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Theoretical Performance Analysis of Different Refrigerants in a Vapour Compression Refrigeration System

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ABSTRACT

This paper comparatively analysis the thermodynamic performance of refrigerants in an ideal vapour compression refrigeration cycle. Refrigerants used for the study are; R-12, R-22, R-134a, R-407c and R410a. Average ambient temperature of Calabar (latitude 4.95^0N and longitude 8.33^0E) was used in this study. Result shows that R-12 refrigerant required the least compressor work input, while R-407c produced the best refrigerating capacity (182.2kJ/kg). R-12 had the lowest power consumption per ton of refrigeration of 0.311. The best Coefficient of Performance (COP) of 11.32 was obtained from the cycle operating with R-12 closely followed by R-410a and R-407c with COPs of 6.97 and 4.91 respectively. However, the environmental impact analysis shows that R-12 has the highest Global Warming Potential (GWP) closely followed by R-410a. R-12 and R-22 have Ozone Depletion Potentials (ODPs) of 0.82 and 0.055 thus indicating a high affinity for ozone depletion. Based on both thermodynamic and environmental analysis, R-407c was selected as the candidate refrigerant to replace R-22 in air conditioners operating in Niger Delta region of Nigeria.

Keywords: Coefficient of Performance; Refrigerating Capacity; Heating Capacity; Global Warming Potential (GWP); Ozone Depletion Potential (ODP)

1 Introduction

Heating, Ventilation, Air-Conditioning and Refrigeration (HVAC&R) provides a broad range of benefits to the society which includes: food preservation, comfort conditioning of living space, temperature control of industrial processes, etc. HVAC&R operates predominantly through vapour compression cycle; this cycle requires a working fluid or refrigerant to operate. Refrigerants are central to refrigeration and air-conditioning equipment. Accordingly, refrigerant selection is cardinal in the reliability and energy consumption of HVAC&R equipment. Refrigerants must satisfy a number of requirements related to safety, chemical stability, environmental properties, thermodynamic characteristics and compatibility among materials. There is no single set off optimum characteristics (especially for thermodynamic properties) and often, there are trade-offs among desirable characteristics. Thus a variety of refrigerants having a range of properties needed to meet the requirement of various applications [1].

As result of ozone layer depletion and increase in global warming due to the emission of greenhouse gases, halons, chlorofluorocarbons (CFC), and hydrochlorofluorocarbons (HCFC) which are used predominantly as working fluids in the HVAC&R industry due to their non-toxicity and non-falmmability have been scheduled for phase out.

In 1987, the Montreal Protocol was adopted for the purpose of restricting the production, consumption and trade of particular substances in order to protect the ozone layer. CFCs had been used as refrigerants for air conditioning equipment and had a significant impact on ozone-layer depletion. The CFCs were designated by this protocol as specified fluorocarbons. Additionally, in 2015, the Sustainable Innovation Forum (COP21) held in Paris adopted the “Paris Agreement” in December of 2015, which is the new international legal framework of the post-2020 period of the United Nations Framework Convention on Climate Change (UNFCCC). The Paris agreement establishes a goal to maintain the increase in the global average temperature to <<<2°C and to pursue efforts to limit the temperature increase to 1.5°C.

In this work, we will thermodynamically compare the performance of five refrigerants used in HVAC&R systems namely: R12, R22, R134a, R407c and R410A. Environmental impact assessment will also be carried out and a candidate refrigerant will be recommended for use based on both studies carried out above for a typical refrigeration system operating in sub Saharan Africa, precisely, Calabar (latitude 4.95°N and longitude 8.33°E), Nigeria.

2 Literature Review

Shaik and Babu [2] theoretically investigated the performance of over 20 ozone friendly refrigerants with GWP ranging from 0.0244 to 1.685 times the GWP of R22 in a window airconditioner. The thermodynamic analysis was conducted using condensing and evaporating temperatures of 54.4°C and 7.2°C. Results obtained showed that COP for the refrigerant mixture R134a/R1270/R290 (50:5:45 by mass percentage) was 2.1% higher than all the other refrigerants studied. The studied also showed that reasonable savings can be achieved if the refrigerant is sused to replace R22.

