Nature & Environment
Vol. 19 (2), 2014: 219-231
Website: www.natureandenvironment.com
ISSN (Print) : 2321-810X
ISSN (Online) : 2321-8738

RESEARCH ARTICLE

Method for Improving Thermal Performances of Vapour Compression Refrigeration Systems Using Energy and Exergy Analysis for Reducing Global Warming and Ozone Depletioning Using Ecofriendly Refrigerants

R.S. Mishra
Mechanical Engineering Department, Delhi College of Engineering (Now DTU), Delhi
Email: professor_rsmishra@yahoo.co.in

Received: 2nd June 2014, Revised: 20th June 2014, Accepted: 29th June 2014

ABSTRACT

In this paper the method for improving thermal performance of vapour compression refrigeration system using multiple evaporators and compressors with individual or multiple expansion valves have been considered by using first law and second law analysis. Numerical models have been developed for parallel and series expansion valves in the VCR. The comparison of above systems have been done in terms of first law efficiency, second law efficiency and exergy destruction ratio by using R410a, R290, R600, R600a, R1234yf, R502, R404a, R1234ze, R134a and R152a. it was observed that for the same degree of subcooling, fixed evaporators and condenser temperatures multiple evaporators and compressors with multiple expansion valves system is the best system with comparisons of system with individual expansion valves. The comparison was also done using eight ecofriendly refrigerants and it was found that R600, R600a, R290 and R152A show better performances than other refrigerants for both systems but due to inflammable property of R600 and R600a, R152a is preferred for both systems.
Key Words: *Energy and exergy analysis, thermal performance, global warming*

INTRODUCTION

Refrigeration is a technology which absorbs heat at low temperature and provides temperature below the surrounding by rejecting heat to the surrounding at higher temperature. Simple vapour compression system which consists of four major components compressor, expansion valve, condenser and evaporator in which total cooling load is carried at one temperature by single evaporator but in many applications like large hotels, food storage and food processing plants, food items are stored in different compartment and at different temperatures. Therefore there is need of multi evaporator vapour compression refrigeration system. The systems under vapour compression technology consume huge amount of electricity, this problem can be solved by improving performance of system.

Performance of systems based on vapour compression refrigeration technology can be improved by following:-

The performance of refrigerator is evaluated in term of COP which is the ratio of refrigeration effect to the net work input given to the system. The COP of vapour compression refrigeration system can be improved either by increasing refrigeration effect or by reducing work input given to the system.

It is well known that throttling process in VCR is an irreversible expansion process. Expansion process is one of the main factors responsible for exergy loss in cycle performance because of entering the portion of the refrigerant flashing to vapour in evaporator which will not only reduce the cooling capacity but also increase the size of evaporator. This problem can be eliminated by adopting multi-stage expansion with flash chamber where the flash vapours is removed after each stage of expansion as a consequence there will be increase in cooling capacity and reduce the size of the evaporator.

Work input can also be reduced by replacing multi-stage compression or compound compression with single stage compression. Refrigeration effect can also be increased by passing the refrigerant through subcooler after condenser to evaporator.

Table 1: Represents the ODP and GWP for various refrigerants.

Refrigerant		Atmospheric Lifetime (Years)	ODP	GWP (100 Year)
CFC	CFC-11 (Baseline ODP)	50	1	4000
	CFC-12	102	1	8500
CFC Blend	R-502		0.33	5260
HCFCs	HCFC-22	13.3	0.06	1700
	HCFC-123	1.4	0.02	93
	HCFC-141b	9.4	0.11	630
HFCs	HFC-134a	14.6	0	1300
	HFC-245fa	7.3	0	820
HCs	HC-290 (Propane)	-	0	3
	HC-600a (Isobutene)	-	0	3
	Cyclopentane	-	0	3
HFC Blends	R-404A	-	0	3260
	R-407A	-	0	1770
	R-407C	-	0	1530
	R-410A	-	0	1730

Vapour compression refrigeration system based applications make use of refrigerants which are responsible for greenhouse gases, global warming and ozone layer depletion. Montreal protocol was signed on the issue of substances that are responsible for depleting Ozone layer and discovered how much consumption and production of ozone depletion substances took place during certain time period for both developed and developing countries. Another protocol named as Kyoto aimed to control emission of green house gases in 1997 (Johnson 1998). The relationship between ozone depletion potential and global warming potential is the major concern in the field of GRT (green refrigeration technology) so Kyoto proposed new refrigerants having lower value of ODP and GWP. Internationally a program being pursued to phase out refrigerants having high chlorine content for the sake of global environmental problems (QiyuChen and Prasad 1999): Due to presence of high chlorine content, high global warming potential and ozone depletion potential after 90's CFC and HCFC refrigerants have been restricted. Thus, HFC refrigerants are used nowadays, showing much lower global warming potential value, but still high with respect to non-fluorine refrigerants. Research has recently been focused on development of new refrigerants to replace CFCs and HCFCs. These new working fluids are synthetic compounds-namely hydro-fluorocarbons (HFCs). Although the ozone-depletion potential (ODP) of some HFCs is zero, their global warming potential (GWP)--related to the greenhouse effect-can be large. An alternative to HFCs is the use of naturally occurring substances (refrigerants), namely; ammonia (NH3), hydrocarbons (HCs), carbon dioxide (CO2), water, air. These refrigerants have zero ODP, and the majorities also have zero GWP. However, some of them can be flammable and/or toxic. Table 1 shows the ODP and GWP for various refrigerants. From the table 1.1 It has been observed that R134a, R404A, R407A, R407C and R410C have low ODP and GWP than R12 and R22. Lots of research work has been done for replacing "old" refrigerants with "new" refrigerants (Padilla *et al.* 2010, Spauschus 1988, Ahamed *et al.* 2011, Llopis *et al.* 2010, Arora and Kaushik 2008 and Havelsky 2000).

