METHODS FOR IMPROVING THERMAL PERFORMANCE OF VAPOUR COMPRESSION REFRIGERATION SYSTEM USING MULTIPLE EVAPORATORS COMPRESSORS SYSTEM

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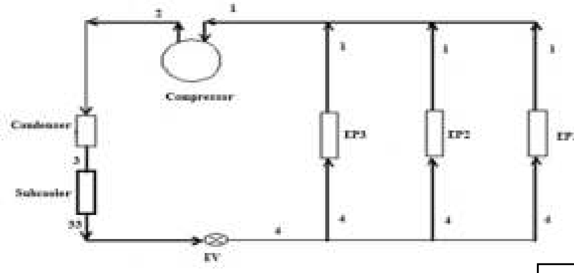
Abstract

The methods for improving first law and second law efficiency have been considered in this paper. Detailed energy and exergy analysis of multi-evaporators at different temperatures with multiple compressors and multiple expansion valves in parallel and series with intercooler and flash chambers in the six type vapour compression refrigeration systems have been done in terms of performance parameter for R410a, R290, R600, R600a, R1234yf, R502, R404a and R152a refrigerants. The numerical computations have been carried out for six systems. It was observed that first law and second law efficiency improved by 22% . It was also observed that performance of above six systems using R600 and R152a nearly matching same values under the accuracy of 5% can be used in the above system .But difficulties using R600, R290 and R600a have flammable problems therefore safety measures are required using these refrigerants, therefore R152a refrigerant is recommended.

Keywords*- Vapour compression refrigeration systems, First and second law analysis,, Irreversibility analysis in VCR,*

INTRODUCTION

It is well known the fact that after 90's CFC and HCFC refrigerants have been forbidden due to chlorine content and their high ozone depleting potential (ODP) and global warming potential (GWP). Thus, HFC refrigerants are used nowadays, presenting a much lower GWP value, but still high with respect to non-fluorine refrigerants. Many research papers have been published on this subject, of replacing "old" refrigerants with "new" ones [1-6]. Lately, many papers focused on researches about finding better and better refrigerants or mixtures, considering different criteria, as for example: Relative COP, COP, EDR, energetic efficiency, and energy defect in compressor, condenser, expansion valve subcooler and evaporators. This paper presents a comparative analysis of eight refrigerants working in a multi-evaporators VCR system with subcooling and superheating. These eight refrigerants are:1,2-Difluoroethane (R152a), Propane (R290), Butane (R600),Isobutane (R600a),2,3,3,3-Tetrafluoropropene (R1234yf), a azeotropic blend (R404a), (R410a) and (R502). R404a is a near-azeotropic blend of R125 / R143a / R134a with mass percentages of 44% / 52% / 4%.R410a is an azeotropic blend of Difluoromethane R32 Pentafluorethane R125 with mass percentages of 50% / 50%. Blends do not necessarily remain at constant temperature during constant pressure evaporation or condensation. This paper deals with a comparative analysis of the refrigerant impact on the performances of six types multi-evaporators multiple compression and multiple expansion valves in series and parallel with introducing intercoolers in the vapor compression refrigeration systems. The aim of this paper is to present and propose an analysis model for comparing the effects of multi-evaporators, Multiple expansion valves in series and parallel combination and multiple compressors VCR System for improving first law and second law efficiency with different ecofriendly refrigerants as compared with R12 and R502..



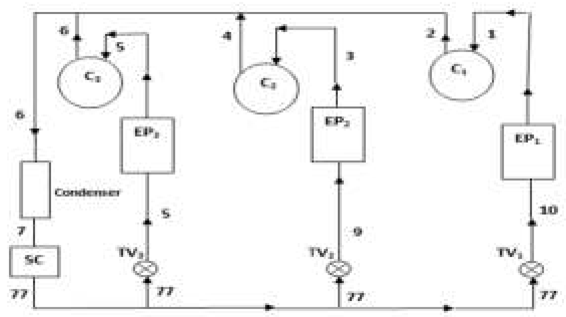


Fig. 1: Models description of multiple evaporators and compressors with individual expansion valves (system-1) and multiple evaporators and compressors with multiple expansion valves (system-2) vapour compression refrigeration systems.

