

Original Research Article**Simulation and Comparison of the performance
of refrigerant fluids in single stage vapor
compression refrigeration system****ABSTRACT**

This paper presents reports on simulation and comparative analysis of single stage vapor compression refrigeration system performance for comparison of refrigerant fluids. A mathematical model was devised by applying the concept of energy balance in the thermodynamic cycle to the components of the vapor compression refrigeration system. The developed model implemented in MATLAB software was used to compare the performance of the system using Hydrocarbons, R134a, and ammonia as refrigerants in place of refrigerants 12 and 22. Simulation data was generated over a wide range of evaporation and condensation temperatures of -25 to 15°C and 30 to 60°C respectively for the selected working fluids considered in this study to observe the performance of the system in terms of refrigerating effect, coefficient of performance (COP) and overall efficiency of the system. In the present study, close match of COP and the system overall efficiency values for, R134a, R290 and R600a and R290 are observed with that of R12 and R22 counterpart under the similar operating conditions. Moreover, among the refrigerants simulated in the system under the similar operating conditions, the system with the use of ammonia yields highest COPs and are of up to 6.3 and 7.5% increment compared with those of R12 and R22 respectively. It can be concluded that R134a, R290, R600a and ammonia may act as substitutes for R12 and R22 without affecting the energy efficiency of vapor compression refrigeration system, provided the safety issues are addressed in terms of manufacturing, handling, storage and servicing so as to prevent flammability and corrosive/toxic natures of both hydrocarbons and ammonia refrigerants respectively, thus helping to solve the ozone depletion potential (ODP) and global warming potential (GWP) problems regarding environmental issues.

Keywords: Vapor compression refrigeration system, refrigerant, coefficient of performance, refrigerating effect, overall efficiency of the system

1. INTRODUCTION

Vapor compression refrigeration system based applications make use of refrigerants such as chlorofluorocarbons (CFCs) and hydro chlorofluorocarbons (HCFCs) which are responsible for greenhouse gases, global warming and ozone layer depletion effects. These effects cause a lot of ill health and diseases for living and non living things. These refrigerants have been used widely over the last eight decades in refrigeration and air-conditioning due to their favourable characteristics such as low freezing point, non-flammability, non-toxicity and chemically stable behavior with other materials, Mohan [1]. The role of these refrigerants in the process of ozone depletion is now widely accepted, this is due to high chlorine content of

these substances. The relationship between ozone depletion potential and global warming potential is the major concern in the field of GRT (green refrigeration technology). As pointed out in the study of Dalkilic and Wongwises [2], ozone depletion potential and global warming potential have become the most important criteria in the development of new refrigerants. This had lead researchers to have started focusing on investigation into more environmental friendly refrigerants than CFCs and HCFCs refrigerants for the protection of the environment such as the use of R134a, Ammonia and hydrocarbon (HC) refrigerants as working fluid in refrigeration and air-conditioning systems. Hydrocarbon refrigerants have the advantages of low local availability and environmental acceptability when compared to CFCs and HCFCs. This is due to the fact that, the absence of chlorine in Hydrocarbon (HC) and ammonia results in zero ozone depleting potential (ODP) and has a negligible global warming potential (GWP). The studies according to Kalla and Usmani [3] also provide a review of the efforts to replace the HFCs (hydrofluorocarbons) which are harmful to the environment. The performance of a vapor compression refrigeration system can be improved in a number of ways, other than by testing the system in a controlled environment experimentally; one of those ways is the use of computer models to simulate the thermal and fluid-dynamic behavior of refrigeration systems to achieve rapid and accurate result that will aid optimum design of the system. Application of simulation performance prediction and optimum design of refrigeration systems has been pointed out in the study of Guo-liang Ding [4]. Simulation techniques have also been used by researchers for design of vapor compression refrigeration system under steady state conditions (Sanaye and Malekmohammadi [5]). According to Winkler [6], a steady-state simulation provides details regarding the system performance at a set of design points and describes how the system will perform at off-design conditions. D.V.Raghunatha Reddy et al. [7] carried out investigation on application of soft computing techniques for analysis of vapor compression refrigeration system. The result from their study revealed that intelligent systems such as autonomous self-tuning systems and automated designed systems are applicable with the aids of computer simulation techniques. Many investigations have been carried out both experimentally and numerically in search for more eco- friendly refrigerants that could be retrofitted to existing vapor compression refrigeration system so as to minimize adverse impact of thermal systems usage on the environment. Tallita et al. [8] developed a mathematical model using adaptive time step Runge-Kutta Fehlberg fourth-fifth order method to compare the performance of vapor compression refrigeration system substituting R12 for R134a, ammonia and R600a. The simulation results of their study revealed R134a as the best fluid that could be used to replace R12 in vapor compression refrigeration system. Mohan [1] reported comparative analysis of the refrigerant impact on the operation and performances of a one stage vapor compression refrigeration system using R12 and R134a as refrigerants. According to the author, R134a is observed to be more sensitive to variation in degree of sub-cooling from COP evaluation point of view. Hadya et al. [9] studied and compared theoretically the possibility of using R32 and R290 refrigerants with R22 in a lower capacity air-conditioning system. Close match of COP values for R290 and R32 are observed with that of R22 counterpart based on the experimental operating conditions considered in their study.