LITERATURE REVIEW

Reddy *et al.* (2012) performed numerical computation of vapour compression refrigeration system using R134a, R143a, R152a, R404A, R410A, R502 and R507A , for finding the effect of evaporator temperature, degree of subcooling at condenser outlet, superheating of evaporator outlet, vapour liquid heat exchanger effectiveness and degree of condenser temperature on COP and exergetic efficiency using energy- exergy analysis and found that evaporator and condenser temperature have significant effect on both COP and exergetic efficiency and also found that R134a has the better performance while R407C has poor performance in all respect. Saravanakumar and Selladurai (2013) compared the performance between R134a and R290/R600a mixture on a domestic refrigerator which is originally designed to work with R134a and found that R290/R600a hydrocarbon mixture showed higher COP and exergetic efficiency than R134a and also the highest irreversibility obtained in the compressor compare to condenser, expansion valve and evaporator in the vapour compression refrigeration system. Nikolaidis and Probert (1998) studied analytically that change in evaporator and condenser temperatures of two stage vapour compression refrigeration plant using R22 and found that there is a significant effect of plant irreversibility and suggested that there is need for optimizing the conditions imposed upon the condenser and evaporator. Kumar *et al.* (1989) carried out energy and exergy analysis of vapour compression refrigeration system by the use of exergy-enthalpy diagram and performed first law analysis (energy analysis)for calculating the coefficient of performance and exergy analysis (second law analysis) for evaluation of various losses occurred in different components of vapour compression cycle using R11 and R12 as refrigerants. Mastani Joybari *et al.* (2013) performed experiments on a domestic refrigerator originally manufactured by using of 145g of R134a. They concluded that exergetic defect occurred in compressor was highest as compare to other components and through their analysis it has been found that instead of 145g of R134a if 60g of R600a is used in the considered system gave same performance which ultimately result into economical advantages and reduce the risk of flammability of hydrocarbon refrigerants. Anand and Tyagi (2012) carried out detailed exergy analysis of two ton of refrigeration capacity window air conditioning test rig with R22 as working fluid and concluded , that irreversibility in system components will be highest when the system is 100% charged and lowest when 25% charged and irreversibility in compressor is highest among system components. Arora and Kaushik (2008) developed numerical model of actual vapour compression refrigeration system with liquid vapour heat exchanger and carried out energy and exergy analysis on the same in the specific temperature range of evaporator and condenser and concluded that R502 is the best refrigerant compared to R404A and R507A and compressor is the worst component and liquid vapour heat exchanger is best component of the system in case of exergy transfer. Ahamed *et al.* (2011) had performed experiments on domestic refrigerator with hydrocarbons (isobutene and butane) by using energy and exergy analysis and found that energy efficiency ratio of hydrocarbons comparable with R134a but exergy efficiency and sustainability index of hydrocarbons much higher than that of R134a at considered evaporator temperature. It was also found that compressors shows highest system defect (69%) among components of considered in the system. Ahamed et al. (2012) emphasized on use of hydrocarbons and mixture of hydrocarbons and R134a in vapour compression refrigeration system and found that compressor shows much higher exergy destruction as compared to rest of components in the vapour compression refrigeration system and this exergy destruction can be minimized by using of nanofluid and nanolubricants in compressor. Bolaji *et al.* (2011) had done experimentally comparative analysis of R32, R152a and R134a refrigerants in vapour compression refrigerator and concluded that R32 shows lowest performance whereas R134a and R152a showing nearly same performance but best performance was obtained of system using R152a. Yumrutas *et al.* (2002) carried out exergy analysis based investigation on VCR for effect of condensing and evaporating temperature on vapour compression refrigeration cycle in terms of pressure losses, COP, second law efficiency and exergy losses and found that the variation in temperature of condenser as well as have negligible effect on exergy losses of compressor and expansion valve, also first law efficiency and exergy efficiency increase but total exergy losses of system decrease with increase in evaporator and condenser temperature. Padilla *et al.* (2010) carried out the exergy analysis of domestic vapour compression refrigeration system with R12 and R413A and found that performance in terms of power consumption, irreversibility and exergy efficiency of R413A is better than R12, and also concluded that R12 can be replaced with

R413A in domestic vapour compression refrigeration system. Getu and Bansal (2008) optimized the design and operating parameters of like condensing temperature, subcooling temperature, evaporating temperature, superheating temperature and temperature difference in cascade heat exchanger R744-R717 cascade refrigeration system and regression analysis was also done to obtain optimum thermodynamic parameters of same system. Spatz and Motta (2004) had mainly focused on replacement of R12 with R410a through experimental investigation of medium temperature vapour compression refrigeration cycles. In terms of thermodynamic analysis, comparison of heat transfer and pressure drop characteristics, R410a gives best performance among R12, R404a and R290a. Mohanraj *et al.* (2009) concluded through experimental results of domestic refrigerator they arrived on conclusions that under different environmental temperatures COP of system using mixture of R290 and R600a in the ratio of 45.2: 54.8 by weight showing up to 3.6% greater than same system using R134a, also discharge temperature of compressor with mixture of R290 and R600a is lower in the range of 8.5-13.4K than same compressor with R134a. Han et al. (2007) Through experimental results revealed that there could be replacement of R407C under different working conditions in vapour compression refrigeration system having rotor compressor by using mixture of R32/R125/R161 showing higher COP, less pressure ratio and slightly high discharge compressor temperature without any modification in the same system. Halimic *et al.* (2003) had compared the thermal performance of R401A, R290 and R134A with R12 by using in vapour compression refrigeration system, which is originally designed for R12.Due to similar performance of R134a in comparison with R12, R134A can be replaced in the same system without any medication in the system components. But in reference to green house impact R290 presented best results.

Cabello *et al.* (2007) studied about the effect of operating parameters on first law efficiency (COP), work input and cooling capacity of single-stage vapour compression refrigeration system. There is great influence on energetic parameters due change in suction pressure, condensing and evaporating temperatures. Cabello *et al.* (2007) discussed the effect of condensing pressure, evaporating pressure and degree of superheating was experimentally investigated on single stage vapour compression refrigeration system using R22, R134a and R407C.It was observed that mass flow rate is greatly affected by change in suction conditions of compressor in results on refrigeration capacity because refrigeration capacity depended on mass flow rate through evaporator. It was also found that for higher compression ratio R22 gives lower COP than R407C. Stanciu and Alvarado (2005) carried out numerical and graphical investigation on single stage vapour compression refrigeration system for studied refrigerants (R22, R134a, R717, R507a, R404a) in terms of COP, compressor work, exergy efficiency and refrigeration effect. Effect of subcooling, superheating and compression ratio are also studied on the same system using considered refrigerants and also presented system optimization when working with specific refrigerant in the vapour compression.

Based on the literature it was observed that researchers have gone through detailed first law analysis in terms of coefficient of performance and second law analysis in term of exergetic efficiency of simple vapour compression refrigeration system with single evaporator. Researchers did not go through the irreversibility analysis or second law analysis of: Simple VCR with flash intercooler, flash chamber, water intercooler, liquid subcooler and stages in compression (double stage and triple stage) and multiple evaporators systems with multi-stage expansion and compound compression in vapour compression refrigeration systems.