Messineo et al [3] conducted experimental investigations on an air-conditioning set using Refrigerants R22, R417a, R407c and R404a. COP experimental measurements indicated that substituting a pure HCFC fluid such as R22 is disadvantageous due to the less satisfactorily rendering from their particular thermophysical properties in the system sized for the original fluid. They also concluded that from an environmental stand point, the Tota;L Equivalent Warming Impact (TEWI) may be far more damaging than the the low ODP of the original field.

Choudhari and Sapali [4] investigated the performance of a natural refrigerant, R290 as a possible refrigerant to replace R22. The authors carried their analysis using the standard vapour compression refrigeration system with evaporation and condensation temperature ranged of 10 – 25°C and 45°C respectively. Regrigerant propertieds used in the analysis were obtained from REFROP 9.0 software. Result shows that R290 gave lower estimates for discharge temperature, volumetric refrigerating capacity and mass flow of refrigerant relative to R22. COP of R290 was slightly lower than R22; however the authors noted that the system was designed to operate on R22. They concluded that R290 is a suitable candidate refrigerant to replace R22 as a result of its environmental and thermophysical properties.

Devotta et al. [5] studied R290 refrigerant as an alternative to R22 in a window unit of an air-conditioning system. The study showed that that the cooling capacity and energy consumption of R290 were lower than those of R22 by 6.6 to 9.7% and 12.4 to 13.5% respectively. The COP of R290 was higher than that of R22 by 2.8 to 7.9%

Padalkar et al. [6] conducted simulation and experimental studies on the performance of R290 and R22 for a split air-conditioning unit with cooling capacities up to 5kW. In the work, an initial level air conditioner performance is simulated for cooling capacity, Energy Efficiency Ratio (EER) and refrigerant charge. Tests were conducted in a psychometric test chamber with R-22 and R-290. Test conditions considered as per Indian Standards, IS 1391 (1992) Part I. Rsults obtained showed that R-290 had an EER, cooling capacity and refrigerant charge of 3.7, 4.9 kW and 360 g respectively. Power consumption for R290 was 74% lower than that of R22 while R290 charge was 32% lower than that of R22. Split AC with 5 mm condenser tube OD using R290 as refrigerant gave a 16.5% higher EER and equal cooling capacity compared with R22.

Cheng et al. [11] evaluated the performance of alternative refrigerants, R32 and R290 to replace R22 and R410a in household air-conditioning system based on small finned (5 mm) tube heat exchanger. Results showed that in nominal cooling conditions, the COP of R32 and R290 were 27% and 21% higher than R22, 8% and 3% higher than R410a.

In nominal heating conditions, the COP of R-32 and R-290 were 12% higher than R22, 6% higher than R410A. The systems with R32 and R290 have similar cooling capacities to that with R22 and R410A in heating mode, but huge difference of cooling capacities in cooling mode.

Using charge amount as a factor for considerations, results showed that R290 could be considered as most superior alternative refrigerant in air conditioners with the small finned tube heat exchanger.

From the above research work reviewed, it is seen that several candidate refrigerants have been investigated for recommendation as possible replacement for the refrigerants currently in used especially the R22. However, it is noted that none of these studies were conducted considering the ambient conditions in sub-Saharan Africa. In this work, we will perform a comparative theoretical thermodynamic analysis of five different refrigerants, R12, R22, R134a, R407 and R410a. Environmental analysis will also weigh in heavily in selecting the candidate refrigerants. R12 is included to highlight its merits and also to show why it was discontinued in HVAC&R systems. R22 is currently the predominant refrigerant in domestic application in Nigeria. R134a, R407c and R410A are candidate refrigerants amongst which the best will be recommended for use to Air-conditioners manufactures in Nigeria.

2.1 Basis of Comparative Study

Comparative study is conducted based on an ideal vapour compression refrigeration system with the following basis as shown in Table 1 below:

The parameters shown in Table 1 above are used in the thermodynamic evaluation of the ideal vapour compression refrigeration system, a cycle in which the airconditioning and refrigeration system operates with refrigerants as the working fluids.