To prevent the environmental damage and to reduce the harmful effects of the CFCs and HCFCs application in refrigeration industry further investigation are carried out in the present study using computer model to simulate fluid-dynamic behavior of alternate refrigerants in refrigeration systems. Simulation and comparative analysis of performance of R134a, R290, R600a and Ammonia as refrigerants in a single stage vapor compression system was carried out. The performance evaluation of the system in terms of COP, refrigerating effect and overall efficiency of the system values obtained for R134a, HCs and Ammonia refrigerants were comparatively analysed with that of CFCs and HCFCs refrigerants.

2. VAPOR COMPRESSION REFRIGERATION SYSTEM DESCRIPTION

Figure 1 shows schematic diagram of a single stage vapor compression refrigeration system and the corresponding P-h diagram of the system is presented in Fig. 2. This system consists of a compressor, a condenser, expansion valve (capillary tube) and an evaporator. The arabic numbers in Fig. 1 from 1 to 4 show the different state of the vapor compression refrigeration system and the number sequence indicates the flow direction of refrigerant in the system. The refrigerant enters the compressor at state 1, with a superheating degree and also with respect to the evaporation temperature. It follows the irreversible compression process 1-2. At state 2 the refrigerant is with extremely high pressure and superheated. The compressed refrigerant vapor runs from state 2 to state 3. The refrigerant vapor at state 2 influxes into the condenser to be condensed and takes place the heat exchange with the surroundings hence arriving in state 3 as sub-cooled liquid which is further throttled at constant enthalpy during the process 3-4. The cycle is closed by a vaporization process 4-1 in which the refrigerant (two-phase mixture) is evaporated at constant pressure heat interaction in internally reversible condition to a saturated vapor at state 1. The process of the evaporation of refrigerant in the evaporator thus receives heat from the cooling/refrigerated space.