To improve thermal performance of vapour compression refrigeration systems (both single and multiple evaporator system) by improving (i) First law efficiency, (ii) second law efficiency, (iii) reduction of system defect in components of system which results into reduction of work input and (iv) detailed analysis of vapour compression refrigeration systems using ecofriendly refrigerants. This paper mainly deals the energy and exergy analysis of multiple evaporators and compressors with individual expansion valves (system-1) and multiple evaporators and compressors with multiple expansion valves (system-2) vapour compression refrigeration systems for finding irreversibility of the systems for improvement in system designs.

Models Description of Multiple Evaporators and Compressors with Individual Expansion Valves (System-1) and Multiple Evaporators and Compressors with Multiple Expansion Valves (System-2) Vapour Compression Refrigeration Systems

The multiple evaporators and compressors with individual expansion valves vapour compression refrigeration system (system-1) consists of compressors (C_1, C_2, C_3) throttle valves (TV_1, TV_2, TV_3), condenser and evaporators(EP_1, EP_2, EP_3) as shown in Fig.1(a).The pressure versus enthalpy chart for this system is shown in Fig.1(b). In this system all refrigerants coming out in point '77' from subcooler distributed by mass $\dot{m}_1$, $\dot{m}_2$, $\dot{m}_3$ to expansion valves TV_1, TV_2, and TV3 respectively. Both liquid and vapour formed by TV_1 ,TV_2 ,TV_3 represented by point '10', '9' and '8' take care the load of EP_1 ,EP_2 and EP_3 respectively. The low pressure vapours formed by EP_1 ,EP_2 and EP_3 supplied to the compressor C_1 ,C_2 and C_3 represented by point '1', '3' and '5' respectively. The high pressure vapours formed by compressor C_1 ,C_2 and C_3 respectively represented by points '2', '4' and '6' .Then high pressure vapours coming out from compressor C_1 , C_1 , C_1 collectively enter through the condenser by point '7'.

The main components of multiple evaporators and compressors with individual expansion valves vapour compression refrigeration system (system-2) are compressors (C_1, C_2, C_3) throttle valves (TV_1, TV_2, TV_3), condenser and evaporators (EP_1, EP_2, EP_3) as shown in Fig. 2(a).The corresponding pressure versus enthalpy chart for this system is shown in Fig. 2(b).In this system all the refrigerant from the condenser at point 'g' followed by the subcooler exit at point 'gg' flows through the throttle valve TV3 where its pressure is reduced from the condenser pressure of the third evaporator. All the vapours formed after leaving the expansion valve TV3 at point 'h' plus enough liquid to take care of the load of evaporator EP3.The remaining refrigerant then enter at point 'i' through the expansion valve TV2 where its pressure is reduced from the pressure of the third evaporator to the pressure of the second evaporator. Again all the vapour formed after leaving the expansion valve TV_2 at point 'j'plus enough liquid to take care of the load of evaporator EP_2 passes through this evaporator. The remaining liquid now enters at point 'k' through the expansion valve TV_1 and exit at point 'l'which supplied it to the first evaporator EP_1. The vapours formed by EP_1, EP_2, EP_3 supplied to compressors C_1, C_2 and C_3 shown by point 'a', 'c' and 'e' respectively. High pressure vapours formed by compressors C_1, C_2 and C_3 as is shown by points 'b', 'd' and 'f' respectively supplied to the condenser.

First Law Analysis (COP & Work Input Analysis) of Multiple Evaporators and Compressors with Individual or Multiple Expansion Valves Vapour Compression Refrigeration Systems

The multiple evaporators and compressors with individual or multiple expansion valves vapour compression refrigeration system as shown in Fig. 1 and Fig. 2 respectively. From the energy analysis point of view first law of thermodynamics, evaluate the performance of the vapour compression systems as given below:-

System-1

$$\dot{m}_{e1} = \dot{m}_{c1} \quad \text{..............} (1)$$

$$\dot{m}_{e2} = \dot{m}_{c2} \quad \text{..............} (2)$$

$$\dot{m}_{e3} = \dot{m}_{c3} \quad \text{..............} (3)$$

$$\dot{Q}_{e\_1} = \dot{Q}_{e1} + \dot{Q}_{e2} + \dot{Q}_{e3} \quad \text{..............} (4)$$

$$\dot{W}_{comp1} = \dot{m}_{c1}(\psi_2 - \psi_1) \quad \text{..............} (5)$$

$$\dot{W}_{comp2} = \dot{m}_{c2}(\psi_4 - \psi_3) \quad \text{..............} (6)$$

$$\dot{W}_{comp3} = \dot{m}_{c3}(\psi_6 - \psi_5) \quad \text{..............} (7)$$

$$\dot{W}_{comp\_1} = \dot{W}_{comp1} + \dot{W}_{comp2} + \dot{W}_{comp3} \quad \text{..............} (8)$$

$$COP\_1 = \frac{\dot{Q}_{e\_1}}{\dot{W}_{comp\_1}} \qquad \text{.............. (9)}$$

System-2

$$\dot{m}_{c1} = \dot{m}_{e1} \qquad \text{.............. (10)}$$

$$\dot{m}_{c2} = \dot{m}_{e2} = \dot{m}_2 + \dot{m}_{e1}\left(\frac{\varphi_j}{1-\varphi_j}\right) \qquad \text{.............. (11)}$$

$$\dot{m}_2 = \left(\frac{\dot{Q}_{e2}}{\psi_c - \psi_j}\right) \qquad \text{.............. (12)}$$

$$\dot{m}_{c3} = \dot{m}_{e3} = \dot{m}_3 + (\dot{m}_{e1} + \dot{m}_{e2})\left(\frac{\varphi_h}{1-\varphi_h}\right) \qquad \text{.............. (13)}$$

$$\dot{m}_3 = \left(\frac{\dot{Q}_{e3}}{\psi_e - \psi_h}\right) \qquad \text{.............. (14)}$$

$$\dot{Q}_{e\_2} = \dot{Q}_{e1} + \dot{Q}_{e2} + \dot{Q}_{e3} \qquad \text{.............. (15)}$$

$$\dot{W}_{comp1} = \dot{m}_{c1}(\psi_b - \psi_a) \qquad \text{.............. (16)}$$

$$\dot{W}_{comp2} = \dot{m}_{c2}(\psi_d - \psi_c) \qquad \text{.............. (17)}$$

$$\dot{W}_{comp3} = \dot{m}_{c3}(\psi_f - \psi_e) \qquad \text{.............. (18)}$$

$$\dot{W}_{comp\_2} = \dot{W}_{comp1} + \dot{W}_{comp2} + \dot{W}_{comp3} \qquad \text{.............. (19)}$$

$$COP\_2 = \frac{\dot{Q}_{e\_2}}{\dot{W}_{comp\_2}} \qquad \text{.............. (20)}$$

