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Analysis of Compressor Work and Cooling Effect of Refrigerants

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ABSTRACT

The performance of different refrigerants, R-132, R-404A, R-407C, R-410a, R-507A, R-123 and R-134a, in vapor compression refrigeration cycles were investigated. Analysis was made on the vapor compression refrigeration cycle and the experimental test rig developed from locally sourced materials. The co-efficient of performance (COP) obtained as the ratio of cooling effect of the evaporator to work done on the compressor, was used for performance evaluation of the refrigerants. The COP of R-132a obtained as 7.178 for 0.8 bar, 3.722 for 1 bar, 4.696 for 1.2 bars and 5.612 for 1.4 bars showed good performance on the reference scale of R-12 with 8.652 for 0.8 bars, 4.011 for 1 bar, 5.792 for 1.2 bars and 6.421 for 1.4 bars. It was revealed that R-132 with the closest COPs to R-12 in addition to its zero ozone depleting and low global warming potential could functionally replace the CFCs based R-12 thereby averting environmental degradation.

Keywords: Refrigerants, COP, Pressure, Vapour- cycle, cooling effect.

INTRODUCTION

Refrigeration is the achievement of a temperature below that of the immediate surroundings [1]. To maintain this low temperature, it requires the removal of heat from the product at low temperature and the discharge of this heat to a higher temperature. The science of refrigeration is based on the fact that a liquid can be vaporized at any desired temperature by changing the pressure above it [2]. This liquid serving as the working fluid of a refrigerating system is referred as refrigerant and its selection involves compromises between conflicting desirable properties.

The group of chemical compounds called Chlorofluorocarbon (CFC) refrigerants has been in wide spread use since the1930s in such diverse applications as refrigerants for refrigerating and air-conditioning systems, blowing agents for plastic foam solvents for micro electronic circuitry and dry cleaning sterilants for medical instruments [3]. The linkage of the CFC refrigerants to the destruction of the ozone layer, which has already been established. This was attributed to their exceptional stability which allows them to thrive in the atmosphere for decades and ultimately diffusing to the rarefied heights where the stratospheric ozone layer resides [4]. The inventors of these refrigerants could not have visualized the ravaging effects of the refrigerants on the ozone layer. According to [5], refrigerants followed intentionally standard with the exceptional stability and force as one of the essential ideal refrigerant requirements.

The adverse severity was further emphasized through government intervention through the ban of their uses.The most environmentally unsafe refrigerants, such as CFCs are already banned. HCFC will be phased out by developed countries in 2020 and for developing countries in 2030. R22 was accepted as the most suitable refrigerant after R12 but it will be phased out as per the schedule [6]. Consequently, more environmentally friendly refrigerant are investigated, replacing Feron 12 (R-12) and R22 that is CFCs and HCFCs based with huge attendant environmental hazard. Also, when selecting the refrigerant, the device application and temperature range must always be analyzed in order to be able to determine the optimal refrigerant.

This work aimed at experimental investigations of the selected refrigerants: R410a, R407c, R134a, R132, R123, R507c and R404a in the vapour refrigeration system and comparative evaluation of their coefficient of performance against the high COP of R-12 though with its ozone depletion tendency will be conducted. At the end of this study, the refrigerant that has the highest COP nearer to that of the environmentally un-friendly refrigerant (feron-12) will be recommended in addition to its zero ozone depleting and low global warming potential.

MATERIALS

In order to carry out an experiment on eco-friendly refrigerant that replaced refrigerant R-12, an experimental test rig of vapour compression refrigeration laboratory system was designed and constructed in MPEAL, ESUT, Enugu Nigeria using locally sourced material. The materials including refrigerants were sourced from Kenyata, Camp and Timber-Abakpa Markets all in Enugu. The selections of the refrigerants were based on availability and eco-friendliness. Meanwhile, Refrigerants 12 which is eco unfriendly because of ozone depletion potential was selected for purpose of comparison. Such eco-friendly refrigerants needed to replace CFCs based feron-12 (R-12) and HCFCs based R-22 include the following; R-132, R-404A, R-407C, R-410a, R-507A, R-123, R-134a and their properties were shown in Table 1.