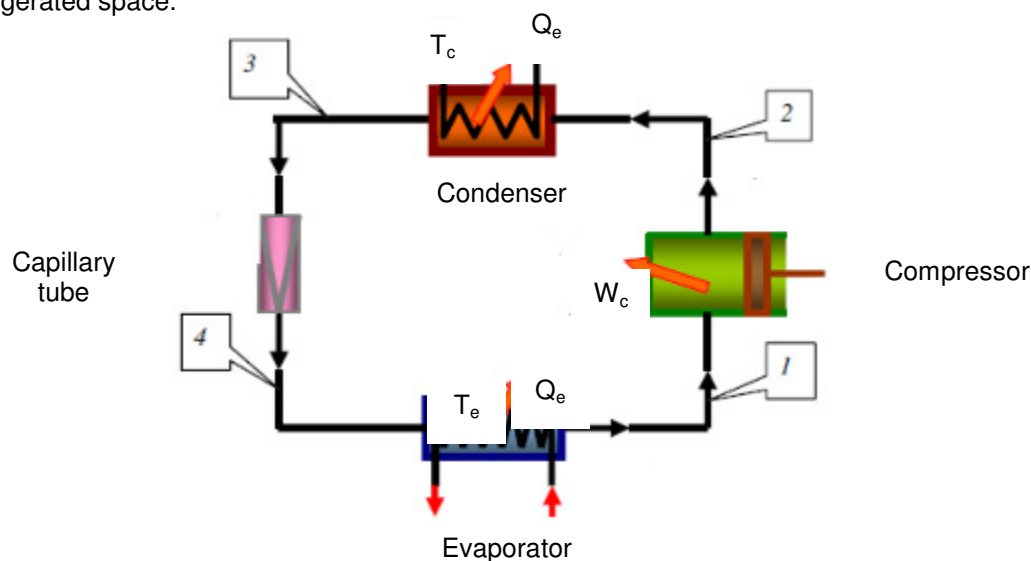


Fig. 1: Single stage Vapor Compression Refrigeration System.

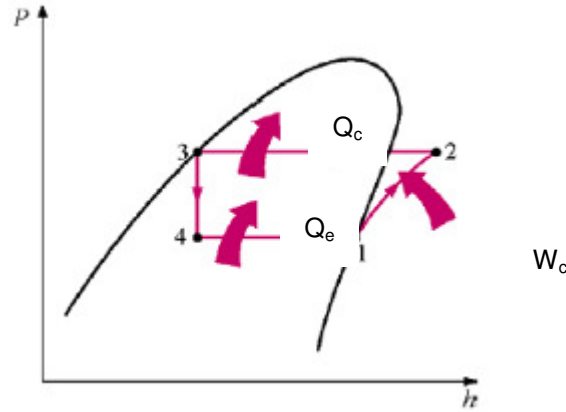


Fig. 2: P-h Diagram Vapor Compression Refrigeration System.

3. MATHEMATICAL MODEL

In this section the system components level mathematical models were developed based on the mass and energy conservation principles described as follows:

3.1 Refrigeration system cooling load model

In the present study, the system cooling load (Q_{CL}) which comprises of both the product load (Q_{PT}) and the infiltration load (Q_I) is model as follows:

$$Q_{CL} = Q_{PT} + Q_I \quad (1)$$

where Q_{PT} is the total product cooling load estimated such that for n product stored in the system, the total product cooling load is calculated as:

$$Q_{PT} = \sum_I^n Q_P \quad (2)$$

The term Q_P in Eq. (2) is the total load required to cool a product from storage temperature t_I to final temperature t_3 and is determined using Eq. (3):

$$Q_P = Q_{AF} + Q_F + Q_{BF} \quad (3)$$

where the terms Q_{AF} , Q_F and Q_{BF} are defined as sensible heat load above freezing, latent heat of freezing, and sensible heat load below freezing respectively for the selected products and they are given as follow:

$$Q_{AF} = mc_a(t_1 - t_2) \quad (4)$$

$$Q_F = mh_{fg} \quad (5)$$

$$Q_{BF} = mc_b(t_2 - t_3) \quad (6)$$

The detail of the terms $(n, m, t_2, c_a, c_b, h_{fg})$ for the selected products considered in the present study are shown in Table 1.

Table 1. Properties of the selected products

Products	Mass, m [Kg]	Highest freezing temperature, t_2 [°C]	Specific heat above freezing, c_a [KJ/KgK]	Specific heat below freezing, c_b [KJ/KgK]	Latent heat of fusion, h_{fg} [KJ/KgK]
Apple	5	-1.5	3.64	1.88	506.26
Fresh meat	5	-1.67	3.18	2.13	418.40
Water	5	-0.3	3.94	2.01	310.24

Source: Heat load in refrigeration systems [10]

It is interesting to highlights that the average ambient temperature of the environment t_1 and the final temperature t_3 are assumed to be 30 °C and -10 °C respectively.

The infiltration load (Q_i) given in Eq. (1) is calculated from:

$$Q_i = 1.08V(t_1 - t_3) \quad (7)$$

where 1.08 is a multiplying factor and V is the average velocity of the door and is computed as:

$$V = v_r \sqrt{\frac{H}{H_r}} \sqrt{\frac{T_a}{T_r}} \quad (8)$$

where,

v_r is the average velocity of the reference door

H is the height of the door

H_r is the height of the reference door

T_a is the temperature difference between the refrigerated space and the environment

T_r is temperature difference of the reference door.