Fig. 1 (a): Schematic diagram of multiple evaporators at different temperatures with individual compressors and individual expansion valves

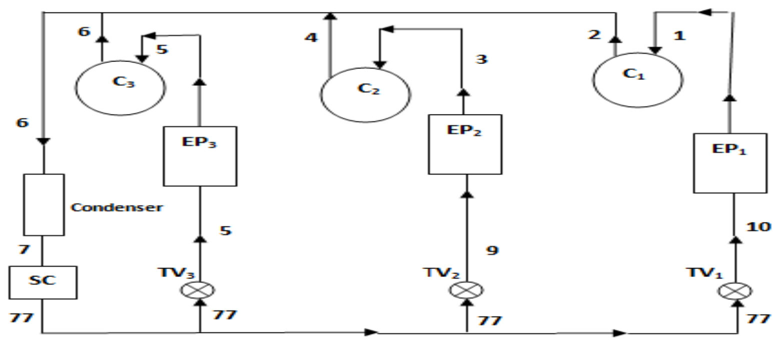


Fig. 1 (b): Pressure enthalpy diagram of multiple evaporators at different temperatures with individual compressors and individual expansion valves

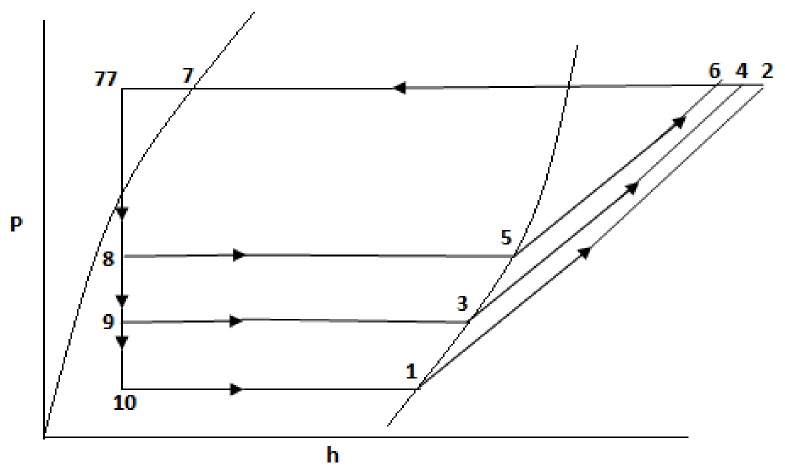


Fig. 2 (a): Schematic diagram of multiple evaporators at different temperatures with individual compressors and multiple expansion valves

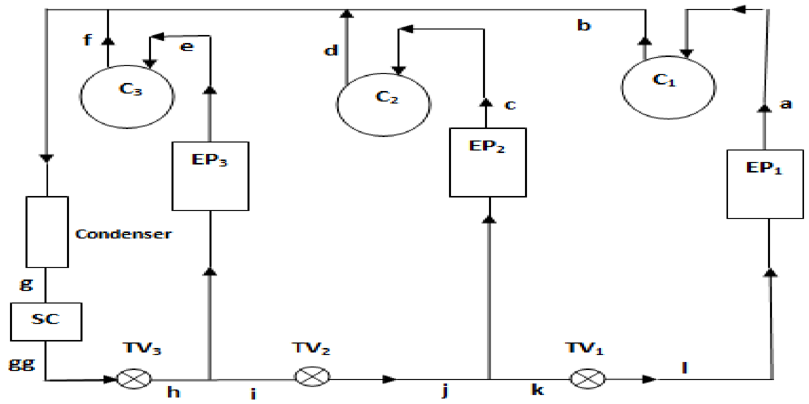
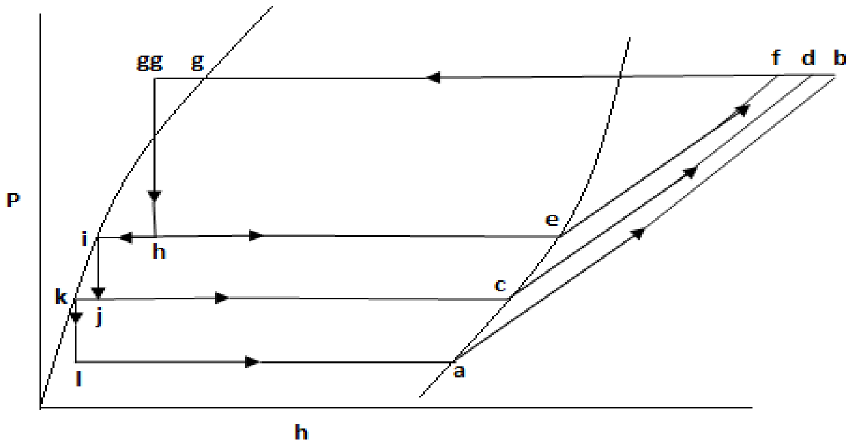


Fig. 2 (b): Pressure enthalpy diagram of multiple evaporators at different temperatures with individual compressors and multiple expansion valves



Second Law Analysis of Multiple Evaporators and Compressors with Individual or Multiple Expansion Valve Vapour Compression Refrigeration System

The concept of exergy was given by Second law of thermodynamics. Exergy is the measure of usefulness, quality or potential of a stream to cause change and an effective measure of the potential of a substance to impact the environment (12).