Description of the Experimental Rig

The schematic diagram and the assembled rig of the developed vapour compression refrigeration cycle are shown in Fig. 1 and Fig. 2. The rig setup consists of:

- the compressor (capacity required for the design is about 1.12kW to 1.87kW (1.5Hp – 2.5Hp).)
- Condenser
- Evaporator
- Throttllig Valve
- Fan
- Pressure Gage
- Mercury In Bulb Thermometer
- Temperature Regulator
- Compressor Oil
- Refrigerants and
- Frame

The compressor mounted at the downside of the rig, connected to the condenser with copper tube. The condenser is mounted at the middle of the frame rear or back, with pressure gage and mercury in bulb thermometer connected between the compressor outlet and condenser inlet. The condenser is connected to the throttling valve, with pressure gage and mercury in bulb thermometer between the condenser outlet and throttling valve inlet. The evaporator is mounted at the top of the rig enclosed in a transparent glass box. It is connected with throttling valve outlet, with pressure gage and mercury in bulb thermometer in between the two.

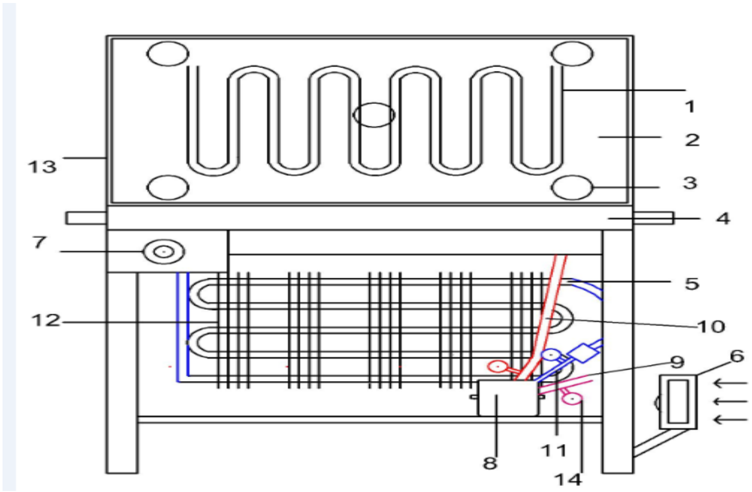

Fig. 1: Schematic diagram of an experimental apparatus for demonstrating vapour compression refrigeration system

1. Copper pipes, 2.Fibre glass, 3.Themometer opening, 4.Bed, 5.condenser, 6.Fan 7. Thermostat, 8.Compressor, 9.Gas inlet (P1), 10.Pressure exit (P3), 11.Expansion, 12.Fins 13. Body frame and 14.Pressure gauge meter

The evaporator is connected back to the compressor with the help of copper wire to complete the cycle. The pressure gauge used in this study was calibrated from 1 to 10bar. The thermometer was mercury in bulb thermometer. Temperature Regulator is a device in the trainer system used to regulate the power and temperature variations, so that the system will maintain steady state. At each of the experimental run, the system was flushed with refrigerant oil. It kept the system from being contaminated at any point in time. They were also used for lubrication, removal of excess heat and for checking leakages. The temperature and pressure of the refrigerant at the compressor inlet and temperature is measured in degree Celsius (°C) and pressure is measure in bar.

Experimental Procedure

After all the components were fixed rigidly on the board. The compressor chosen was a reciprocating type, power 0.746 kW, and swept volume 30.4 cm^3. The evaporator is a bare plate with inner coil tube for refrigerant flow. The tube inner diameter is 6.8 mm and tube length is 6.6 m. The dimension of the evaporator is 0.58 x 1.27 m. The evaporator is connected at one end to the capillary tube and at other\ end to the compressor. The selection of the capillary tube was based on the following requirements; ability to provide the required pressure drop to tolerate the refrigerant and to operate within the temperature range adequate capacity. The required length of capillary tube depends mostly on the size of the system. In this system the coiled capillary tube has the following dimensions: pipe inner diameter 1.2 mm, outer diameter 1.9 mm, tube length 1000 mm and coiled diameter 52 mm.