The multiple evaporators and compressors with individual expansion valves vapour compression refrigeration system (system-1) consists of compressors (C1, C2, C3) throttle valves (TV1, TV2, TV3), condenser and evaporators(EP1, EP2, EP3) as shown in Fig.1(a).The pressure versus enthalpy chart for this system is shown in Fig.1(b). In this system all refrigerant coming out at point '77' from subcooler distributed by mass (m_1, m_2 ,m_3 to expansion valves TV1, TV2, and TV3 respectively. Both liquid and vapour formed by TV1 ,TV2 ,TV3 represented by point '10', '9' and '8' take care the load of EP1 ,EP2 and EP3 respectively. The low pressure vapours formed by EP1 ,EP2 and EP3 supplied to the compressor C1 ,C2 and C3 represented by point '1', '3' and '5' respectively. The high pressure vapours formed by compressor C1 ,C2 and C3 respectively represented by points '2', '4' and '6' .then high pressure vapours coming out from compressor C1 , C1 ,C1 collectively enter through condenser by point '7'. The main components of multiple evaporators and compressors with individual expansion valves vapour compression refrigeration system (system-2) are compressors (C1, C2, C3) throttle valves (TV1, TV2, TV3), condenser and evaporators(EP1, EP2, EP3) as shown in Fig. 2(a)

Energy and exergy analysis of Vapour compression Refrigeration systems

The multiple evaporators at the same temperature with single compressor and expansion valve vapour compression refrigerator with subcooler is shown in Fig. 1.According to first law of thermodynamics, the measure of performance of the refrigeration cycle is the coefficient of performance (COP), which is defined as the net refrigeration effect produced per unit of work input. It is expressed as

$$\mathrm{COP} = \frac{Q_e}{W_{comp}} \qquad \text{.............. (1)}$$

The concept of exergy was given by second law of thermodynamics, which always decreases due to thermodynamic irreversibility. Exergy is defined as 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 [7]. Exergy balance for a control volume undergoing steady state process is expressed as [8].

$$IR_k = \sum(me_x)_{in} - \sum(me_x)_{out} + \left[\sum\left(Q\left(1-\frac{T_0}{T}\right)\right)_{in} - \sum\left(Q\left(1-\frac{T_0}{T}\right)\right)_{out}\right] \pm \sum \qquad \text{.............. (2)}$$

Where IRk indicates the rate of irreversibility occurring in compressor, expansion valve, evaporators ,Condenser, subcooler. The first two terms on the right hand side represent exergy of streams entering and leaving the control volume. The third and fourth terms are the energy associated with heat transfer Q from the source maintained at constant temperature T and is equal to work obtained by Carnot engine operating between T and To, and is therefore equal to maximum reversible work that can be obtained from heat energy Q. The last term is the mechanical work transfer to or from the control volume.

2.1 Irreversibility (IR) in the system components

Irreversibility in each component of the cycle is calculated as per given equations. Specified below:

Evaporator-1

$$IR_{e1} = E_{x4} + Q_{e1}\left(1 - \frac{T_0}{T_r}\right) - E_{x1} =$$

$$m_{r1}(h_4 - T_0 s_4) + Q_{e1}\left(1 - \frac{T_0}{T_r}\right) - m_{r1}(h_1 - T_0 s_1) \quad \text{.............. (3)}$$

For Evaporator-2

$$IR_{e2} = E_{x4} + Q_{e2}\left(1 - \frac{T_0}{T_r}\right) - E_{x1} \quad \text{.............. (4)}$$

$$= m_{r2}(h_4 - T_0 s_4) + Q_{e2}\left(1 - \frac{T_0}{T_r}\right) - m_{r2}(h_1 - T_0 s_1)$$

Thermal exergy loss rate is related to external irreversibility which takes place because of temperature difference between the control volume and the immediate surroundings. It depends upon how the boundary of the system is selected. If the system includes the immediate surroundings then the boundary of the thermal system is at the same temperature as the temperature of immediate surroundings and hence the value of thermal exergy loss turns out to be zero. However, temperature differential between system boundary and immediate surroundings exists if the system boundary does not include the immediate surroundings. In a vapour compression refrigeration system, condenser is the component where heat is rejected. However in the present case, thermal energy loss in condenser is neglected as the boundary of the condenser is assumed to be at the environment temperature. Second law performance of the system can be measured in terms of exergetic efficiency [9]. Exergetic efficiency is the ratio between exergy rate of product and fuel. If we consider a system at steady state where, in terms of exergy, the rates at which the fuel is supplied and the product is generated are EF and EP, respectively, and $\sum IRk$ and $\sum ELk$ represent rate of total irreversibility and total thermal energy loss in a system, respectively, then energy rate balance for the system is given by (5) and exergetic efficiency by (6).