1. EXERGY DESTRUCTION (ED)

Exergy destruction in each component of the multiple evaporators and compressors with individual expansion valves vapour compression refrigeration system (System-1) is evaluated as per Eqs. (21)– (32) given below:-

Evaporators

(EP_1) System-1

$$\dot{ED}_{e1} = \dot{E}_{x10} + \dot{Q}_{e1}\left(1 - \frac{T_0}{T_{r1}}\right) - \dot{E}_{x1}$$

$$= \dot{m}_{e1}(\psi_{10} - T_0 s_{10}) + \dot{Q}_{e1}\left(1 - \frac{T_0}{T_{r1}}\right) - \dot{m}_{e1}(\psi_1 - T_0 s_1) \quad \text{............... (21)}$$

(EP_2) System-1

$$\dot{ED}_{e2} = \dot{E}_{x9} + \dot{Q}_{e2}\left(1 - \frac{T_0}{T_{r2}}\right) - \dot{E}_{x3}$$

$$= \dot{m}_{e2}(\psi_9 - T_0 s_9) + \dot{Q}_{e2}\left(1 - \frac{T_0}{T_{r2}}\right) - \dot{m}_{e2}(\psi_3 - T_0 s_3) \quad \text{............... (22)}$$

(EP_3) System-1

$$\dot{ED}_{e3} = \dot{E}_{x8} + \dot{Q}_{e3}\,(1 - \frac{T_0}{T_{r3}}) - \dot{E}_{x5}$$
$$= \dot{m}_{e3}(\psi_8 - T_0 s_8) + \dot{Q}_{e3}\left(1 - \frac{T_0}{T_{r3}}\right) - \dot{m}_{e3}(\psi_5 - T_0 s_5) \quad \text{..............} (23)$$

Compressors

(C_1) System-1

$$\dot{ED}_{comp1} = \dot{E}_{x1} + \dot{W}_{comp1} - \dot{E}_{x2} = \dot{m}_{c1}(T_0(s_2 - s_1)) \quad \text{...............} (24)$$

(C_2) System-1

$$\dot{ED}_{comp2} = \dot{E}_{x3} + \dot{W}_{comp2} - \dot{E}_{x4} = \dot{m}_{c2}(T_0(s_4 - s_3)) \quad \text{...............} (25)$$

(C_3) System-1

$$\dot{ED}_{comp3} = \dot{E}_{x5} + \dot{W}_{comp3} - \dot{E}_{x6} = \dot{m}_{c3}\big(T_0(s_6 - s_5)\big) \quad \text{...............} (26)$$

Condenser

(Condenser) System-1

$$\dot{ED}_c = (\dot{E}_{x2} - \dot{E}_{x7}) + (\dot{E}_{x4} - \dot{E}_{x7}) + (\dot{E}_{x6} - \dot{E}_{x7})$$
$$= \dot{m}_{c1}\big((\psi_2 - T_0 s_2) - (\psi_7 - T_0 s_7)\big) + \dot{m}_{c2}\big((\psi_4 - T_0 s_4) - (\psi_7 - T_0 s_7)\big)$$
$$+ \dot{m}_{c3}\big((\psi_6 - T_0 s_6) - (\psi_7 - T_0 s_7)\big) \quad \text{...............} (27)$$

Subcooler

(SC) System-1

$$\dot{ED}_{sc} = \dot{E}_{x7} - \dot{E}_{x77}$$
$$= (\dot{m}_{c1} + \dot{m}_{c2} + \dot{m}_{c3})((\psi_7 - T_0 s_7) - (\psi_{77} - T_0 s_{77})) \quad \text{...............} (28)$$

Throttle valves

(TV_1) System-1

$$\dot{ED}_{TV_1} = \dot{E}_{x77} - \dot{E}_{x10} = \dot{m}_{c1}(T_0(s_{10} - s_{77})) \quad \text{...............} (29)$$

(TV-2) System-1

$$\dot{ED}_{TV_2} = \dot{E}_{x77} - \dot{E}_{x9} = \dot{m}_{c2}(T_0(s_9 - s_{77})) \quad \text{...............} (30)$$

(TV-3) System-1

$$\dot{ED}_{TV_3} = \dot{E}_{x77} - \dot{E}_{x8} = \dot{m}_{c3}(T_0(s_8 - s_{77})) \quad \text{...............} (31)$$

The total irreversibility in the system-2 is the sum of irreversibility in each component of the system and is given by-

$$\sum \dot{ED}_k = \dot{ED}_{e1} + \dot{ED}_{e2} + \dot{ED}_{e3} + \dot{ED}_{comp1} + \dot{ED}_{comp2} + \dot{ED}_{comp3}$$
$$+ \dot{ED}_c + \dot{ED}_{sc} + \dot{ED}_{TV_1} + \dot{ED}_{TV_2} + \dot{ED}_{TV_3} \quad \text{...............} (32)$$

Similarly exergy destruction in each component of the multiple evaporators and compressors with multiple expansion valves vapour compression refrigeration system (System-2) is evaluated as per Eqs. 33–44 given below:-

Evaporators

(EP1) System-2

$$\dot{ED}_{e1} = \dot{E}_{xl} + \dot{Q}_{e1}\left(1 - \frac{T_0}{T_{r1}}\right) - \dot{E}_{xa}$$
$$= \dot{m}_{e1}(\psi_l - T_0 s_l) + \dot{Q}_{e1}\left(1 - \frac{T_0}{T_{r1}}\right) - \dot{m}_{e1}(\psi_a - T_0 s_a) \text{..............} (33)$$

(EP2) System-2

$$\dot{ED}_{e2} = \dot{E}_{xj} + \dot{Q}_{e2}\left(1 - \frac{T_0}{T_{r2}}\right) - \dot{E}_{xc}$$
$$= \dot{m}_{e2}(\psi_j - T_0 s_j) + \dot{Q}_{e2}\left(1 - \frac{T_0}{T_{r2}}\right) - \dot{m}_{e2}(\psi_c - T_0 s_c) \quad \text{...............} (34)$$

$(EP3)_{System-2}$

$$\dot{ED}_{e3} = \dot{E}_{xh} + \dot{Q}_{e3}\left(1 - \frac{T_0}{T_{r3}}\right) - \dot{E}_{xe}$$
$$= \dot{m}_{e3}(\psi_h - T_0 s_h) + \dot{Q}_{e3}\left(1 - \frac{T_0}{T_{r3}}\right) - \dot{m}_{e3}(\psi_e - T_0 s_e) \quad \text{..........} (35)$$

Compressors

$(C\text{-}1)_{System-2}$

$$\dot{ED}_{comp1} = \dot{E}_{xa} + \dot{W}_{comp1} - \dot{E}_{xb} = \dot{m}_{c1}(T_0(s_b - s_a)) \quad \text{...............} (36)$$