Dryer-filter and receiver were connected in between capillary tube and condenser. The Condenser is a finned tube pipe with inner diameter 6.8 mm, outer diameter 7.6 mm and tube length 8.4 m. The condenser is fixed together by the side of compressor, which formed a compact assembly of a condensing unit. The joints were all brazed. The sizing of the tube was done with Ashrae recommendations and guide lines. Following the complete assembling of the components, the copper lines were tested for leaks then the system was charged with refrigerant R-132, R-404A, , R-407C, R-134a, R-507A, R-123, R-410, and eco-unfriendly refrigerant R-12.

Additionally, duct tape was used to insulate the copper lines. The experimental set-up has a control system that consists of an on/off switch triggered by temperature-sensing bulb, to control the temperature of the evaporator. The control system turns the motor on at 7°C and off at 5°C under control point of 6°C.

Analysis of Vapour Compression Refrigeration System

The analysis of the vapour compression cycle is based on the refrigerants alternately evaporating and condensing, with one of intervening processes being a compression of the vapour. Fig.3 is ideal refrigeration, fig. 4 is T-S diagram of standard vapour compression cycle process, and figure 3.14 is the p-h diagram of standard vapour compression cycle. From 1-2 compression process, 2-3 condensation process, 3-4 expansion process and 4- 1 evaporation process. Fig.4 and 4 are the temperature- entropy T-S) and pressure-enthalpy (P-H) diagrams for the analysis.

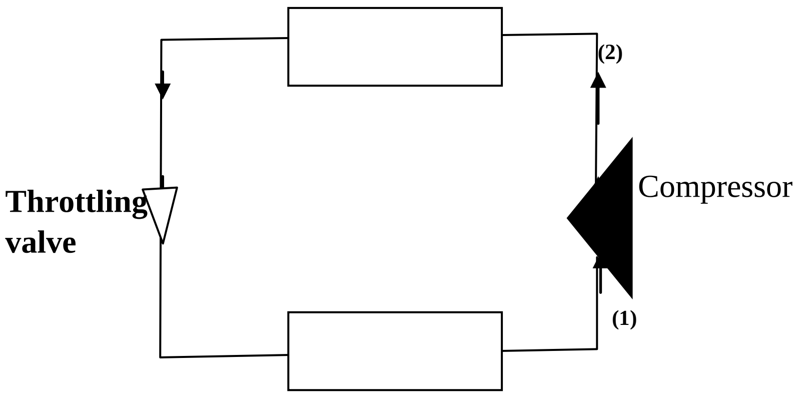

Fig. 2: Ideal Refrigeration Cycle

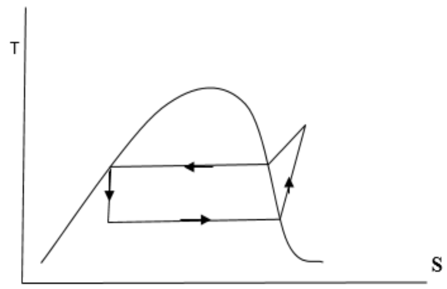

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Fig. 3.: T-S diagram of standard vapour compression cycle

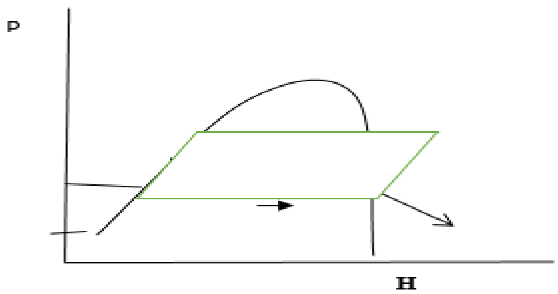

Fig.4: The p-h diagram of standard vapour compression cycle

The processes comprise the following:

i. Reversible and adiabatic compression from saturated vapor to the condenser pressure.
ii. Reversible rejection of heat at constant pressure de superheating and condensation.
iii. Irreversible expansion at constant enthalpy of saturation liquid to the evaporation pressure.
iv. Reversible addition of heat at constant pressure in evaporation to saturator vapour

