Energy 2016;41(29):12465–76.
[22] Engineering Equation Solver, EES version 9.908, F-chart software.

Please cite this article in press as: Ben Jemaa R, et al., Energy and exergy investigation of R1234ze as R134a replacement in vapor compression chillers, International Journal of Hydrogen Energy (2016), http://dx.doi.org/10.1016/j.ijhydene.2016.12.010