$(C\text{-}2)_{System-2}$

$$\dot{ED}_{comp2} = \dot{E}_{xc} + \dot{W}_{comp2} - \dot{E}_{xd} = \dot{m}_{c2}(T_0(s_d - s_c)) \quad \text{...............} (37)$$

$(C\text{-}3)_{System-2}$

$$\dot{ED}_{comp3} = \dot{E}_{xe} + \dot{W}_{comp3} - \dot{E}_{xf} = \dot{m}_{c3}(T_0(s_f - s_e)) \quad \text{...............} (38)$$

Condenser

$(Condenser)_{System-2}$

$$\dot{ED}_{cond} = (\dot{E}_{xb} - \dot{E}_{xg}) + (\dot{E}_{xd} - \dot{E}_{xg}) + (\dot{E}_{xf} - \dot{E}_{xg})$$
$$= \dot{m}_{c1}\left((\psi_b - T_0 s_b) - (\psi_g - T_0 s_g)\right) + \dot{m}_{c2}\left((\psi_d - T_0 s_d) - (\psi_g - T_0 s_g)\right)$$
$$+\dot{m}_{c3}\left((\psi_f - T_0 s_f) - (\psi_g - T_0 s_g)\right) \quad \text{...............} (39)$$

$(SC)_{System-2}$

$$\dot{ED}_{sc} = \dot{E}_{xg} - \dot{E}_{xgg}$$
$$= (\dot{m}_{c1} + \dot{m}_{c2} + \dot{m}_{c3})\left((\psi_g - T_0 s_g) - (\psi_{gg} - T_0 s_{gg})\right) \text{...............} (40)$$

Throttle valves

$(TV\text{-}1)_{System-2}$

$$\dot{ED}_{TV_1} = \dot{E}_{xk} - \dot{E}_{xl} = \dot{m}_{c1}(T_0(s_l - s_k)) \quad \text{...............} (41)$$

$(TV\text{-}2)_{System-2}$

$$\dot{ED}_{TV_2} = \dot{E}_{xi} - \dot{E}_{xj} = (\dot{m}_{c1} + \dot{m}_{c2})(T_0(s_j - s_i)) \quad \text{...............} (42)$$

$(TV\text{-}3)_{System-2}$

$$\dot{ED}_{TV_3} = \dot{E}_{xgg} - \dot{E}_{xh}$$
$$= (\dot{m}_{c1} + \dot{m}_{c2} + \dot{m}_{c3})(T_0(s_h - s_{gg})) \quad \text{...............} (43)$$

The total irreversibility in the system-2 is the sum of irreversibility in each component of the system and is given by-

$$\sum \dot{ED}_k = \dot{ED}_{e1} + \dot{ED}_{e2} + \dot{ED}_{e3} + \dot{ED}_{comp1} + \dot{ED}_{comp2} + \dot{ED}_{comp3}$$
$$+\dot{ED}_c + \dot{ED}_{sc} + \dot{ED}_{TV_1} + \dot{ED}_{TV_2} + \dot{ED}_{TV_3} \quad \text{...............} (44)$$

2. EXERGETIC EFFICIENCY

$$\eta_{ex} = \frac{\text{Exergy in product}}{\text{Exergy of fuel}} = \frac{\dot{EP}}{\dot{EF}} \quad \text{...............} (45)$$

For the multi evaporator vapour compression refrigeration system, the product is the exergy of the heat abstracted in to the evaporators' i.e.$Q_e = Q_{e1} + Q_{e2} + Q_{e3}$ from the space to be cooled at temperature T_r, and exergy of fuel is actual compressor work input. Hence, exergetic efficiency is given by-

$$\dot{EP} = \dot{Q}_{e1} + \dot{Q}_{e2}\left|\left(1 - \frac{T_0}{T_{r2}}\right)\right| + \dot{Q}_{e3}\left|\left(1 - \frac{T_0}{T_{r3}}\right)\right| \quad \text{...............} (46)$$

$$\eta_{ex} = \frac{\dot{Q}_{e1}\left|\left(1-\frac{T_0}{T_{r1}}\right)\right| + \dot{Q}_{e2}\left|\left(1-\frac{T_0}{T_{r2}}\right)\right| + \dot{Q}_{e3}\left|\left(1-\frac{T_0}{T_{r3}}\right)\right|}{(\dot{W}_{comp1}+\dot{W}_{comp2}+\dot{W}_{comp3})} \quad \text{............... (47)}$$

3. EXERGY DESTRUCTION RATIO (EDR)

EDR is the ratio of total exergy destruction in the system to exergy in the product (9) and it is given by Eq. (48). EDR is related to the exergetic efficiency by Eq. (49)-

$$EDR = \frac{\dot{ED}_{total}}{\dot{EP}} = \frac{1}{\eta_{ex}} - 1 \quad \text{............... (48)}$$

$$\eta_{ex} = \frac{1}{1+EDR} \quad \text{............. (49)}$$

RESULTS AND DISCUSSIONS

Using Engineering Equation Solver software eq. (13) a numerical model has been developed for comparison of performance parameters of systems (system 1 & system-2).
The performance parameters are evaluated by considering following specifications of the systems given below:-

1. Degree of sub cooling (ΔT_{sc}): 10K.
2. Adiabatic efficiency of compressor (η_{comp}): 75%.
3. Difference between evaporator and space temperature (T_r-T_e): 5K.
4. Temperature of evaporators EP_1, EP2 and EP3 are 263K ,273K and 283K respectively
5. Condenser temperature (T_c): 313K
6. Dead state temperature (T_0): 298K
7. Dead state enthalpy (ψ_0) and entropy (s_0) of the refrigerants have been calculated corresponding to the dead state temperature (T_0) of 298K.
8. Loads on the evaporators EP1, EP2 and EP3 are 35KW, 70KW and 105KW respectively.