$$EF = EP + \sum IR_k + \sum EL_k \quad \text{.............. (5)}$$

and

$$\eta_{ex} = \frac{Exergy\ in\ product}{Exergy\ of\ fuel} = \frac{EP}{EF} = 1 - \frac{\sum IR_k + \sum E}{EF} \quad \text{.............. (6)}$$

For the vapour compression refrigeration system, product is the energy of the heat abstracted in to the evaporators i.e. Qe = Qe1 + Qe2+ Qe3 from the space to be cooled at temperature Tr, i.e.

$$EP = Q_e\left(1 - \frac{T_0}{T_r}\right) \quad \text{.............. (7)}$$

and exergy of fuel is actual compressor work input, Wc. Hence, exergetic efficiency is given by

$$\eta_{ex} = \frac{Q_e\left|\left(1 - \frac{T_0}{T_r}\right)\right|}{W_{comp}} \quad \text{.............. (8)}$$

Exergy Destruction Ratio (EDR) is the ratio of total exergy destruction in the system to exergy in the product [10] and it is given by Eq.(9). EDR is related to the exergetic efficiency by Eq. (10)

$$EDR = \frac{IR_{total}}{EP} = \frac{1}{\eta_{ex}} - 1 \quad \text{.............. (9)}$$

$$\eta_{ex} = \frac{1}{1 + EDR} \quad \text{.............. (10)}$$

Efficiency defect is defined as the ratio between the exergy flow destroyed in each component and the exergy flow required to sustain the process [11] (i.e. the electrical power supplied to the compressor in the present case) and is given by

$$\delta_k = \frac{\sum IR_k + \sum EL_k}{W_{comp}} \quad \text{.............. (11)}$$

where k stands for particular component. The efficiency defects of the components are linked to the exergetic efficiency of the whole system by means of the following relation:

$$\eta_{ex} = \left(1 - \sum_k \delta_k\right) \quad \text{............. (12)}$$

Evaporator-3

$$IR_{e3} = E_{x4} + Q_{e3}\left(1 - \frac{T_0}{T_r}\right) - E_{x1}$$

$$= m_{r3}(h_4 - T_0 s_4) + Q_{e3}\left(1 - \frac{T_0}{T_r}\right) - m_{r3}(h_1 - T_0 s_1) \quad \text{............. (13)}$$

Compressor

$$IR_{comp} = E_{x1} + W_{comp} - E_{x2} = m_r(T_o(s_2 - s_1)) \quad \text{............. (14)}$$

Condenser

$$IR_c = E_{x2} - E_{x3} = m_r(h_2 - T_o s_2) - m_r(h_3 - T_o s_3) \quad \text{............. (15)}$$

Expansion Valve

$$IR_{ev} = E_{x33} - E_{x4} = m_r(T_o (s_4 - s_{33})) \quad \text{............. (16)}$$

Subcooler

$$IR_{sc} = E_{x3} - E_{x33} = m_r(h_3 - T_o s_3) - m_r(h_{33} - T_o s_{33}) \quad \text{............. (17)}$$

The total irreversibility in the system is the sum of irreversibility in each components of the system and is given by

$$\sum IR_k = IR_{e1} + IR_{e2} + IR_{e3} + IR_{comp} + IR_c + IR_{ev} + IR_{sc} \quad \text{............. (18)}$$

Thermal exergy loss rate in a component is given by

$$EL_k = Q_k\left(1 - \frac{T_0}{T_k}\right) \quad \text{............. (19)}$$

where Q_k is the heat rejected by the kth component and T_k is the temperature at the boundary of the kth component. When considering thermal exergy loss rate, Eq. (2) can be rewritten as

$$IR_k + EL_k = \sum(me_x)_{in} - \sum(me_x)_{out} + \left[\sum\left(Q\left(1 - \frac{T_0}{T}\right)\right)_{in}\right] \pm \sum W \quad \text{............. (20)}$$

3. 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

$$COP1 = \frac{\dot{Q}_{e\_1}}{\dot{W}_{comp\_1}} \quad \text{............. (1b)}$$

similarly for system-2

$$COP2 = \frac{\dot{Q}_{e\_2}}{\dot{W}_{comp\_2}} \quad \text{............. (1c)}$$

3.1: Second law analysis of multiple evaporators and compressors with individual or multiple expansion valves vapour compression refrigeration system

Second law of thermodynamics gives the concept of exergy, which always decreases due to thermodynamic irreversibility. Exergy is defined as 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 [7]. Exergy balance for a control volume undergoing steady state process is expressed as [8].