Analysis of Vapour Compression Cycle

The analysis is based on energy equation of fig. 2, for a steady-flow process of Bernoulli's equation(1) (Rajiput, 2007), as;

$$\frac{V_1^2}{2g} + z_1 + h_1 + q = \frac{v_2^2}{2g} + z_2 + h_2 + w \quad (1)$$

For the analysis, changes in kinetic and potential energies were neglected as a consequence of negligible fluid velocity and equal height from the control volume. This reduces equation (1) to equation (2) as

$$h_1 + q = h_2 + w \quad (2)$$

Where h_1 is reference enthalpy (kJ/kg) at point 1

$h_2$is reference enthalpy(kJ/kg) at point 2

q is quantity of heat (kJ)

w is work done (KJ)

For process 1.2: Reversible and adiabatic compression, q = 0

thus equation (3) reduces to equation (4)

$$h_1 + 0 = w + h_2$$

$$h_1 - h_2 = w,$$

$$w_{in} = h_1 - h_2 \quad (3)$$

For process 2-3: Irreversible heat rejection, no work done (w=0), equation (3) reduces to equation (4), as ;

$$h_2 + q = h_3 + 0, \quad (4)$$

$q = h_3 - h_2$, thus

$$\boldsymbol{q_{cond.} = h_3 - h_2} \quad (5)$$

For process 3-4: Irreversible expansion; w = 0, Q = 0

Thus, equation (3.3) reduces to equation (3.6), i.e;

$$h_3 + q^0 = h_4 + w^0,$$

Hence

$$h_3 = h_4 \tag{3.6}$$

For process 4-1: Irreversible heat addition: no work done (w=0),

thus equation (3) reduces to equation (6), as ;

$h_4 + q = h_1 + w^0$, from which

$$q_{evap} = h_1 - h_4 \tag{6}$$

Then, equation 6$\left(q_{evap} = h_1 - h_4\right)$is known as the refrigerating effect and represents the amount of cooling capacity of the system of refrigerating effect. This is one of the parameters used to evaluate refrigerant performance.

The coefficient of performance (COP), is determined as the ratio of the cooling capacity or refrigerating effect of the system (Equation 6) to work input to the system (Equation 4) as given in Equation (7);

$$\mathrm{C.O.P} = \frac{q_{evap}}{W_{in}} = \frac{h_1 - h_4}{h_2 - h_1} \tag{7}$$

This importance performance parameter of equation 7 is the basis for comparative evaluation of and the choice of refrigerant in addition to its Ozone layer depletion tendency and Global warming potential. The COPs of each refrigerant

RESULTS AND DISCUSSION

Analysis of Compressor Work/Cooling Effect of Refrigerants

The result of the effect of refrigerants on compressor work/cooling effect at 0.8bar were shown in Fig. 5. Fig.5 shows that the refrigerants compressor work at 0.8bar is lower than the cooling effect. The compressor work started with an increase from 80 KJ/kg to 89.2 KJ/kg at refrigerants of R-410 and R-404, as the cooling effect decreased from 210KJ/kg to 150.8. However, compressor work decreased to 31.7KJ/kg, when the cooling effect was 53.9 at R-123. Thus, R-12 recorded least compressor work of 19 53.9 with an increased cooling effect 164.4 nearer to the cooling effect 152.9 KJ/kg of R-132.