Fig. 3 presents the comparison of coefficient of performance of multiple evaporators and compressors with individual expansion valves (System-1) and multiple evaporators and compressors with multiple expansion valves (System-2) for different refrigerants. COP of system-2 is better by comparison of system-1 for all considered refrigerants.R600 shows highest COP among all considered refrigerants for both systems. Though in System-1 R152a shows second highest COP among all refrigerants but as it has the lowest flammability in comparison with R600 and for system-2 R152a, R600a and R290 show almost same COP but lower than R600 and again as R152a has lowest flammability among R600, R600a and R290.The maximum difference observed between COPs of R600 and R404A is 11.65% for system-1 and 9% for system-2.
Fig.4 presents the comparison of exergetic efficiency (second law efficiency) for system-1 & system-2 for different refrigerants. It was observed that exergetic efficiency of system-2 for all refrigerants is better as comparison with system-1.As clear from the Eq.47 that exergetic efficiency is the ratio of sum of product of all evaporators to the total work input, the sum product of all evaporators in system-2 is higher with comparison to the system-1 because arrangement of expansion valves in system-2 in such a fashion that flashed vapour at the pressure of the high temperature evaporator is not allowed to go to the lower temperature evaporator and increase the products of evaporators without affecting work input, thus improving its exergetic efficiency. R404 shows lowest and R600 shows highest second law efficiency for both systems. The maximum difference observed between second law efficiency of R600 and R404A is 11% of system-1 and 9.2% of system-2. It is observed from Fig. 5 that variation of EDR and exergetic efficiency is almost opposite. This fact is also cleared from Eq. (49) that exergetic efficiency is inversely proportional to ED.

Fig. 3: Comparison of COP for system-1 &2 for different ecofriendly refrigerants

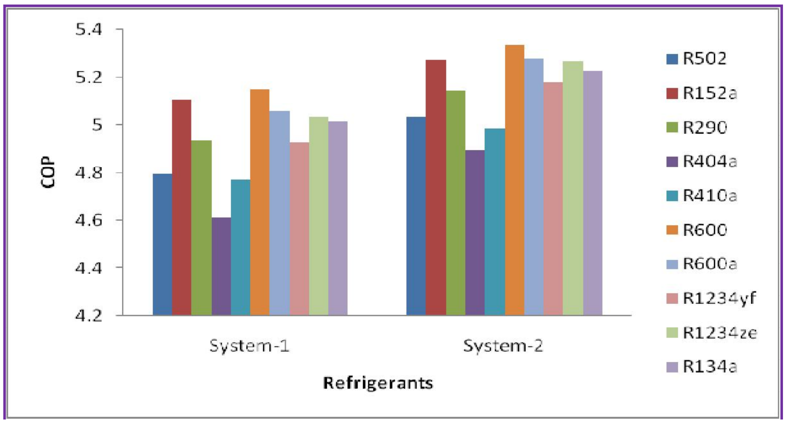


Fig. 4: Comparison of second law efficiency (η_{II}) for system-1 &2 for different ecofriendly refrigerants

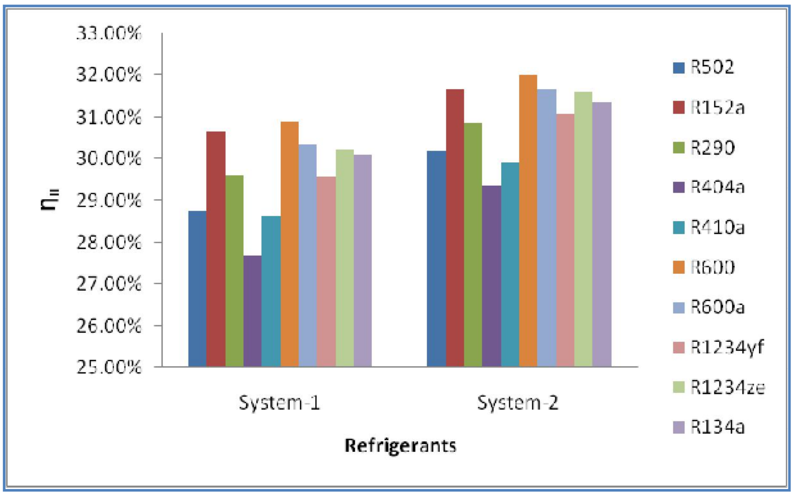
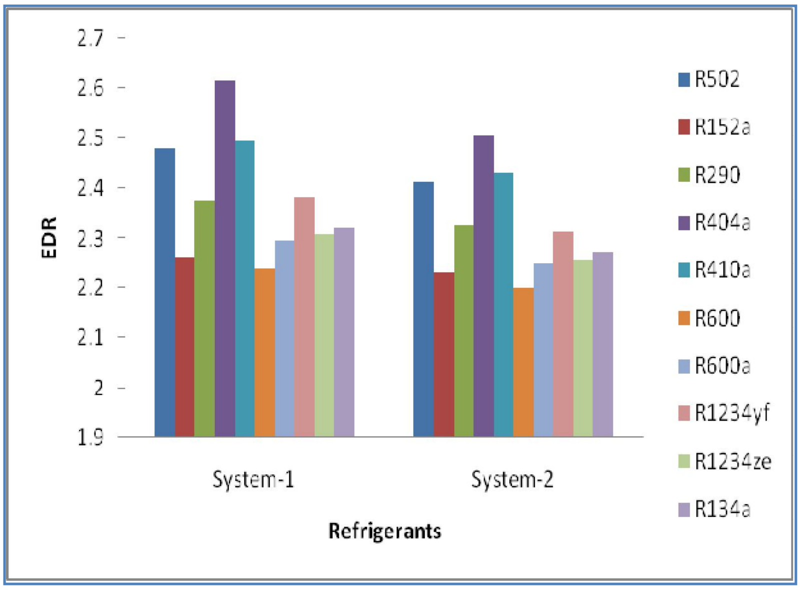


Fig. 5: Comparison of exergy destruction ratio (EDR) for system-1 &2 for different ecofriendly refrigerants



NOMENCLATURE

$\dot{E}P$	exergy rate of product (kW)	ODP	ozone depletion potential
$\dot{E}F$	exergy rate of fuel (kW)	S	specific entropy (kJ/kgK)
$\dot{Q}$	rate of heat transfer (kW)	C	compressor
$\dot{W}$	work rate (kW)	Ψ	specific enthalpy (kJ/kg)
ΔT_{sc}	degree of subcooling	K	kth component
CFC	chlorofluorocarbon	ev	expansion valve
comp	compressor	Φ	dryness fraction(non-dimensional)
cond	condenser	EP	evaporator
COP	coefficient of performance (non-dimensional)	0	dead state
E	evaporator	sc	subcooler
E_x	exergy rate of fluid (kW)	$\dot{E}D$	rate of exergy destruction (kW)
ex	exergetic	$\dot{m}$	mass flow rate (kg/s)
HCFC	hydrochlorofluorocarbon	r	refrigerant, space to be cooled
HFC	hydrofluorocarbon	H	efficiency (non-dimensional)
II	second law efficiency	GWP	global warming potential
T	temperature (K)	VCR	vapour compression refrigeration
TV	throttle valve		

CONCLUSIONS

Thermodynamic analysis in terms of energy and exergy analysis of multiple evaporators and compressors with individual expansion valves (system-1) and multiple evaporators and compressors with multiple expansion valves (system-2) have been carried out and following conclusions was drawn from present investigation. For same degree of subcooling, fixed evaporators and condenser temperatures system-2 is the best system with comparisons of system-1.

