

Development of a Refrigerant Recovery and Recycling Machine

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Abstract
Indiscriminate discharge of refrigerants into the atmosphere during servicing or overhauling of refrigerating systems by Heating, Ventilation and Air-conditioning (HVAC) Practitioners is one of the major contributing factors to ozone depletion and climate change. **The objectives of this study are to:** design, fabricate and evaluate the performance of refrigerants recovery and recycling machine. The machine with 19.44 kg/hr rated capacity produced at cost of N106, 503.00 (about USD 500) with locally sourced materials comprises: compressor, drier, capillary tube, solenoid valves, two (2) pressure gauges and heat exchanger as functional parts. In order to evaluate the performance of this machine, R-12 and R-22 refrigerants were considered for its analysis and results showed that for every 1 kg refrigerant recovered and recycled it has average recovery and recycling efficiencies of 88.5 % and 85.68 % whilst recycling used refrigerant to 99.9 % of its original purity.
Keywords: Refrigerants, Ozone Depletion, Global Warming, Recovery, Recycling, Performance evaluation

1.0: Introduction
Global warming is contributed to by the emission of man-made “greenhouse” gases. These gases when collected and held in the earth, radiates out the heat evolved into space. This heat causes the temperature in the atmosphere to rise and has effect on climate. It is noticeable that climate change causes a number of effects including damage to crops, or even the melting of polar ice caps (Brian 2004). Due to these environmental problems, concerns associated with refrigerants, in March 1985, the Montreal protocol was signed in Vienna, Austria. The protocol controls consumption, production plus importation minus exportation and production of Ozone depleting substances. The enforcement of this protocol commenced in January 1989. The protocol has since been amended and adjusted to set internationally agreed phase-out schedules for all significant Ozone Depleting and global Warming substances such as CFCs and HCFCs, (Kortenhorst, 2010).

In Nigeria as a catchall, it was observed that refrigeration and air conditioning (RAC) practitioners contributed majorly to the rate at which the OD's refrigerants is being released, indiscriminately, to the air space during their practice. In order to reduce this high rate, United Nations Development Programme (UNDP) in collaboration with the Federal Ministry of Environment in Nigeria (FME) conducted international-train-the-trainer-training workshop on good refrigeration practice. At the end of the training of the practitioners, the UNDP in conjunction with the FME procured and distributed ODs Recovery and Recycling machine (4 to each state of the federation) which is about 150 machines for over 28, 000 trained practitioners. Due to funding capacity of these artisan, it is very difficult for them to procure this machine; The reason for this is not far fetch, the capital cost of the machine and the cost of importation is very high (Omotosho, 2006), this makes the machine to be scarce Therefore, this calls for the need to construct a functional recovery and recycling machine using available locally sourced materials to substitute for the high cost imported CFCs recovering and recycling machines.

2.0: Refrigerant Recovery and Recycling Equipment
The use of refrigerant recovery and recycling equipment is an essential means of conserving refrigerant during servicing, maintenance, repair, or getting rid of refrigerants prior to disposal of refrigeration equipment. The temporary storage capability of the equipment prevents the release of refrigerants into the atmosphere that may otherwise exist if the refrigeration and air-conditioning equipment were opened to the atmosphere during servicing. Recycling equipment is expected to remove oil, acid, particulate, chloride, moisture, and non-condensable (air) contaminants from used refrigerants. A variety of recycling equipment is available over a wide price range. Table 1 shows some of the types of refrigerant recovery and recycling machine in existence as at 2015, their specifications and market values.

Table 1 Different type of Refrigerant Recovery and Recycling Machine

Machine	Manufacturer	Specification		Market Value ($)
		Power Source	Operating Range (^0F)	
AR2788S	CPS	115 V / 60 Hz	$50-120$	4,575.00
MAS69789	Mastercool	115 V / 60 Hz	$50-120$	5,585.00
ROB17800B	Robinair	115 V / 60 Hz	$32-120$	6,599.00
RTIRHS980H	RTI	120 V / 60 Hz	$50-120$	6,130.00
ARS3000	ARS	220 V / 60 Hz	$50-120$	5,150.00
ECOSAVERRS13	Asada	220 V / 60 Hz	$50-120$	7,130.00
FR747	YCE	220 V / 60 Hz	$32-120$	7,219.00
RCC6A	Tektino	220 V / 60 Hz	$32-120$	8,650.00
ACM8600	Winsen	220 V / 60 Hz	$50-120$	9,344.00
HOL800	Honow	220 V / 60 Hz	$50-120$	7,500.00

Source: *Toolbox, 2011*

Other contributory effcets of this device include: minimum atmospheric emissions coupled with reduction in unfavourable enviromental impacts of refrigerants when allowed to escape into the air space, increment in market opportunities for used refrigerants, reduction in enviromental compliance costs, reduction in the need for new refrigerant after servicng and ultimately increaese in the lifetime of refrigeration equipment due to contaminants removal.