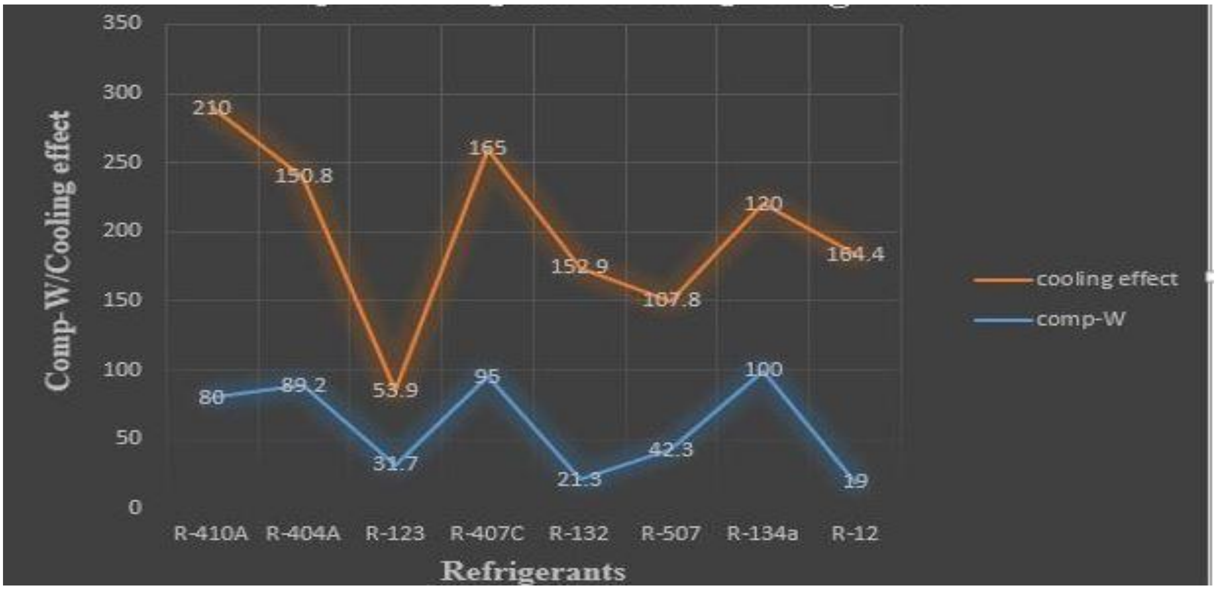

Fig. 5 : Effect of refrigerants on compressor work/cooling effect at 0.8bar

The result of the effect of refrigerants on compressor work/cooling effect at 1bar are shown in fig.6 . Fig.6 shows that the refrigerants compressor work at 1 bar is also lower than cooling effect. Here, the compressor work increased from 118 to 132.5 KJ/kg at refrigerants of R-410 and R-404, with the cooling effect increase of 180 to 167.5 KJ/kg. However, compressor work decreased to 49.9 KJ/kg, when the cooling effect was 58.4 KJ/kg at R-123. Then R-12 recorded compressor work of 45.75 KJ/kg with an increased cooling effect 183.5 KJ/kg nearer to the cooling effect 172 KJ/kg of R-132.