156 It is interesting to point that the concept of energy balance is based on the First Law of
157 Thermodynamics for control volumes to obtain performance result that can meet the
158 operating conditions imposed on each component shown in Fig.1 was adopted in this study
159 and is mathematically expressed according to Eq. (9)
160

$$161 \quad \dot{Q}_{vc} + \sum \dot{m}_o \left(h_o + \frac{v_o^2}{2} + gz_o \right) = \frac{dE_{vc}}{dt} + \sum \dot{m}_i \left(h_i + \frac{v_i^2}{2} + gz_i \right) + \dot{W}_{vc} \quad (9)$$

162

163 Where the subscripts i and o in Eq. (9) stands for inlet and outlet states, respectively.

164 It is well known that in vapor compression refrigeration system, changes in kinetic, $v^2/2$
165 and potential energies, gz are negligible. Thus Eq. (9) becomes:
166

$$167 \quad \dot{Q}_{vc} - \dot{W}_{vc} = \sum \dot{m}_o h_o + \sum \dot{m}_i h_i \quad (10)$$

168

169 Referring to the P-h diagram shown in Fig. 2 and application of Eq. (10) to each component
170 of the system, the mathematical equations used to obtain the energy balance in each
171 component are expressed as follows:
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173 3.2 Heat exchangers models: evaporator, condenser

174 The heat absorbed by the evaporator (i.e., cooling capacity) is calculated from:
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$$176 \quad Q_e = \dot{m}(h_1 - h_4) \quad (11)$$

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178 The heat released by the condenser is computed according to Eq. (12) as follows:
179

$$180 \quad Q_c = \dot{m}(h_2 - h_3) \quad (12)$$

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182 3.3 Compressor

183 An overall energy balance applied to calculate the rate of work input to the compressor is
184 expressed mathematically as:
185

$$186 \quad W_c = \dot{m}(h_2 - h_1) \quad (13)$$

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188 3.4 Expansion valve

189 For the expansion process, the overall energy balance in the capillary tube is calculated
190 from:

$$191 \quad \dot{m}h_3 = \dot{m}h_4 \quad (14)$$

192 The refrigerant mass flow rate ($\dot{m}$) of the systems is calculated from:
193

$$\dot{m} = \frac{Q_{CL}}{h_1 - h_4} \quad (15)$$

The Mathematical model described above was implemented in MATLAB software to predict the response of principles components i.e compressor, condenser, expansion valve (capillary tube) and evaporator. The simulation model of the single stage vapor compression refrigeration system shown in Fig.1 was devised assuming the following conditions (i) the refrigeration system operates at steady state regime, (ii) irreversibilities within the evaporator, condenser and compressor are ignored, (iii) no frictional pressure drops, (iv) refrigerant flows at constant pressure through the two heat exchangers (evaporator and condenser) , heat loss to the surrounding are ignored and compression process is isentropic. The solution algorithm is illustrated in the information flow diagram depicted in Fig. (3). The software input data are refrigerant type, product properties, evaporation temperature and condensing temperature. The thermodynamics parameters (P, h, v, s) for the refrigerants considered were set from COOLPACK saturation table [11]. The first simulation of the system was performed using the thermodynamic properties of R12. Subsequently, new simulations were carried out for other refrigerants such as R22, R134a, R600a, R290, and Ammonia considering their respective thermodynamic properties. Based on the simulation procedure carried out for each refrigerant, the performance of the system is evaluated as follows: The coefficient of performance (COP) of the system is calculated from:

$$COP_{Ref} = \frac{Q_e}{W_c} \quad (16)$$

The overall efficiency of the system (η) is estimated from:

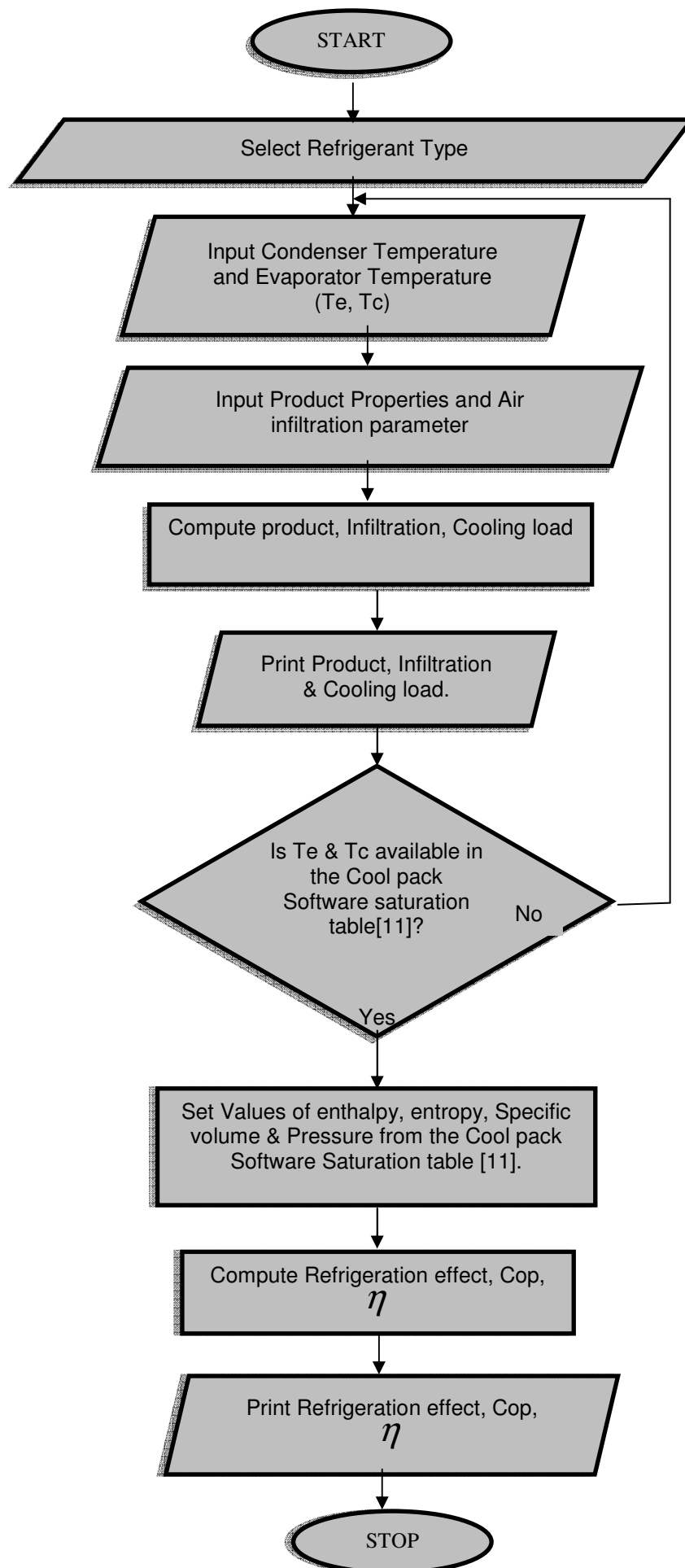
$$\eta = \frac{COP_{Carnot}}{COP_{Ref}} \quad (17)$$

The term COP_{Carnot} in Eq. (17) is calculated as follow:

$$COP_{Carnot} = \frac{T_e}{T_e - T_c} \quad (18)$$

where, T_e and T_c are the evaporation and condensation temperature respectively.

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Fig. 3. Flow chart of the simulation program.