2.1 Design Analysis and Procedure

The design focused on the thermodynamics working conditions of the machine. The important components considered are; compressor, heat exchanger (the heat exchanger was designed to be used as condenser and evaporator) and capillary tubes. It is assumed that there is a steady flow of refrigerant through all these components to get a desired effect. The values of any of the various properties of refrigerant can be directly read off the P-h chart which is for 1kg mass of refrigerant and hence all the properties are for 1kg mass.

2.2 Design Assumptions and Criteria

During the design the following factors were assumed based on the proposed refrigerants to be recovered, that is R12 and R22:

- Mass flow rate $\dot{m} = 0.00667\ kg/s$
- Suction Temperature $T_1 = -32$ ℃
- Ambient Temperature $T_2 = 25$ ℃
- Specific volume V_1 at -32℃$= 0.174706\ \mathrm{m}^3/kg$
- Compressor with volumetric efficiency (η_{vol}) between 70-80 % (Arora, 2010) for the purpose of this design assuming η_{vol} = 75% = 0.75
- Mean Piston Speed, V_p. for modern compressor = 4 m/s, (Arora, 2010 and Ballaney, 2002). Then, a V_p of 4 m/s was used.
- Condensing temperature of refrigerant is 54.44 ˚C and temperature of hot refrigerant leaving compressor to heat exchanger is 93.3 ˚C (Althouse, 1998)
- Recommended fluid velocity through pipes and hoses in hydraulic system is between (2 and 5) m/s (Arora, 2010), therefore, V_p = 4 m/s; Discharge temperature = 10 ºC
- Based on the National Grid, electrical energy is being generated in the country and transmitted with bipolar generator of frequency 50 Hz. Therefore Piston speed $\mathrm{N} = 60 \times 50 = 3000\ rpm$
- compressor have polytrophic index, m, for CFC =1.1 (Arora, 2010)
- Capillary tube diameters range from 0.4 mm to 2 mm and the length ranges from 0.6 m to 6 m (Arora, 2010), but Copper tube of sizes 6.35 mm and 9.525 mm were used because the total pressure drops through it matches the pressure difference in the heat exchanger, designed parameters, design equations and estimated values of the parameters are shown in Table 2.
- Heat Capacities of fluid to remain unaltered
  Steady flow conditions to exit and
- No heat transfer external to the heat exchanger

The summary of refrigerant recovery and recycling machine design analysis is shown in the Table 2