$$\dot{ED}_k = \sum(\dot{m}e_x)_{in} - \sum(\dot{m}e_x)_{out} + \left[\sum\left(\dot{Q}\left(1 - \frac{T_0}{T}\right)\right)_{in} - \sum\left(\dot{Q}\left(1 - \frac{T_0}{T}\right)\right)_{Out}\right] \pm \sum \dot{W} \quad \text{............. (2b)}$$

Where $(ED)_k$ represents the rate of irreversibility occurring in compressors, throttle valves, evaporators, condenser and subcooler. The first two terms on the right hand side represent exergy of streams entering and leaving the control volume. The third and fourth terms are the exergy associated with heat transfer Q from the source maintained at constant temperature T and is equal to work obtained by Carnot engine operating between T and T_o, and is therefore equal to maximum reversible work that can be obtained from heat energy Q . The last term is the mechanical work transfer to or from the control volume. Exergy destruction (ED) in system-1can be find out in terms of irreversibilities. Exergy destruction in each component of the multiple evaporators and compressors with individual expansion valves vapour compression refrigeration system is evaluated as per given below equations.

Evaporators

$(EP_1)_{\text{System-1}}$

$$\dot{ED}_{e1} = \dot{E}_{x10} + \dot{Q}_{e1}\left(1 - \frac{T_0}{T_{r1}}\right) - \dot{E}_{x1} = \dot{m}_{e1}(\psi_{10} - T_0 s_{10}) + \dot{Q}_{e1}\left(1 - \frac{T_0}{T_{r1}}\right) - \dot{m}_{e1}(\psi_1 - T_0 s_1) \quad \text{.............. (3b)}$$

$(EP_2)_{\text{System-1}}$

$$\dot{ED}_{e2} = \dot{E}_{x9} + \dot{Q}_{e2}\left(1 - \frac{T_0}{T_{r2}}\right) - \dot{E}_{x3} = \dot{m}_{e2}(\psi_9 - T_0 s_9) + \dot{Q}_{e2}\left(1 - \frac{T_0}{T_{r2}}\right) - \dot{m}_{e2}(\psi_3 - T_0 s_3) \quad \text{.............. (4b)}$$

$(EP_3)_{\text{System-1}}$

$$\dot{ED}_{e3} = \dot{E}_{x8} + \dot{Q}_{e3}\left(1 - \frac{T_0}{T_{r3}}\right) - \dot{E}_{x5} = \dot{m}_{e3}(\psi_8 - T_0 s_8) + \dot{Q}_{e3}\left(1 - \frac{T_0}{T_{r3}}\right) - \dot{m}_{e3}(\psi_5 - T_0 s_5) \quad \text{.............. (13b)}$$

Compressors

$(C_1)_{\text{System-1}}$

$$\dot{ED}_{comp1} = \dot{E}_{x1} + \dot{W}_{comp1} - \dot{E}_{x2} = \dot{m}_{c1}(T_0(s_2 - s_1)) \quad \text{.............. (14b)}$$

$(C_2)_{\text{System-1}}$

$$\dot{ED}_{comp2} = \dot{E}_{x3} + \dot{W}_{comp2} - \dot{E}_{x4} = \dot{m}_{c2}(T_0(s_4 - s_3)) \quad \text{.............. (15b)}$$

$(C_3)_{\text{System-1}}$

$$\dot{ED}_{comp3} = \dot{E}_{x5} + \dot{W}_{comp3} - \dot{E}_{x6} = \dot{m}_{c3}(T_0(s_6 - s_5)) \quad \text{.............. (16b)}$$

(Condenser) System-1

$$\dot{ED}_c = (\dot{E}_{x2} - \dot{E}_{x7}) + (\dot{E}_{x4} - \dot{E}_{x7}) + (\dot{E}_{x6} - \dot{E}_{x7}) = \dot{m}_{c1}((\psi_2 - T_0 s_2) - (\psi_7 - T_0 s_7)) + \dot{m}_{c2}((\psi_4 - T_0 s_4) - (\psi_7 - T_0 s_7)) + \dot{m}_{c3}((\psi_6 - T_0 s_6) - (\psi_7 - T_0 s_7)) \quad \text{.............. (17b)}$$

Subcooler

$(SC)_{\text{System-1}}$

$$\dot{ED}_{sc} = \dot{E}_{x7} - \dot{E}_{x77} = (\dot{m}_{c1} + \dot{m}_{c2} + \dot{m}_{c3})((\psi_7 - T_0 s_7) - (\psi_{77} - T_0 s_{77})) \quad \text{.............. (18b)}$$