271 4. RESULTS AND DISCUSSION

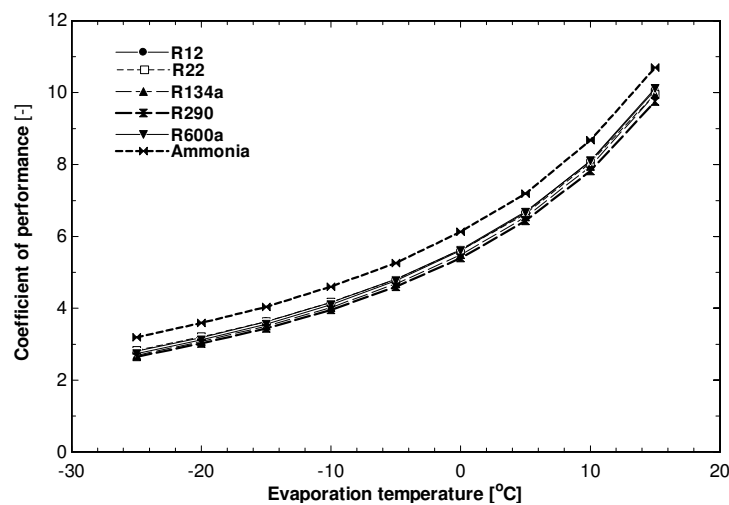
272 In this section, analysis of performance of HCs, R134a, and Ammonia as refrigerants in a
 273 single stage vapor compression refrigeration system based on the use of numerical model
 274 developed for the system are comparatively reported with those of R12 and R22 refrigerants.
 275 Simulation data was generated over a wide range of evaporator and condenser
 276 temperatures -25 to 15°C and 30 to 60°C respectively for various working fluids such as
 277 R12, R22, R134a, R290, R600a and ammonia to observe the performance of the system in
 278 terms of refrigerating effect, coefficient of performance (COP) and overall efficient of the
 279 system.

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281 4.1 Comparative analysis

282 An overview of the performance evaluation of the system based on the effects of
 283 evaporation and condensation temperatures using the selected refrigerants as working fluid
 284 in vapor compression refrigeration system are shown in Figures 4-7. Fig. 4 presents the
 285 variation of coefficient of performance with the evaporation temperature at 40°C condenser
 286 temperature. Evaluating the Fig. 4, it is clear that the COP which is an important parameter
 287 in the analysis of cooling systems like vapor compression refrigeration system increases as
 288 expected with increasing the evaporation temperatures of the system. Close match of COP
 289 values for R600a is observed with that of R12 and R22 counterpart under the similar
 290 operating conditions considered in the present study. It can also be noticed that for the same
 291 capacity compressor, COP of R134a and R290 is less than that of R12 and R22. However,
 292 among the refrigerants used in the simulated system under the similar operating conditions,
 293 the system with the use of Ammonia yields higher COPs and are of up to 6.3 and 7.5%
 294 increment compared with those of R12 and R22 respectively. The effects of condensation
 295 temperatures on the COP of the system at 10°C evaporator temperature using the selected
 296 refrigerants considered in the present study as shown in Fig. 5 revealed that the COP for the
 297 system decrease as the condensation temperature increases. This behaviour is similar to
 298 those observed in the study of Elgendy [12]. From Fig. 5, it can be observed that the COP
 299 value was nearly invariable among the systems simulated with the use of R12, R22, R290
 300 and R600a. However, the simulated system with Ammonia gave highest COP value as
 301 similarly observed in the study of Kilcarslan and Muller [13] and the COP value is of about 6
 302 and 4 at condensation temperatures of 30 and 50°C respectively. This behaviour also
 303 revealed that the system with the use of Ammonia as a working fluid has the better
 304 performance compares with that of R12 and R22 under similar operating conditions.
 305 Simulation of the system with the use of R290 and R600a also showed better performance
 306 compares with other refrigerants considered in this study from the effect of condensation
 307 temperature on the system refrigerating effect point of view as shown in Fig. 7. It can also be
 308 noticed from this figure that the performance of the system with the use of R134a is relatively
 309 close to those of the systems with R12 and R22. The overall efficiency results of the
 310 simulated system with the use of the selected refrigerants obtained using Eq. (18) by taking
 311 into consideration the effects of evaporation and condensation temperatures on the system
 312 are presented in Tables 2 and 3. The results contained in Tables 2 and 3 also revealed that
 313 the overall efficiency of the system with R12, R22, R134, R290 and R600a are nearly
 314 matching the same values while that of the system with Ammonia gave the highest overall
 315 efficiency of the system and the simulation resulted in overall efficiency of about 84 and 92%
 316 at high evaporation and condensation temperatures of 15 and 50°C respectively. These
 317 results justify the reason for better performance of the system with the use of Ammonia
 318 among others refrigerants as displayed in Figs. 4 and 6. The results from this study revealed
 319 that R12 and R22 may be replaced by ammonia, R134a, R600a and R290 without any