Table 2: Summary of Refrigerant Recovery and Recycling Machine Design Analysis

S/N	Components	Design Factors	Mathematical Formula Used	Design Value
1	Compressor	Swept Flow Rate	$V_S = \frac{\dot{m}V_1}{\eta_{VOL}}$	$1.553718 \times 10^{-3} \mathrm{m}^3/s$
		Displacement Volume	$V_D = \frac{60 \times V_S}{N}$	$3.1074 \times 10^{-5} \mathrm{m}^3$
		Length of Stroke	$L = \frac{60V_p}{2NL}$	$0.04\ m$
		Bore Diameter	$D = \sqrt{(4V_D)/(\pi l)}$	$0.031\ m$
		Work Done	$\mathrm{w} = \frac{n}{n-1}\left[MRT\left(\frac{T2}{T1} - 1\right)\right]$	$13405.26\ J$
		Power Requirement	$P = W\ \dot{m}$	$89.41\ W$
2	Heat Exchanger	Diameter	$D = \sqrt{(4\dot{m})/(\pi V \ell)}$	$10\ mm$
		Fluid Reynolds Number	$\mathrm{Re} = \frac{d\ell\, V}{\mu}$	175338.404
		Fluid Prandt Number	$\mathrm{Pr} = \frac{Cp\ \mu}{K}$	1.0789
		Fluid Nusselts Number	$N_u = C\ \mathrm{Re}^n \mathrm{Pr}^{1/3}$	$548.246\ W/\ \mathrm{m}^2.K$
		Coefficient of heat transfer of fluid	$h_c = \frac{KN_u}{D}$	$5482.46\ W/\ \mathrm{m}^2.K$
		Air Reynolds Number	$R_{ea} = \frac{d\ \ell_a\ V}{\mu_a}$	197126.4368
		Air Prandt Number	$P_{ra} = \frac{C_{pa}\mu_a}{k_a}$	0.6822
		Air Nusselt Number	$N_{ua} = C\ {R_{ea}}^n {P_{ra}}^{1/3}$	428.3398717
		Coefficient of heat transfer of air	$h_a = \frac{N_{ua}k_a}{d}$	$1211.173821\ W/\ \mathrm{m}^2.K$
		Overall co-efficient of heat transfer	$U = \frac{1}{(\frac{1}{h_c} + \frac{D_x}{K_{cu}} + \frac{1}{h_a})}$	$377.3305644\ W/\mathrm{m}^2.K$
		logarithmic mean temperature difference	$\Delta_{tm} = \frac{\Delta_{t1} - \Delta_{t2}}{log_e(\frac{\Delta_{t2}}{\Delta_{t1}})}$	$45.38\ ^0\mathrm{C}$
		Heat Transfer	$Q = \dot{m}\ cp\Delta\ t$	$0.373127475\ kJ/s$
		Area	$A = \frac{Q}{U\Delta_{tm}}$	$0.021790678\ \mathrm{m}^2$
		Length of heat exchanger	$L = \frac{A}{\pi D}$	$693.618823\ mm$
3	Capillary Tube	Maximum pressure allowed for a given wall thickness for capillary tube of size 6.35 mm	$P = \frac{2\ S_E(t_m - A_l)}{d}$	$9954426.709\ Pa$
		Maximum pressure allowed for a given wall thickness for capillary tube of size 9.525 mm	$P = \frac{2\ S_E(t_m - A_l)}{d}$	$46660534.8\ Pa$
4	Housing	Capacity of the main housing	$tc = l_1 + l_2 + l_3 + l_4 + l_5 + l_6$	$695\ \mathrm{mm} \times 307\ \mathrm{mm} \times 2\ mm$

3.0: Materials and Construction

The Refrigerant recovery and recycling machine components were made from materials such as: copper and mild steel. These materials were used because they satisfied the design requirements of the machine and are readily available. Table 3 shows equipment components and factors considered for their selections.

Table 3: Design Components Materials and Material Selection

S/N	Components	Selected Materials/ Type	Reason for Selection	Methodology	Function
1	Frame	Mild steel	Tensile strength and heat resistance	The metal plate was cut into sizes of 740 mm by 310 mm with the use of a shearing machine (Guillotine). It was then bent to the required shape at an angle 90^0 and 30^0 with height of 240 mm using bending machine.	It serves as frame and houses the machine.
2	Angle plate	Mild steel	Tensile strength , heat resistance and strength to withstand the load of the system	The angle plate (30 x 30 x3 mm) was bolted at angle 90 degree to the base of the main housing for support to maintain balancing	It forms the base plate upon which the compressor and other components were attached
3	Hermetically sealed reciprocating compressor	Forged carbon steel	Light and strong, strong at elevated temperature	It was mounted by M10 bolts and Nuts, the angle plate support bolted to the base of the housing by M10 bolts and nuts	It supplies power to the system
4	Heat exchangers	Copper	High thermal conductivity, corrosion resistance, maximum allowable strength and internal pressure.	It was fastened to the housing by riveting and joined to the discharge and suction line with copper tube by brazing equipment with silo brazing rods	The heat exchanger (whilst functioning as a condenser) sub-cools the refrigerant being recovered and increases the operating efficiency of the machine
5	Capillary tube	Copper	High thermal conductivity, corrosion resistance, maximum allowable stress and internal pressure	The capillary tube was joined to the heat exchanger by brazing and was also used to connect the pressure gauges to the suction recovery valve and discharge recycling valve.	It serves as metering device and control
6	Gauges	Plastic and brass	Maximum pressure service	Two different types of gauges were used, the high pressure gauge and the vacuum gauge. The high pressure gauge was connected by capillary tube by brazing to the filter drier and the vacuum gauge was connected with capillary tube by brazing to the suction recovery valve	The gauges indicate the internal pressure within the systems (DOT Cylinder and refrigerating system) during operation.
7	Solenoid valve	Brass	Malleability, corrosion resistance and durability	The solenoid valve was connected by copper tube to the suction recovery valve and discharge recycling valve and also electrically connected to the compressor and the main switch of the machine by flexible wire.	
8	Filter drier	Molecular sieve liquid line filter drier	Maximum water removal, refrigerant lubricant compatibility	The filter drier was connected to the pressure gauge by capillary tube and also joined to the solenoid valve with copper tube	It removes foreign materials from recovered refrigerant.
9	Copper pipe/ tube	Copper	High thermal conductivity, corrosion resistance, maximum allowable stress and internal pressure	Copper pipe / tube was used to join the heat exchanger to the discharge and suction line of the compressor and was also used to join the recovery and discharge valves to the solenoid valves . It was also used to join the filter drier to the solenoid valve	Copper tubing were used to join the components together.
10	Handle	Stainless steel	Corrosion resistance, high and low temperature resistance and high strength.	It was joined to the compressor head by welding.	It helps in carrying the system.