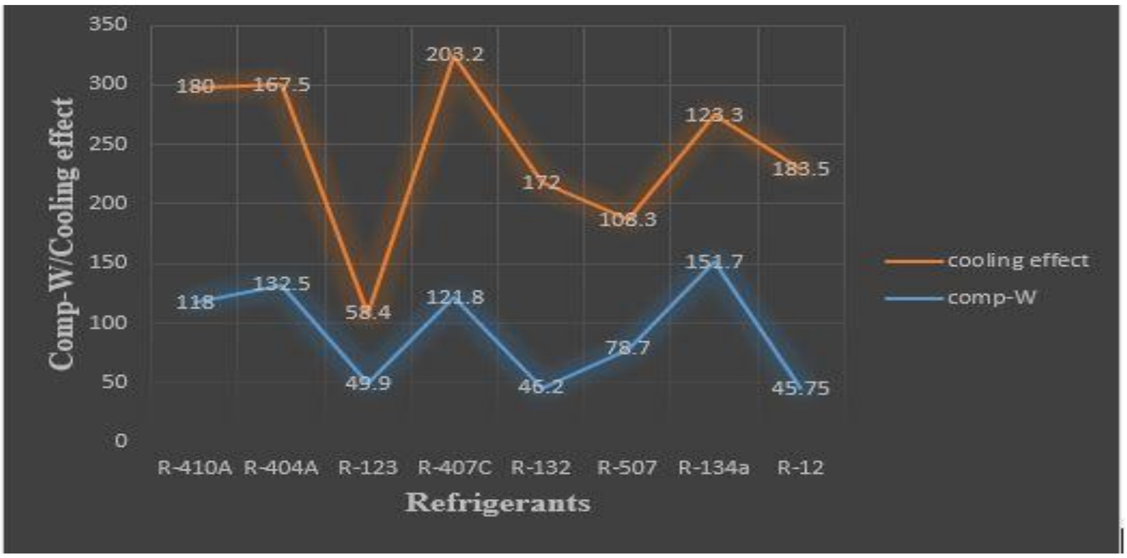

Fig.6 : Effect of refrigerants on compressor work/cooling effect at 1bar

The result of the effect of refrigerants on compressor work/cooling effect at 1.2 bar were shown in fig.7. Fig.7 shows that the refrigerants compressor work at 1.2 bars is also lower than the cooling effect. Here the compressor work decreased from 135KJ/kg at refrigerants of R-410 and R-404, with the cooling effect decrease of 300 to 225 KJ/kg. However, compressor work decreased to 48 watt, when the cooling effect was 81.9 KJ/kg at R-123. Thus, R-12 also recorded least compressor work of 42.7 KJ/kg with an increased cooling effect 247.6 KJ/kg nearer to the cooling effect 240 KJ/kg of R-132.

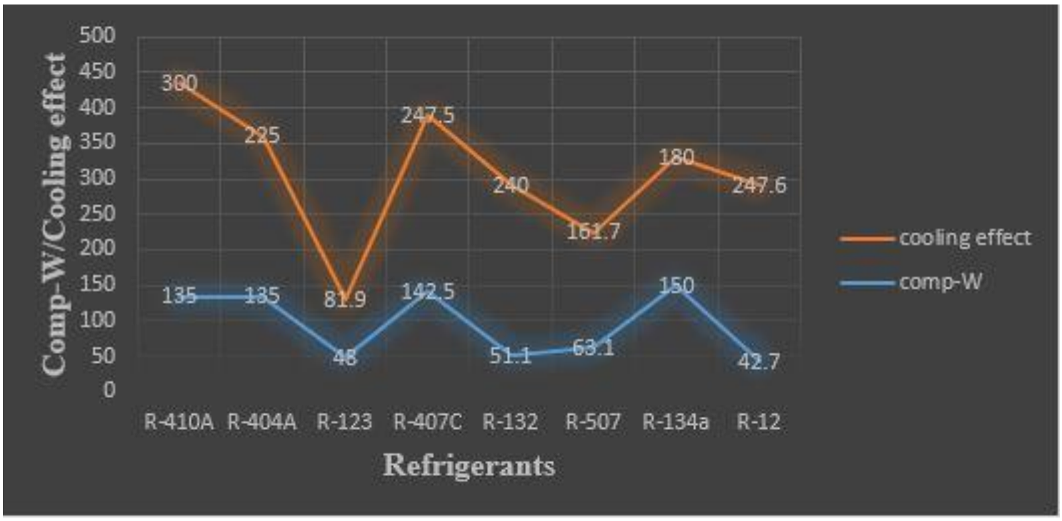

Fig.7: Effect of refrigerants on compressor work/cooling effect at 1.2bar

The result of the effect of refrigerants on compressor work/cooling effect at 1.4 bar were shown in fig.8. Fig.8 shows that the refrigerants compressor work at 1.4 bar is equally lower than the cooling effect. The compressor work increased from 140 to 157.5 kJ/kg at refrigerants of R-410 and R-404, with the cooling effect decrease of 367.5 to 262.5 kJ/kg. However, compressor work decreased to 55.4 KJ/kg when the cooling effect was 96.2kJ/kg at R-123. Then R-12 recorded again least compressor work of 43.25KJ/kg with an increased cooling effect 277.7 watt nearer to the cooling effect 245.8KJ/kg of R-132. The above effects deduced that R-123 compressor works and cooling effects were always lower followed by R-132. However R-12 being eco-unfriendly can be replaced with R-132 of eco-friendly that has nearly the same cooling effect of 240 KJ/kgat 0.8bar, 245.8 KJ/kg at 1bar, 245.8 KJ/kg at 1.2 bar and 172 KJ/kg at 1.4 bar.