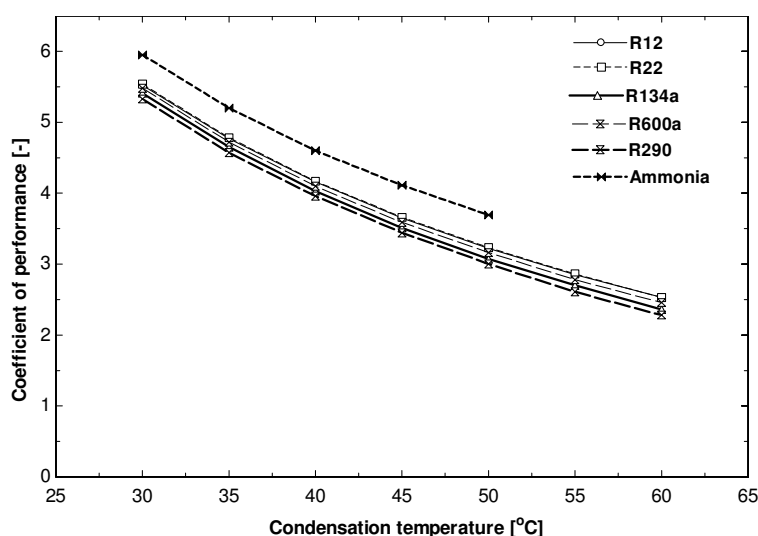
320 significant loss in the overall performance vapor compression refrigeration system
 321 considering the fact that the impact of Ammonia on ozone layer (ODP) and global warming
 322 potential (GWP) is null but based on its corrosive and toxic nature, it can be used by using
 323 safety measure for industrial applications, R134a is easily available in the market and its
 324 impact on the ozone layer is negligible compares with that of R12 and R22, also with the use
 325 of modern hermetically sealed system in refrigeration system, the problems of flammability
 326 posed by the use of hydrocarbons refrigerant are now reduced to some extent. Moreover,
 327 among the refrigerants comparatively analysed, the use of Ammonia was the best working
 328 fluid for the vapor compression refrigeration system simulated in this study. This is because,
 329 the simulated system with ammonia presented the best COP and highest overall efficiency of
 330 the system compares with other refrigerants considered in this work.
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334 **Fig. 4. Variation of coefficient of performance with evaporation temperature**

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337 **Fig. 5. Variation of coefficient of performance with condensation temperature**