4.0: Experimental Set up

Detailing below are the procedures involved when the device was used to carry out recovery and recycling operations:

4.1: Recovery Experiment

Gas, in form of air, was momentarily purged from both hoses by opening and quickly closing their valves to eliminate vacuum. The suction line (Hose, H1) of the recovery machine was connected to the compressor discharge line of the refrigeration system from which the refrigerant is to be recovered from; whilst the discharge line (Hose H2) of the recovery machine was also connected to the recovery tank, a DOT Cylinder (an empty cylinder used for storing refrigerant cylinder) already placed on a digital scale (a mass measuring instrument). The machine, after being plugged to a power source, was then switched on and values of pressure and temperature at 30 minutes interval of time were taken; the mass of refrigerant recovered at each of the interval was, also, noted with the digital scale on which the DOT Cylinder is mounted. The pressure on high side dropped whilst that on the low side rose and the trends continued until the pressure on high side fully drops; these indicate a complete refrigerant recovery process. This procedure was repeated three times and average of values recorded was used for calculation. Plate 1 shows the experimental set up for carrying out recovery operation

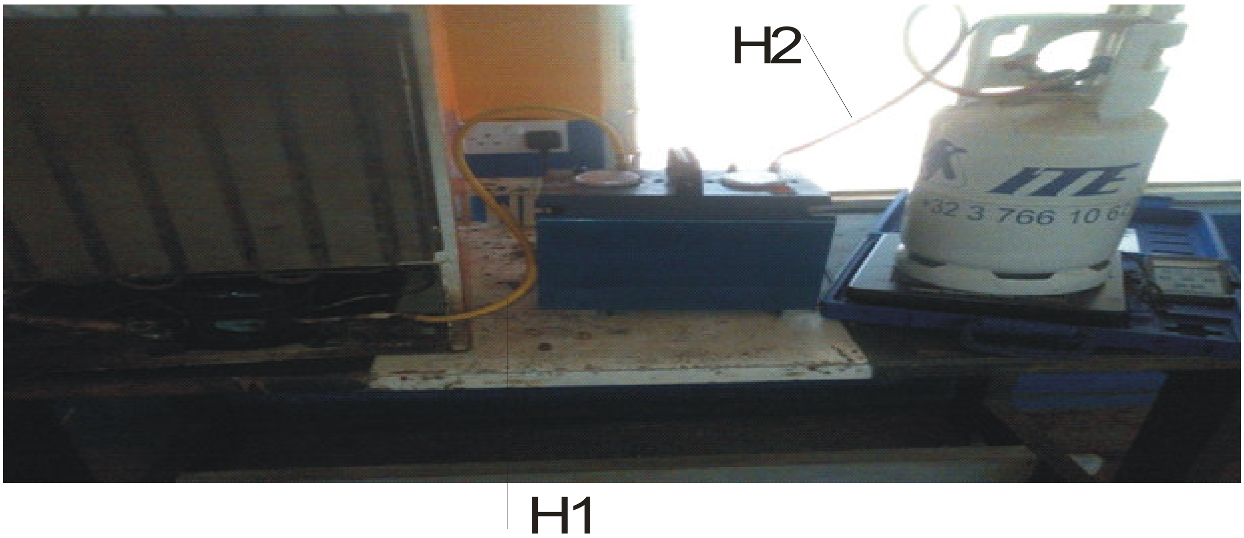

Plate 1: Recovery experimental set up

4.2: Recycling Experiment

Hose (H1) from the suction line of the recovery/recycling machine was connected to the recovery DOT cylinder (which served as the storing can for the recovered refrigerant) already mounted on a digital scale. Hose (H2) from the discharge line of the recovery/recycling machine was connected to another (empty) DOT cylinder where the refrigerant will be recycled to. The recovery/recycling machine after being connected to a power source was switched on; the deflection of the pointers on the low pressure and high pressure gauges monitored. The machine allowed running and readings of pressure and temperatures on the gauges at 30 seconds interval, as needle on the high pressure gauge dropped