Throttle valves

$(TV_1)_{\text{System-1}}$

$$\dot{ED}_{TV_1} = \dot{E}_{x77} - \dot{E}_{x10} = \dot{m}_{c1}(T_0(s_{10} - s_{77})) \quad \text{.............. (19b)}$$

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

$$\dot{ED}_{TV_2} = \dot{E}_{x77} - \dot{E}_{x9} = \dot{m}_{c2}(T_0(s_9 - s_{77})) \quad \text{.............. (20b)}$$

(TV-3)System-1

$$\dot{ED}_{TV_3} = \dot{E}_{x77} - \dot{E}_{x8} = \dot{m}_{c3}(T_0(s_8 - s_{77})) \quad \text{.............. (5b)}$$

(Mass balance)System-1

$$\dot{m}_{e1} = \dot{m}_{c1}$$
$$\dot{m}_{e2} = \dot{m}_{c2}$$
$$\dot{m}_{e3} = \dot{m}_{c3}$$

The total irreversibility in the system is the sum of irreversibility in each components of the system and is given by

$$\sum \dot{ED}_k = \dot{ED}_{e1} + \dot{ED}_{e2} + \dot{ED}_{e3} + \dot{ED}_{comp1} + \dot{ED}_{comp2} + \dot{ED}_{comp3} + \dot{ED}_c + \dot{ED}_{sc} + \dot{ED}_{TV_1} + \dot{ED}_{TV_2} + \dot{ED}_{TV_3} \quad \text{.............. (6b)}$$

For system 2, exergy destruction in each component of the multiple evaporators and compressors with multiple expansion valves vapour compression refrigeration system is evaluated as per Eqs. (21)– (33) given below:

Evaporators

$(EP1)_{System\text{-}2}$

$$\dot{ED}_{e1} = \dot{E}_{xl} + \dot{Q}_{e1}\left(1 - \frac{T_0}{T_{r1}}\right) - \dot{E}_{xa}$$
$$= \dot{m}_{e1}(\psi_l - T_0 s_l) + \dot{Q}_{e1}\left(1 - \frac{T_0}{T_{r1}}\right) - \dot{m}_{e1}(\psi_a - T_0 s_a) \qquad (15)$$

.... (21)

$(EP2)_{System\text{-}2}$

$$\dot{ED}_{e2} = \dot{E}_{xj} + \dot{Q}_{e2}\left(1 - \frac{T_0}{T_{r2}}\right) - \dot{E}_{xc}$$
$$= \dot{m}_{e2}(\psi_j - T_0 s_j) + \dot{Q}_{e2}\left(1 - \frac{T_0}{T_{r2}}\right) - \dot{m}_{e2}(\psi_c - T_0 s_c) \qquad (16)$$

.... (22)

$(EP3)_{System\text{-}2}$

$$\dot{ED}_{e3} = \dot{E}_{xh} + \dot{Q}_{e3}\left(1 - \frac{T_0}{T_{r3}}\right) - \dot{E}_{xe}$$
$$= \dot{m}_{e3}(\psi_h - T_0 s_h) + \dot{Q}_{e3}\left(1 - \frac{T_0}{T_{r3}}\right) - \dot{m}_{e3}(\psi_e - T_0 s_e) \qquad (17)$$

.... (23)

Compressors

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

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

.... (24)

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

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

.... (25)

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

$$\dot{ED}_{comp3} = \dot{E}_{xe} + \dot{W}_{comp3} - \dot{E}_{xf} = \dot{m}_{c3}(T_0(s_f - s_e)) \qquad (20)$$

.... (26)

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

$$\dot{ED}_{cond} = (\dot{E}_{xb} - \dot{E}_{xg}) + (\dot{E}_{xd} - \dot{E}_{xg}) + (\dot{E}_{xf} - \dot{E}_{xg})$$

.... (27)

$$= \dot{m}_{c1}\left((\psi_b - T_0 s_b) - (\psi_g - T_0 s_g)\right) + \dot{m}_{c2}\left((\psi_d - T_0 s_d) - (\psi_g - T_0 s_g)\right) + \dot{m}_{c3}\left((\psi_f - T_0 s_f) - (\psi_g - T_0 s_g)\right)$$

.... (28)

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

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

.... (29)

Throttle valves

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

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

.... (30)

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

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

.... (31)

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

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

.... (32)