TABLE 1
BASIS OF COMPARATIVE STUDY

Comparative Study Parameters	
Ambient Temperature	27 °C
Temperature of conditioned space	15 °C
Maximum System operating pressure range	340 kPa
Minimum System operating pressure range	3.4 MPa

3 THEORETICAL ANALYSIS

Fig. 1 below shows a schematic of the main components in a typical Air-conditioning system with the Temperature-Enthropy diagram shown in Fig. 2. Thermodynamic analysis in this work is based on this setup.

This study is based on an ideal vapour-compression refrigeration cycle with R22 as the working fluid. It is assumed that the system operates under steady state operating conditions with negligible kinetic and potential energy changes. The lower and upper pressure limits corresponds to the operating pressures in evaporator and condenser respectively.

For an ideal vapour-compression refrigeration cycle, the compression process is isentropic; the refrigerant enters the compressor as a saturated vapour at the evaporator pressure, and leaves the condenser as saturated liquid at the condenser pressure. We assumed that the condenser operates at the ambient temperature while the temperature of the conditioning space is equivalent to the compressor inlet temperature. Work done by the condenser is important in telling us the amount of energy that will be required in achieving the desired objective of the air-conditioning system (refrigerating capacity).

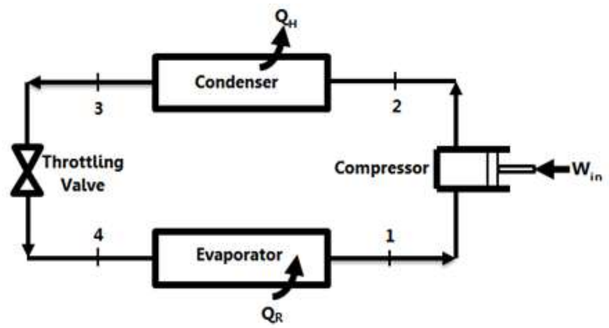

Fig. 1. Schematic of Ideal Vapour Compression Refrigeration Cycle

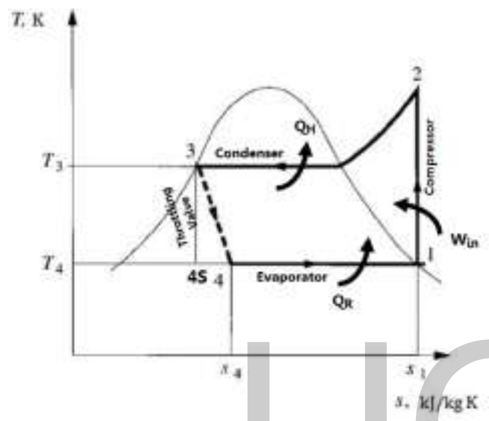

Fig. 2. Temperature-Entropy (T-S) Diagram for an Ideal Vapour Compression Refrigeration System

COP is the significant parameter to predict working effect for cooling and heating systems. For cooling system the COP value means proportion of heat removal from cold reservoir to imported work

From energy balance on the compressor and taking the assumptions into considerations, required work done by the compressor, W_{IN} is given by:

$$W_{IN} = \dot{m}(h_2 - h_1) \quad (1)$$

where m, h_2 and h_1 and are the mass flowrate, enthalpies at the compressor exit and inlet respectively.

Similarly, the energy balance at the condenser can be computed and thus the heat rejection capacity, Q_H can be obtained as:

$$Q_H = \dot{m}(h_2 - h_3) \quad (2)$$

where h_3 is the enthalpy at the condenser exit.

The energy balance on the evaporator and thus the refrigeration capacity, Q_R can be obtained thus:

$$Q_R = \dot{m}(h_1 - h_4) \quad (3)$$

where h_4, is the enthalpy of the working fluid (refrigerant) at the inlet to the evaporator.