and that on low pressure rose, were taken. The masses of refrigerant recycled on the digital scale at these same intervals of time were also recorded and the recording continued to be taken until the needle on the high pressure gauge fully drops, indicating complete refrigerant recycling. The procedure was repeated for three consecutive times and the average values of each the properties considered was used for calculation. Plate 2 shows the experimental set up for carrying out recycling operation

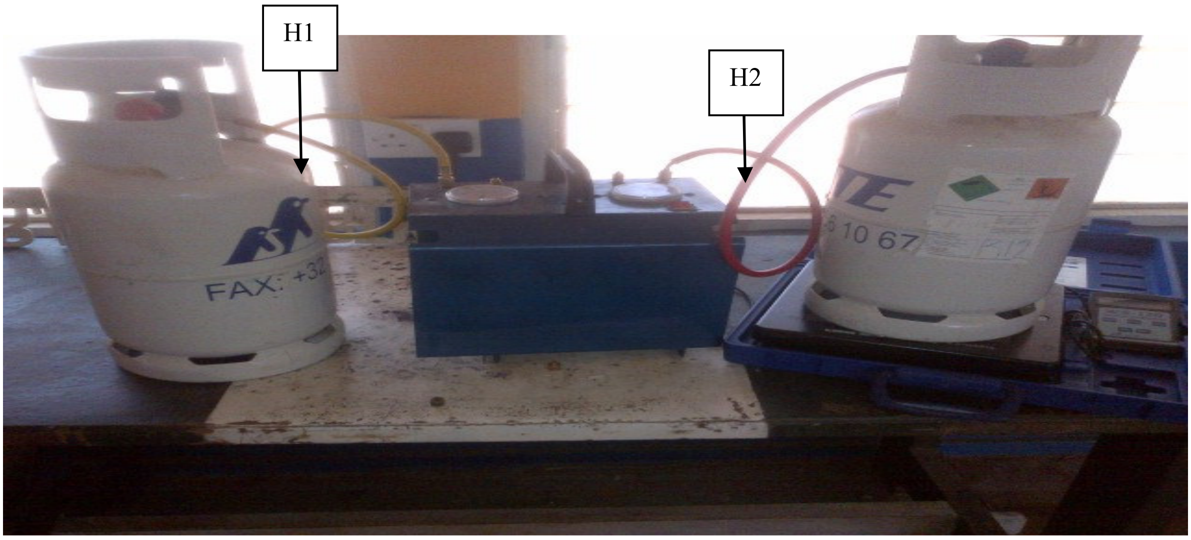

Plate 2: Recycling experimental set up

5.0: Results and Discussion

The developed system was tested with two refrigerants, R-12 and R-22. Measured parameters include: time (s), temperature (℃), pressure (Pa) and mass flow rate (kg/s) of refrigerant using digital weighing scale. These parameters were used to carry out the performance evaluation of the machine. Graphs were plotted relating the variations of these parameters with time as shown in figures 1 to 4. Results of the machine during recovery and recycling of R12 and R22 are detailed in Table 4 below.

Table 4: Summary of Performance Evaluation

	Sample I	**Sample II**	
Refrigerant used	R12	R22	
Initial mass of refrigerant charged (kg)	1	1	
Time of recovery (s)	150	150	
Time of recycling (s)	150	150	
Mass of refrigerant recovered (kg)	0.9	0.85	
Mass of refrigerant recycled (kg)	0.78	0.72	
Mass of refrigerant entrapped (kg)	0.22	0.28	
Recovery efficiency (%)	90	85	
Recycling efficiency (%)	86.66	84.7	
Recovery rate (kg/s)	0.006	0.0056	
Recycling rate (kg/s)	0.0052	0.0048	
Average machine recovery efficiency (%)			87.5
Average machine recycling efficiency (%)			85.68
Average machine recovery rate (kg/s)			0.0058
Average machine recycling rate (kg/s)			0.005
Recovery/Recycling machine capacity (kg/s)			0.0054
Recovery/Recycling machine capacity (kg/hr)			19.44

Legend: R12 Blue Colour line; R22- Red Colour line

Figures 1 to 4 show the graphs of behaviors of R12 and R22 both during recovery (inside the first DOT Cylinder) and recycling (inside the second DOT Cylinder) operations in an attempt to evaluate the performance of the developed machine.