R600, R600a and R152A show better performances than other refrigerants for both systems (system-1 & system-2) but due to inflammable property of R600 and R600a, R134a is preferred for both systems. First law efficiency and second law efficiency of system-2 is 3%-6% higher than System-1.

REFERENCES

1. Ahamed J.U., Saidur R. and Masjuki H.H. (2011): A review on exergy analysis of vapor compression refrigeration system. Int J Renewable and sustainable energy reviews, 15: 1593-1600.
2. Ahamed J.U., Saidur R. and Masjuki H.H. (2011): A review on exergy analysis of vapor compression refrigeration system. Int J Renewable and sustainable energy reviews, 15: 1593-1600.
3. Ahamed J.U., Saidur R., Masjuki H.H. and Sattar M.A. (2012): An analysis of energy, exergy and sustainable development of a vapour compression refrigeration system using hydrocarbon. International journal of Green energy, 9: 707-717.
4. Anand S. and Tyagi S.K. (2012): Exergy analysis and experimental study of a vapour compression refrigeration cycle. Int J Therm Anal Calorim, 110: 961-971.
5. Arora A. and Kaushik S.C. (2008): Theoretical analysis of a vapour compression refrigeration system with R502, R404A and R507A. Int J Refrigeration, 31: 998-1005.
6. Bolaji B.O., Akintunde M.A. and Falade T.O. (2011): Comparative analysis of performance of three ozone-friends HFC refrigerants in a vapor compression refrigerator. International Journal of Sustainable Energy & Environment, 2: 61-64.
7. Cabello R., Navarro-Esbrı J., Llopis R. and Torrella E. (2007): Analysis of the variation mechanism in the main energetic parameters in a single stage vapour compression plant. International Journal of Applied Thermal Engineering, 27: 167-176.
8. Cabello R., Torrella E. and Navarro-Esbr J. (2004): Experimental evaluation of a vapour compression plant performance using R134a, R407C and R22 as working fluids. Int J Applied Thermal Engineering, 24: 1905-1917.
9. Camelia Stanciu, Adina Gheorghian, Dorin Stanciu and Alexandru Dobrovicescu (2011): Exergy analysis and refrigerant effect on the operation and performance lomits of a one stage vapour compression refrigeration system.Termotehnica, 1: 36-42.
10. Getu H.M. and Bansal P.K. (2008): Thermodynamic analysis of an R744-R717 cascade refrigeration system. Int J Refrigeration, 31: 45-54.

11. Halimic E., Ross D., Agnew B., Anderson A. and Potts I. (2003): A comparison of the operating performance of alternative refrigerants. Int J Applied Thermal Engineering, 23: 1441-1451.

12. Han X.H., Wang Q., Zhu Z.W. and Chen G.M. (2007): Cycle performance study on R32/R125/R161 as an alternative refrigerant to R407C. Int J Applied Thermal Engineering, 27: 2559-2565.

13. Havelsky V. (2000): Investigation of refrigerating system with R12 refrigerant replacements .Int J Applied Thermal Engineering, 20: 133-140.

14. Johnson E. (1998): Global warming from HFC. Environ. Impact Asses., 18: 485-492.

15. Kumar S., Prevost M. and Bugarel R. (1989): Exergy analysis of a vapour compression refrigeration system. Heat Recovery Systems & CHP, 9: 151-157.

16. Llopis R., Torrella E., Cabello R. and Sánchez D. (2010): Performance evaluation of R404A and R507A refrigerant mixtures in an experimental double-stage of vapour compression plant. Int J Applied Energy, 87: 1546-1553.

17. MastaniJoybari Md., SadeghHatamipour Md., Amir Rahimi and Fatemeh Ghadiri Modarres (2013): Exergy analysis and optimization of R600a as a replacement of R134a in a domestic refrigerator system. International Journal of refrigeration, 36: 1233-1242.

18. Mohanraj M., Jayaraj S., Muraleedharan C. and Chandrasekar P. (2009): Experimental investigation of R290/R600a mixture as an alternative to R134a in a domestic refrigerator. International Journal of Thermal Sciences, 48: 1036-1042.

19. Nikolaidis C. and Probert D. (1998): Exergy method analysis of a two-stage vapour-compression refrigeration-plants performance. Int J Applied Thermal Engineering, 60: 241-256.

20. Padilla M., Revellin R. and Bonjour J. (2010): Exergy analysis of R413A as replacement of R12 in a domestic refrigeration system. Int J Energy Conversion and Management, 51: 2195-2201.

21. Padilla M., Revellin R. and Bonjour J. (2010): Exergy analysis of R413A as replacement of R12 in a domestic refrigeration system. Int J Energy Conversion and Management, 51: 2195-2201.

22. QiyuChen and Prasad R.C. (1999): Simulation of a vapour compression refrigeration cycles HFC134A and CFC12. Int Comm.Heat Mass Transfer, 26: 513-521.

23. Reddy V.S, Panwar N.L. and Kaushik S.C. (2012): Exergy analysis of a vapour compression refrigeration system with R134a, R143a, R152a, R404A, R407C, R410A, R502 and R507A. Clean Techn Environ Policy, 14: 47-53.

24. Saravanakumar R. and Selladurai V. (2013):Exergy analysis of a domestic refrigerator using eco-friendly R290/R600a refrigerant mixture as an alternative to R134a. Int J Therm Anal Calorim.

25. Spatz Mark W. and Motta Samuel F. Yana (2004): An evaluation of options for replacing HCFC-22 in medium temperature refrigeration systems. Int J Refrigeration, 27: 475-483.

26. Spauschus H.O. (1988): HFC 134a as a substitute refrigerant for CFC 12. Int J of Refrigeration, 11: 389-392.

27. Stanciu Klein A. and Alvarado F. (2005): Engineering Equation Solver, Version 7.441. F Chart Software, Middleton, WI.2005.

28. Yumrutas R., Kunduz M. and Kanoglu M. (2002): Exergy analysis of vapor compression refrigeration systems. Exergy, an International Journal, 2: 266-272.