$(Mass\ balance)_{System\text{-}2}$

$$\dot{m}_{c1} = \dot{m}_{e1}$$
$$\dot{m}_{c2} = \dot{m}_{e2} = \dot{m}_2 + \dot{m}_{e1}\left(\frac{\varphi_j}{1 - \varphi_j}\right)$$
$$\dot{m}_2 = \left(\frac{\dot{Q}_{e2}}{\psi_c - \psi_j}\right)$$
$$\dot{m}_{c3} = \dot{m}_{e3} = \dot{m}_3 + (\dot{m}_{e1} + \dot{m}_{e2})\left(\frac{\varphi_h}{1 - \varphi_h}\right)$$
$$\dot{m}_3 = \left(\frac{\dot{Q}_{e3}}{\psi_e - \psi_h}\right)$$

The total irreversibility in the system is the sum of irreversibility in each components of the system and is given by

$$\sum \dot{ED}_k = \dot{ED}_{e1} + \dot{ED}_{e2} + \dot{ED}_{e3} + \dot{ED}_{comp1} + \dot{ED}_{comp2} + \dot{ED}_{comp3} + \dot{ED}_c + \dot{ED}_{sc} + \dot{ED}_{TV_1} + \dot{ED}_{TV_2} + \dot{ED}_{TV_3}$$

.... (33)

For the multi evaporators vapour compression refrigeration system, 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

$$\dot{EP} = \dot{Q}_{e1}\left|\left(1-\frac{T_0}{T_{r1}}\right)\right| + \dot{Q}_{e2}\left|\left(1-\frac{T_0}{T_{r2}}\right)\right| + \dot{Q}_{e3}\left|\left(1-\frac{T_0}{T_{r3}}\right)\right| \quad \text{............. (34a)}$$

Hence, exergetic efficiency is given by

$$\eta_{ex} = \frac{Q_{e1}\left|\left(1-\frac{T_0}{T_{r1}}\right)\right| + \dot{Q}_{e2}\left|\left(1-\frac{T_0}{T_{r2}}\right)\right| + \dot{Q}_{e3}\left|\left(1-\frac{T_0}{T_{r3}}\right)\right|}{(W_{comp1}+W_{comp2}+W_{comp3})} \quad \text{............. (34b)}$$

3. Results and discussions

A computational model is developed for carrying out the energy and exergy analysis of the system using Engineering Equation Solver software [12].

The result evaluated on the basis of following assumed data shown Figs.2-9 are furnished below:

1. Degree of sub cooling of liquid refrigerant in subcooler (ΔTsc): 5K.
2. Isentropic efficiency of compressor ($_{comp}$h): 75%.
3. Difference between evaporator and space temperature (Tr-Te):5K.
4. Temperature of evaporators EP1, EP2 and EP3 are 263K ,273K and 283K respectively
5. Condenser temperature (Tc): 313K
6. Dead state temperature (T0): 298K
7. Dead state enthalpy (ψ0) and entropy (s0) of the refrigerants have been calculated corresponding to the dead state temperature (T0) of 298K.
7. Loads on the evaporators EP1, EP2 and EP3 are 35KW, 70KW and 105KW respectively.
8. Evaporators' temperature is 273K.
9. Condenser temperature (Tc): 313K (the condenser temperature is based on climatic conditions persisting in summer in tropical countries)..
10. Reference enthalpy (h0) and entropy (s0) of the working fluids have been computed corresponding to the dead state temperature (T0) of 298K.