Coefficient of Performance (COP) of the refrigeration system can be obtained as:

$$COP = Desired\ Output/Required\ Input = Q_R / W_{IN} \quad (4)$$

The specific power, W_{SP}, is the electrical power consumption per ton of refrigeration and is given as:

$$Wsp = 3.561 \cdot COP^{-1} \quad (5)$$

This study is based on an ideal vapour-compression refrigeration cycle with R-22 as the working fluid. It is assumed that the system operates under steady state operating conditions with negligible kinetic and potential energy changes. The lower and upper pressure limits corresponds to the operating pressures in evaporator and condenser respectively. For environmental analysis, the GWP_{100} and ODP will be used as key parameters are selecting a candidate refrigerant.

Thermodynamic properties for the refrigerants used in this study were obtained from the publicly available Dupont® Industries' charts. The charts are based on values computed using the National Istuitute of Standards and Technology (NIST) REFROP Standard Reference 23, Thermodynamic and Transport properties of Refrigerants and Refrigerants mixtures – REFROP version 6.01, standard Reference Data Program, National Institute of Standards and Technology, 1998).

4 Results and Analysis

In this section, results obtained from this study and its corresponding analysis will be presented. Results are delineated into compressor work input, refrigerating capacity, heat rejection capacity, coefficient of performance and specific power. Additionally, the influence of ambient temperature on the COP and their environmental impact of are also analysed. It was worth noting that the thermroperties

4.1 Work Input to the Compressor

The required work input to the compressor for the five refrigerants used in the study was conducted and results are shown in Fig. 2 below. In the figure, work input by the compressor is shown as a function of the different refrigerants. Results indicates that of the five refrigerants, R134a requires the highest compressor work input of 38.96 kJ/kg while the least compressor work input requirement of 11.8 kJ/kg is from R12.

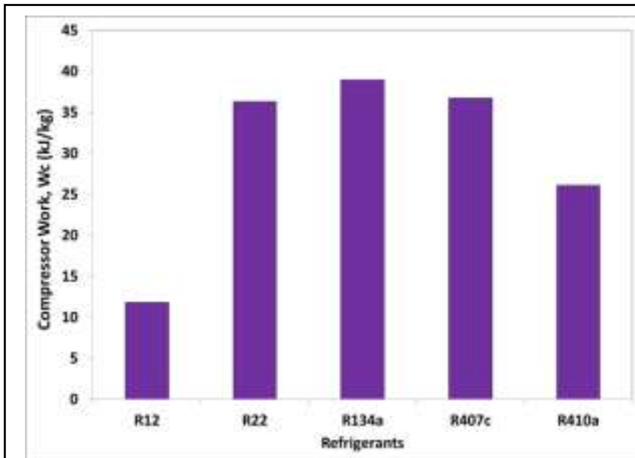

Fig. 3. Compressor Work Input for different Refrigerants

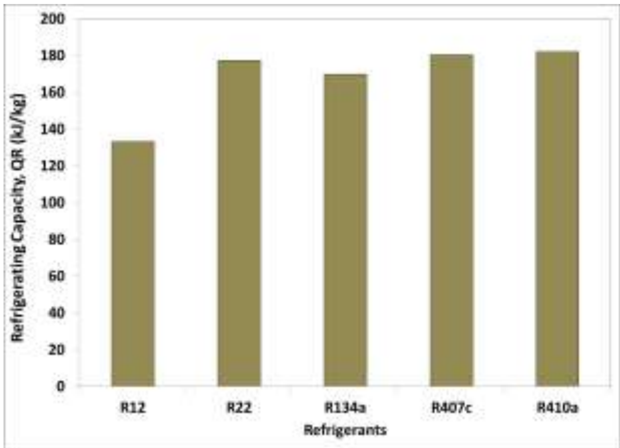

Fig. 4. Refrigerating Capacity for different Refrigerants

4.2 Refrigeration Capacity

The main objective of the air-conditioning system is to keep a confined space under certain pre-set conditions. Refrigerating capacity is a measure of the cooling capacity. Fig. 4 above shows a plot of refrigerating capacity as function of refrigerants. From the plot, it is observed that R410a produces the maximum refrigerating capacity of 182.2 kJ/kg. The minimum refrigerating capacity of 133.3 kJ/kg was observed for R-12.