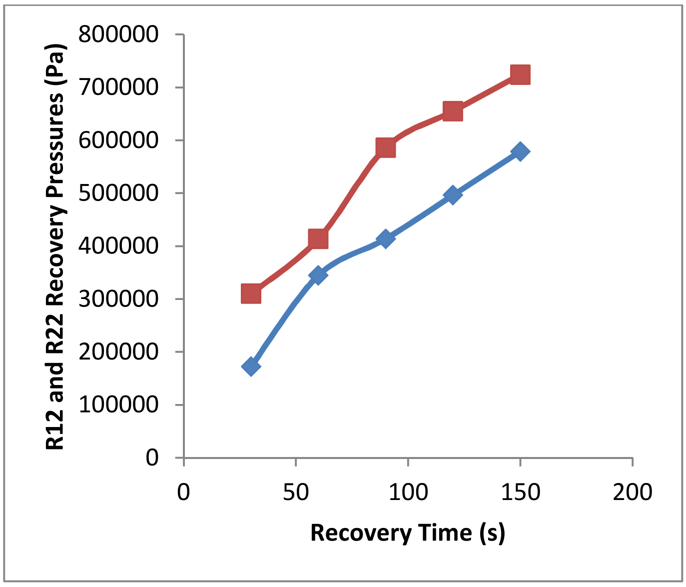

Figure 1: The gragh of R12 and R22 recovery pressure against time

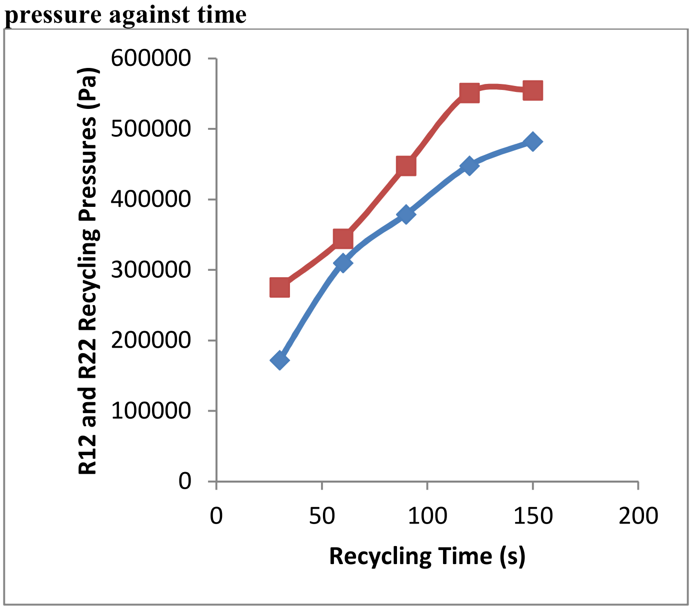

Figure 2: The graph of R12 and R22recycling pressures against time

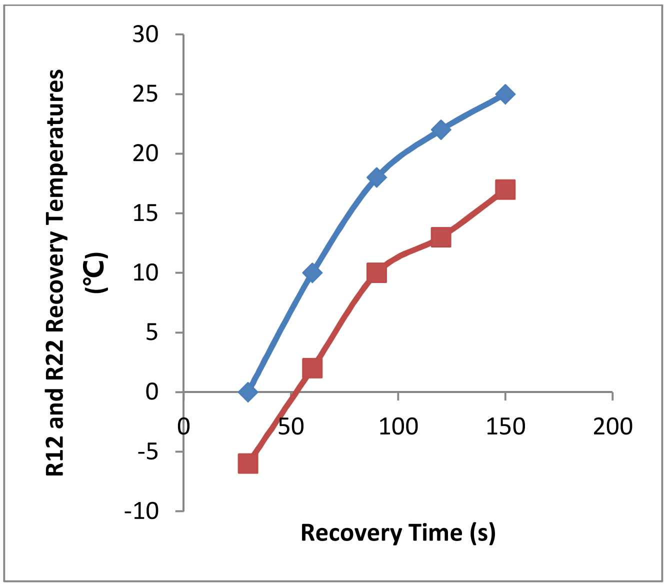

Figure 3: The graph of R12 and R22 recovery temperature against time

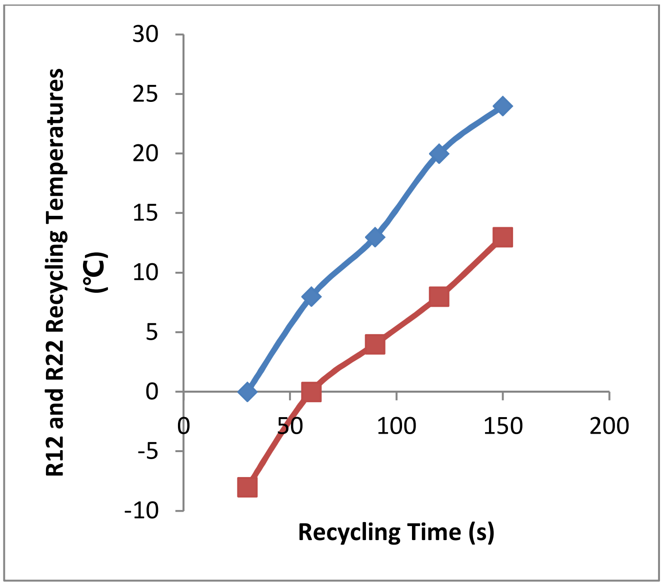

Figure 4: The gragh of R12 and R22 recycling temperature against time

Discussion

From the results of the experiments, when the refrigerant recovery and recycling machine was tested, the recovery rate of the machine was found to be 0.0058 kg/s and the recycling rate to be 0.005 kg/s. The average capacity of the machine is now 0.0054 kg/s (i.e. 19.44 kg/hr). This positive result encourages further development of the machine.the observation of the results is shown in the figures 1 to 4.

Figure 1 shows that at the beginning of the recovery operation for both refrigerants, R-12 and R-22, the pressure-time curves increase linearly; the reason for the linearity is that more molecules are within the container to exert more effective collisions according to kinetic theory of gases (i.e. velocity is directly proportion to pressure) which is in agreement with the findings of Whitman and Johnson (1995). The pressure deviated as the time increases due to less volume of gases within the container to cause collision. However, the linear relationship is attained later because all the droplets are now in gaseous state due to the increase in the heat transfer capacity of the heat exchanger, which ultimately helps increasing the efficiency of the machine and this was in accordance with the findings of Park (2008).