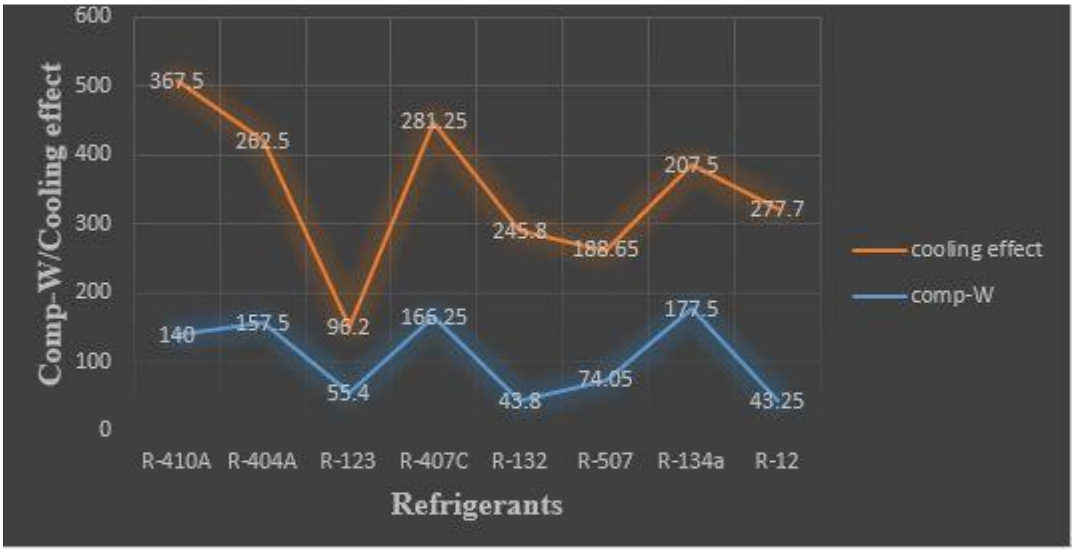

Fig.8: Effect of refrigerants on compressor work/cooling effect at 1.4bar

CONCLUSION

A vapour compression refrigeration test rig has been developed for evaluation of coefficients of performance of seven ecofriendly refrigerants against a reference eco-unfriendly refrigerant. The system coefficient of performance was obtained as the ratio of cooling effect at the evaporator and work done on the compressor. The comparison of COP's for the vapor compression cooling cycle situations carried out showed that pressure and operating temperature of the units in vapour compression system are elements that increase the COP but this increase rate varies depending on the type of refrigerant used. It was seen that for all the refrigerants, the COP values increase with increase in pressure to compressor inlet but decreases as the compressor power increases with increasing evaporation temperatures. COP value of R 132 was high for evaporation temperatures below -25 ˚C and it is advisable to use this refrigerant rather than the others at these temperatures. It was revealed that R-132 that has closest COP to the reference R-12 with other functional properties can comfortably replace it. The COP of R-132 was obtained as 7.178 for 0.8bar, 3.18 for 1bar, 4.69 for 1.2bar and 5.61 for 1.4bar at average mass flow rate of 2.8kg/min as against R-12 of 8.65 for 0.8bar, 4.01 for 1bar, 5.79bar for 1.2bar and 6.42 for 1.4bar. This refrigerant R-132 that has almost the same value of coefficient of performance (COP), as R-12 was suggested for its replacement.

Thus,performance evaluation showed that irrespective of the pressure inlet to compressor, the COP of R-132 was highest among the compared refrigerants. It showed that R-132 that has the closest COPs of 7.1784 to 8.6526 R-12 at 0.8bar, 5.5476 to 6.420809 R-12 at 1bar, 4.69667 to 5.79859 R-12 at 1.2bar and 3.7229 to

4.0109 R-12 at 1.4bar is better suggested for the replacement for environmental eco unfriendly refrigerant R-12.

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