4.3 Heat Rejection Capacity

When air-condition units are used in the reverse direction, it can serve as heating units. Fig. 5 above shows the heat rejection capacity of the refrigerants, from the plots, it is seen that the refrigerant with the best capability for heat rejection is R407c. Heat rejection capacities for R12, R22, R134a and R410a are 145.1 kJ/kg, 213.7kJ/kg, 208.76 kJ/kg and 208.3 kJ/kg respectively.

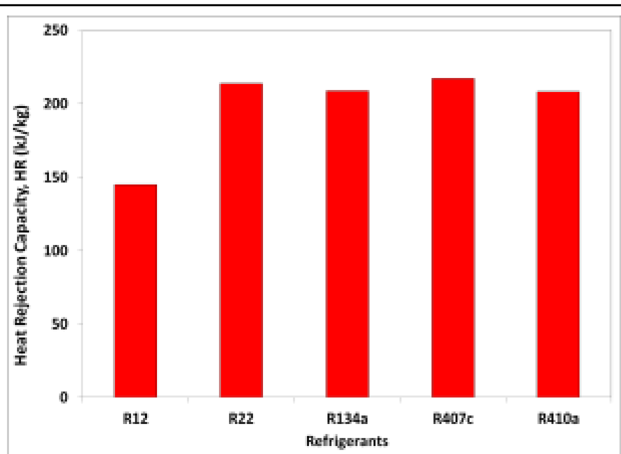

Fig. 5. Heat Rejection Capacity for different refrigerants

4.4 Coefficient of Performance (COP)

The COP of refrigeration is an important parameter that gives the ratio of the desired output and the required work input. It is observed from Fig. 6 above shows that R12 is the refrigerant with the best COP of 11.30 followed by R410a with 6.97. R 134a gave the worst COP with 4.36 kJ/kg amongst those tested.

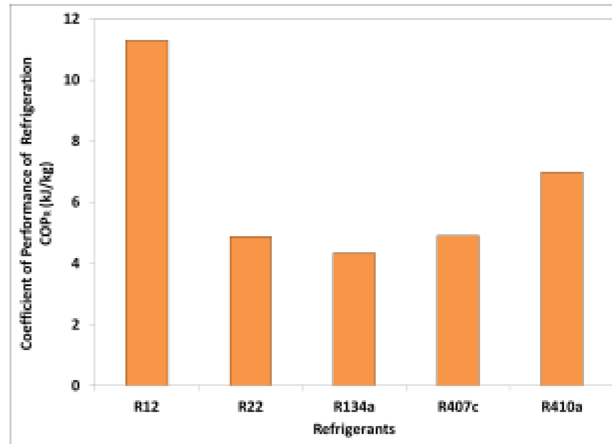

Fig. 6. Coefficient of Performance as a function of differ Refrigerants

4.5 Specific Power

As earlier described, specific power is the electrical power consumption per ton of refrigeration. Fig. 7 shows a plot of specific power as a function of different refrigerants. It can be observed that the most efficient system operates using R12 refrigerant with specific power, *Wsp* given as 0.31. Relative to other refrigerants, R134a has the most power with *Wsp* of 4.36.

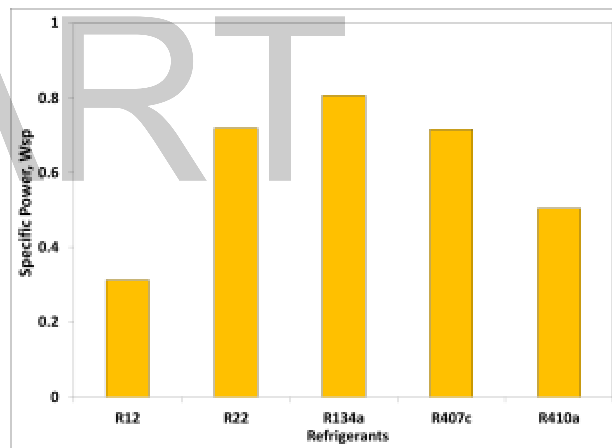

Fig. 7. Specific Power for different Refrigerants

4.6 Influence of Ambient Air Temperature

Ambient air in the parametric study was varied within the range found in Calabar (31°C to 21°C). Using R22 refrigerant, the COP was computed at different ambient temperature.
Fig. 8 shows that the COP decreases as the ambient temperature increases. This is due to the increased work requirements for reducing a temperature from relative high values to the conditioned space temperature of 15°C. Furthermore, we observe that for the ambient temperature at 31°C, the refrigerating space will required more work to reach the target 15°C than it will require for 21°C. Heat rejection will also be imparted as the temperature gradient required for heat rejection will be reduced hence, more difficult to reject heat to ambient.