Loads on the evaporators EP1, EP2 and EP3 are 35KW, 70KW and 105KW respectively. Table-1: presents the variation of coefficient of performance for all six systems for different ecofriendly refrigerants and Bar charts are shown in Table1. It was observed that COP of R12 in all six cases are higher but due to consideration of global warming and ozone depletion one can consider ecofriendly refrigerants for reducing global warming and ozone depletion. The cop of 600 is although is better than R152a but the refrigerants R290, R600 and R600a are flammable properties. Therefore by consideration of safety measures R152a gives better first law performance than R404a ,R134a and R410a. With increase in evaporators' temperature, the pressure ratio across the compressor reduces causing compressor work to reduce and cooling capacity increases because of increase in specific refrigerating effect. The combined effect of these two factors is to increase the overall COP. It was observed that COP of system using R600 and R152a nearly matching same values Both R-600 and R-152a show better COP than R-502, R-290, R-404a, R-410a, R-600a and R-1234yf at 313K condenser temperature. Although R600,R600a and R290 have flammable properties cannot use directly due to safety measures, the system will be modified by taking into the considerations safety measures and precautions must be taken when using these refrigerants and also they are responsible for global warming. The maximum difference observed between COPs of R-152a and R-404a is 22.57% at 313K condenser temperature. Table-2 show the effect of ecofriendly refrigerants on exergetic efficiency at 313K condenser temperature. The increase and decrease of the exergetic efficiency, with increase in evaporators temperature, are based on two parameters. First parameter is energy of cooling effect, i.e., Q_e $|1\text{-}T_o$ / T_r $|$with rise in evaporators temperature Q_e, increases however the term Q_e $|1\text{-}T_o$ / T_r $|$ reduces since Tr approaches T_0, and second being the compressor work which decreases with increase in evaporators temperature. Both Q_e and Wc have positive effect on increase of energetic efficiency whereas the decreasing value of term $|1\text{-}T_o$ / T_r $|$ has a negative effect on increase of energetic efficiency. The combined effect of these factors is to increase the energetic efficiency till the optimum evaporators' temperature is achieved, i.e. the evaporators' temperature at which maximum exergetic efficiency is achieved. Beyond optimum evaporators' temperature, the overall effect of these factors is to reduce the exergetic efficiency. Both R600 and R152a have higher energetic efficiency than R502, R290, R404a, R410a, R600a and R1234yf. energetic efficiency of R152a is 15–22% higher than R404A and R600 is 12– 20% higher than R404aA at 313K condenser temperature. This also confirms that with increase in condenser temperature the difference among the energetic efficiency of R152a, R600 and its alternate refrigerants increases. It is observed from Table.2 - Table.3, that variation of EDR and exergetic efficiency are almost reverse because that exergetic efficiency is inversely proportional to EDR. The EDR initially decreases and then increases with the increase in evaporators' temperature. The exergetic efficiency is inversely proportional to EDR. For a fixed condenser temperature, the increase in dead state temperature causes the irreversibility. (due to finite temperature difference) to decrease and hence EDR decreases and energetic efficiency increases. Table3: presents that R-404a shows maximum EDR among all the refrigerants corresponding to the range of dead state temperatures considered. Both R-152a and R-600 show the identical trends .The energetic efficiency for R-600 is 0.4-0.5% higher than that of R-152a. It was observed that the effect of degree of subcooling on COP, exergetic efficiency and EDR. It is evident that subcooling increases refrigeration capacity whereas there is no change in compressor work, hence COP increases. It apparent that increase in COP decreases EDR and increases energetic efficiency. The increase in COP is nearly 5.6%/K of subcooling in case of R-404a.However, the corresponding increase in COP in R-152a and R-600 is less. The rate of increase of exergetic efficiency is approximately 0.4%/K for R404a.The total increase in energetic efficiency for 10K of subcooling is 3.97% for R404a and 2.5% for R152a and R-600 at 313K condenser temperature. Hence it is easy to understand why EDR increases and exergetic efficiency decreases. It is observed that COP and exergetic efficiency are almost same for considered ecofrigerants as compared with R-12 refrigerant, both COP and EDR will decrease with increase in condenser temperature. EDR increase with increase in condenser temperature rational efficiency with increase in condenser temperature at 273K temperature of all evaporators with 5K degree of subcooling.

CONCLUSIONS

In this paper, first law and second law analysis of six multi-evaporators multiple compressor and multiple expansion valves in series and parallel combinations of vapour compression refrigeration systems using ecofriendly refrigerants (R410a, R290, R600, R600a, R1234yf, R502, R404a and R152a) have been presented. The conclusions of the present analysis are summarized below:

1. COP and exergetic efficiency for R152a and R600 are matching the same values. Both are better than that for R404A at 313K condenser temperature and showing 12–23% higher value of COP and exergetic efficiency in comparison to R404a.

2. The worst component from the viewpoint of irreversibility is expansion valve followed by condenser, compressor and evaporators, respectively. The most efficient

Table-1: Variation of First law efficiency (COP) of multiple evaporators vapour compression refrigeration systems using eco-friendly refrigerants