Figure 2 shows that the pressure-time graph of both R-12 and R-22 deviated from the linear relationship during recycling operation. The R-12 pressure-time graph is almost curve-linear in shape while that of R-22 is staggered and this is due to the low compressor displacement of the refrigerants during recycling processes and this agreed with the findings of Aprea (2002). However, at time t = 150 s, the discharged pressure of R-12 for both recovery and recycling operations are 579154.8 (Pa) and 482629 (Pa) while that of R-22 are 723943.5 (Pa) and 554996.5 (Pa) respectively. These discharge pressures are the maximum recovery and recycling pressure of the machine. The machine attained higher discharge pressure with R-22 than R-12 because the compression ratio of R-22 is higher than that of R-12 and this agreed with the findings of Arora (2010).

The temperature-time curves (lines) of both refrigerants almost increased linearly with time as shown in figures 3 and 4; this is due to the fact that the molecular collision of both refrigerants within the container increases when the refrigerants are being discharged because additional heat energy (heat of compression) is added to the gaseous refrigerant due to compressor's work of compression. Both refrigerants have almost the same behavior, their ranges of pressure and temperature slightly defer, but at similar mass flow rate.

Conclusion

The refrigerant recovery/recycling machine was designed, constructed and evaluated. All the materials used for its construction were locally sourced. The capacity of the machine is 19.44 kg/hr with recovery and recycling efficiency of 87.5 % and 85.68 % respectively. The machine can be used to recover used refrigerants and recycle it to 99.9 % of its original purity. The machine is suitable for all refrigeration and air conditioning (RAC) practitioners and was produced at a cost of about ₦106, 503.00; all necessary factors taken into consideration to ensure reliability of machine and interchangeability of parts to guarantee its easy maintenance.

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