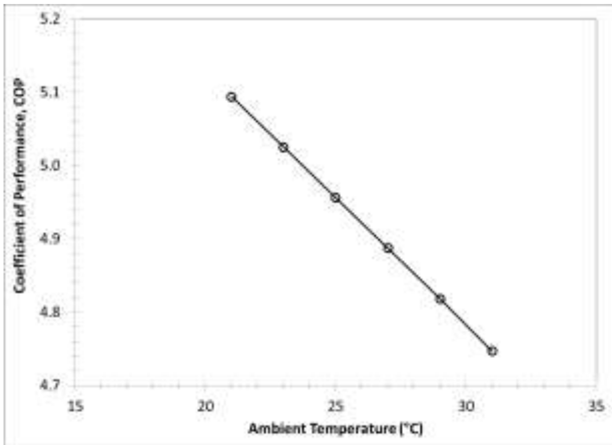

Fig. 8. CoP as a function of Ambient Temperature for R22

4.7 Environmental Impact

Table 2 below shows the Environmental specifications of each refrigerant considered in this study. It is seen that R-12 has the highest GWP100 closely followed by R-410a. This indicates that these two refrigerants contribute the most to global warming. R-12 and R-22 have ODPs of 0.82 and 0.055 thus indicating a high affinity for ozone depletion by these two refrigerants relative to the others considered in this study. It is also worth noting that recent protocols have be banned by the UN protocols on environment as it concerns refrigerants.

4.8 Selecting Candidate Refrigerant

From results analysis above, it is seen that no one refrigerants suits all. We will now select a candidate refrigerant based on power consumption, environment of operation, environmental concerns and material requirements. Conclusively, R410a and R407c are the front runners in this selection. R-410a is seen to possess better thermodynamic performances such as better COP and better refrigerating effect it however requires the entire air-conditioning unit system to be upgraded such that it is able to withstand the extra 50% of pressure the refrigerant adds to that of R22. R407c which is environmentally friendlier and less viscous hence requiring relatively lower compressor work input, lower W_{SP}, higher heat rejection capacity, lower ODP and lower GWP_{100} is chosen over R-410a as the candidate refrigerant to replace R-22.

Conclusion

A study to select a candidate refrigerant to replace R22 predominantly used in Nigeria has been conducted. Refrigerants R12, R22, R134a, R407c and R410a were used in the study. Ambient conditions in Calabar (latitude 4.950N and longitude 8.330E), a city in the Nigerian Niger Delta region was used in the study. Results indicated that R-12 refrigerant required the least compressor work input for the thermodynamic cycle analysis. R-407a produced the best refrigerating capacity of 182.2 kJ/kg. The best COP was obtained the cycle operating with R-12 closely followed by R-410a and R-407c with 6.97 and 4.91 respectively.

Analysis of the COP at varying ambient temperature indicated that the COP increased with decrease in ambient temperature.

R407c which is environmentally friendlier, lower *Wsp*, higher heat rejection, lower ODP and lower GWP_{100} is selected as the candidate refrigerant to replace R22.

TABLE 2: ENVIRONMENTAL SPECIFICATIONS FOR REFRIGERANTS IN THIS STUDY

Specifications	**Refrigerants**				
Industry Name	R12	R22	R134a	R407c	R410a
Chemical Formula	CCl_2F_2	CHClF2	CH_2FCF_3	R32+R125+R13a	R32+R12
				23%+25%+52%	50%+50%
Category	CFC	HCFC	HFC	HFC	HFC
GWP_{100}	2400	1700	1430	1300	2000
ODP	0.82	0.055	0	10^{-5}	2×10^{-5}

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