Refrigerants	COP(Coefficient of Performance)					
Previously	System1	System2	System3	System4	System5	System6
R12	3.117	3.397	4.078	5.243	6.745	5.205
R502	2.819	3.189	3.838	5.033	6.39	4.994
Ecofriendly	System1	System2	System3	System4	System5	System6
R152a	3.173	3.425	4.122	5.276	6.822	5.246
R290	2.983	3.308	3.97	5.145	6.582	5.105
R404a	2.649	3.072	3.685	4.893	6.145	4.835
R410a	2.856	3.192	3.842	4.983	6.386	4.959
R600	3.186	3.473	4.145	5.334	6.862	5.294
R600a	3.061	3.392	4.055	5.277	6.743	5.237
R1234yf	2.887	3.284	3.933	5.18	6.569	5.141
R1234ze	3.02	3.373	4.036	5.267	6.763	5.14
R134a	3.034	3.354	4.031	5.227	6.689	5.188

Table-2: Variation of Second law efficiency of multiple evaporators vapour compression refrigeration systems using eco-friendly refrigerants

Refrigerants	Second Law efficiency (Energetic Efficiency)					
Previously	System1	System2	System3	System4	System5	System6
R12	0.187	0.2913	0.3496	0.3146	0.4047	0.3123
R502	0.1691	0.2734	0.329	0.302	0.3834	0.2996
Ecofriendly	System1	System2	System3	System4	System5	System6
R152a	0.1904	0.2937	0.3534	0.3166	0.4093	0.3147
R290	0.179	0.2836	0.3404	0.3087	0.3949	0.3063
R404a	0.1589	0.2634	0.3159	0.2936	0.3687	0.2901
R410a	0.1714	0.2737	0.3294	0.2989	0.3831	0.2975
R600	0.1911	0.2978	0.3554	0.3201	0.4117	0.3177
R600a	0.1837	0.2908	0.3477	0.3166	0.4046	0.3142
R1234yf	0.1732	0.2816	0.3372	0.3108	0.3942	0.3085
R1234ze	0.1812	0.2892	0.346	0.316	0.3958	0.3095
R134a	0.182	0.2876	0.3456	0.3136	0.4013	0.3113

Table-3: Variation of energy Destruction Ratio (EDR) of multiple evaporators vapour compression refrigeration systems using eco-friendly refrigerants

Refrigerant	EDR					
Previously	System1	System2	System3	System4	System5	System6
R12	4.253	2.02	1.86	2.255	1.47	2.2
R502	5.262	2.192	2.039	2.412	1.608	2.335
Ecofriendly	System1	System2	System3	System4	System5	System6
R152a	4.045	2.003	1.829	2.229	1.442	2.173
R290	4.695	2.092	1.938	2.326	1.532	2.263
R404a	5.829	2.282	2.165	2.504	1.711	2.424
R410a	5.027	2.207	2.035	2.431	1.607	2.349
R600	4.051	1.953	1.814	2.2	1.429	2.147
R600a	4.426	2.011	1.876	2.247	1.472	2.182
R1234yf	4.952	2.088	1.965	2.313	1.537	2.242
R1234ze	4.586	2.024	1.89	2.256	2.902	2.565
R134a	4.504	2.049	1.894	2.274	1.491	2.211

Table-4: Variation of Rational efficiency of multiple evaporators vapour compression refrigeration systems using eco-friendly refrigerants

Refrigerants	Rational Efficiency					
Previously	System1	System2	System3	System4	System5	System6
R12	0.2046	0.4116	0.3496	0.2906	0.4049	0.313
R502	0.1101	0.4007	0.329	0.2717	0.3836	0.3002
Ecofriendly	System1	System2	System3	System4	System5	System6
R152a	0.23	0.4117	0.3534	0.2945	0.4099	0.316
R290	0.1596	0.4068	0.3404	0.2821	0.395	0.3069
R404a	0.0737	0.3987	0.3159	0.265	0.369	0.2967
R410a	0.1384	0.3959	0.3294	0.2733	0.3845	0.301
R600	0.2256	0.4185	0.3554	0.2958	0.4117	0.3179
R600a	0.187	0.415	0.3477	0.2887	0.4046	0.3144
R1234yf	0.1423	0.412	0.3372	0.2811	0.3942	0.3084
R1234ze	0.1689	0.4147	0.346	0.2872	0.3958	0.3094
R134a	0.1801	0.4109	0.3456	0.2868	0.4015	0.3119

component is subcooler. The R-152a has least efficiency defects for 313K condenser temperature.

3. The increase in dead state temperature has a positive effect on energetic efficiency and EDR, i.e. EDR decreases and energetic efficiency increases with increase in dead state temperature. Both R-152a and R-600 show the identical trends and their bar charts for energetic efficiency are nearly overlapping. The energetic efficiency for R-600 is 0.4-0.5% higher than that of R-152a for the range of dead state temperature considered.

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