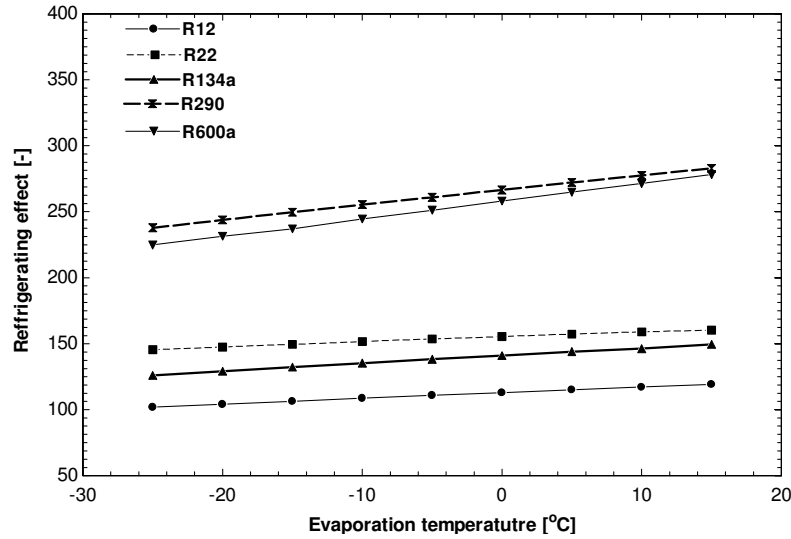


Fig. 6. Variation of refrigerating effect with evaporation temperature

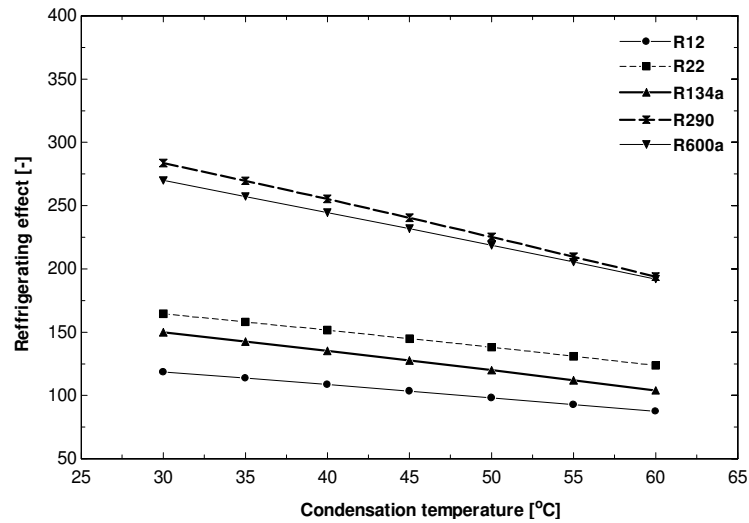


Fig. 7. Variation of refrigerating effect with condensation temperature

Table 2. Effects of evaporation temperatures on the overall efficiency the simulated system.

Tevap [°C]	R12 η [%]	R22 η [%]	R134a η [%]	R290 η [%]	R600a η [%]	Ammonia η [%]
-25	73.7	74.2	70.4	69.5	71.9	83.6
-20	75.5	76.1	72.7	71.6	74.0	85.1
-15	77.3	77.5	74.6	73.3	76.0	86.0
-10	79.1	79.3	76.6	75.4	78.0	87.5
-5	80.7	80.5	78.5	77.0	80.0	88.4
0	82.5	82.3	80.5	79.0	82.0	89.8
5	84.2	83.5	82.3	81.1	84.0	90.5

10	85.8	85.4	84.3	82.9	86.0	91.9
15	87.5	86.4	86.3	84.8	88.0	92.6

Table 3. Effects of condensation temperatures on the overall efficiency of the simulated system.

Tcond [°C]	R12 η [%]	R22 η [%]	R134a η [%]	R290 η [%]	R600a η [%]	Ammonia η [%]
30	84.0	84.3	82.2	81.4	83.4	90.5
35	81.6	81.9	79.5	78.2	80.8	89.0
40	79.1	79.3	76.6	75.4	78.0	87.5
45	76.4	76.6	73.5	72.0	75.1	85.7
50	73.5	73.7	70.1	68.4	72.1	84.2

5. CONCLUSIONS

Analyses of performance of Hydrocarbons (HCs), R134a, and Ammonia as refrigerants in a single stage vapor compression refrigeration system based on the use of simulation model developed for the system are comparatively reported with those of R12 and R22 refrigerants in this paper. Performance evaluation of the system was characterized in terms of coefficient of performance (COP), refrigerating effect and overall efficiency of the system using the various selected working fluid considered in this work. The effects of condensation and evaporation temperatures were studied on the system operation and performances. From the present study, the following main conclusions can be drawn:

- The COP and Refrigerating effect of the vapor compression refrigeration system increase with increasing the evaporation temperatures and decreasing the condensation temperatures of the system.
- Close match of COP and the system overall efficiency values for, R134, R290 and R600a and R290 are observed with that of R12 and R22 counterpart under the similar operating conditions.
- Among the refrigerants simulated in the system under the similar operating conditions, the system with the use of Ammonia yields highest COPs and are of up to 6.3 and 7.5% increment compared with those of R12 and R22 respectively.
- Ammonia was observed to be the best working fluid for the vapor compression refrigeration system presented the best COP and highest overall efficiency of the system compares with other refrigerants considered in this study.
- According to the preceding comparative analysis on performance evaluation of vapor compression refrigeration system. It can be concluded that R12 and R22 may be replaced by Ammonia, R134a, R600a and R290 without any significant loss in the overall performance of the system provided the safety issues are addressed in terms of manufacturing, handling, storage and servicing so as to prevent flammability and corrosive/toxic nature of hydrocarbons and ammonia respectively.

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