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The use of Cooking Gas as Refrigerant in a Domestic Refrigerator

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ABSTRACT
The application of cooking gas refrigerants in refrigeration system is considered to be a potential way to improve energy efficiency and to encourage the use of environment-friendly refrigerants. Refrigeration operation has been met with many challenges as it deals with environmental impact, how it affects humans and how it contributes to the society in general. Domestic refrigerators annually consume several metric tons of traditional refrigerants, which contribute to very high Ozone Depletion Potential (ODP) and Global Warming Potential (GWP). The experiment conducted employs the use of two closely linked refrigerants, R600a (Isobutene) and cooking gas which is varied in an ideal refrigerant mixture of 150 g of refrigerant and 15 ml of lubricating oil (to a rating of 40 wt % expected in the compressor). The Laboratory process involved the use of Gas Chromatography machine to ascertain the values of the mole ratio, molecular weight and critical temperatures. Prode properties and Refprop softwares were used to ascertain other refrigerant properties of the mixture. The results indicated that the mixture of R600a with lubricant confirm mineral oil as being the most appropriate for the operation. The experimental results indicated that the refrigeration system with cooking gas refrigerant worked normally and was found to attain high freezing capacity and a COP value of 2.159. It is established that cooking gas is a viable alternative refrigerant to replace R600a in domestic refrigerators. Hence, its application in refrigerating systems measures up to the current trend on environmental regulations with hydrocarbon refrigerants.
Keywords-Cooking gas, Isobutene, Refrigerant

I. INTRODUCTION

Modern refrigeration as it is today seeks to address the challenges of comfort and how it impacts our environment. These trends have been met with progressive professional advancement in the industry. The global demand for cooling is increasing significantly likewise, its application which cuts across the fields of engineering, medicine, science and environmental conditioning [1]. Refrigeration operation has been met with many challenges; as it deals with the environmental impact, how it affects humans and how it contributes to the society in general. This explains why developments in the nineteenth century led to different protocol (Kyoto and Montreal) which has led to progress of events. The Kyoto meeting of 1997 on Global Climate Change confirmed the United States agreement to reduce emissions of six greenhouse gases by 7% below the levels in 1990 during a commitment period between 2008 and 2012 [2].

Refrigerants are the working fluids in a refrigeration cycle, which enables evaporation thereby, extracting heat from a heat source. There are many requirements when choosing refrigerants for refrigeration plants and air conditioners. Some of these requirements are: suitable pressures, high evaporating enthalpy, low toxicity, non-flammability, compatibility with construction materials, lubricants and high COP[3].

Primarily, the high demand for refrigeration and air-conditioning has brought about extensive search for new refrigerants. This study is centered on the research for hydrocarbon refrigerants as the future for the industry, taking into consideration its availability and desired properties such as having the lowest Ozone depletion potential (ODP) and Global warming potential (GWP).

Over recent years, the main focus of lubricant development has been to ensure reliability of operation in systems. In refrigeration operations lubricants are consider with the refrigerants since it does not act alone. The need for lubricants in refrigeration systems cannot be over emphasized as it helps reduce friction by interposing a direct solid-to-solid contact, acts as coolant by removing heat from the bearings while transferring heat, suppressing the noise generated by moving parts and seals the rotating shaft by retaining gas pressure and minimizing the contaminants.

Most importantly, the need to tap the available petroleum products has been the main target in this write up, being that Nigeria has abundance of these natural resources. Hydrocarbons like liquefied petroleum gas (LPG), natural gas and cooking gas can be used in the refrigeration industry.

The growing demand of refrigeration in terms of trade and investment which will empower indigenous innovation towards meeting the global/local demand needs is also a driving factor for this study. This work looks into the use cooking gas as a refrigerant in a domestic refrigerator, by considering; the percentage of each unknown constituent in the refrigerant mixture by gas chromatographic techniques, the properties of the mixture, using Prode properties and Refprop software in order to find the most suitable alternative and the suitability of using cooking gas as a potential alternative for domestic refrigerators.

Rapid introduction of alternative refrigerants is necessary to make a timely response to environmental issues that challenges the air-conditioning and refrigeration industry. The basis of this research is to expand the knowledge on the subject, thereby creating room for more innovations, since the future of refrigerant would be optimally based on hydrocarbon constituents.

II. MATERIALS AND METHOD

Cooking gas was used as the refrigerant in this research. The Refrigerant working Fluid are a combination the lubricant and the refrigerant. R600a refrigerant is the other product investigated in comparison with the cooking gas as refrigerant. Both gases mix with the lubricating oil in the compressor during the refrigeration process to form the working fluid. The lubricating oils cosidered were: Mineral oil ; MN ISO 36 VG 8

Synthetic oil; i) POE ISO 32 VG 12 , ii) PAG ISO 32 VG 14

The mixture which is a blend of the refrigerant and lubricating oil was obtained based on the 40 wt % required in the compressor. The cooking gas, R600a and lubricating oil were blended as follows:

Cooking gas + POE = Mixture 1
Cooking gas + PAG = Mixture 2
Cooking gas = Mixture 3
Cooking gas + MN = Mixture 4
R600a + MN = Isobutane

The gas samples were tested using gas chromatography machine shown in Figure 1.

Figure 1: Gas chromatography machine

The machine was fed in with a helium carrier gas. The startup operations required initializing the unit by allowing helium or nitrogen to run through the system for some time. The gas chromatography machine was activated after setting temperature and machine parameters. The machine was left to warm for 30 minutes before the sample product was fed into the machine. The product was then transferred into the bladder and then fixed to the machine inlet valve and charged for few seconds. Then the machine was switch on to inject the gas sample with a simultaneous start-up of the display on the machine.

The machine was set by allowing the carrier gas (helium) to move through the system. Normal parameter was being set for different product samples. The setting of column temperature was done specially to regulate the detection of component for a period of 10minutes and in cases of reversal of column, allowed cooling time can take up to 45minutes. Each sample was filled into the bladder which was then connected to the inlet port of the machine.

The Refpropsoftware developed by the National Institute of Standards and Technology (NIST) based in America developed was used to determine the thermodynamic and transport properties of fluids mixtures. Refprop was seen to handle the complexity of the data generated. The data available included; molecular weight, mole ratio, temperature range and pressure. Prode properties were used to determine the flammability limits for the mixtures. The properties are displayed in tables and plots through the graphical user interface with spread sheets or user-written applications.

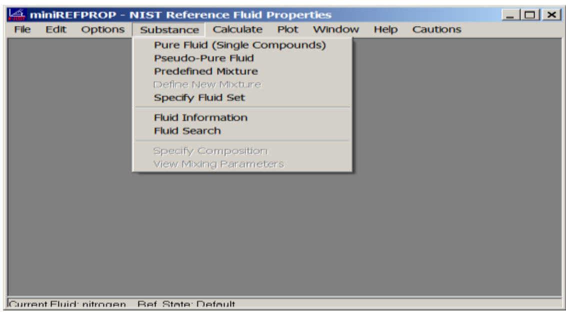

Figure 2: Refprop interface

Refprop user interface is shown in Figure 2 provides the most accurate pure fluid and mixture models. The thermodynamic properties of pure fluids is gotten using the Helmholtz energy equation. The modified Benedict-Webb-Rubin equation of state and an extended corresponding states (ECS) model are still used to solve other problems. The Equation of state used in Refprop is the Gerg 2008 (Groupe Européen de Recherches Gazières) equation. The Gerg-2008 Wide-Range Equation of State for Natural Gases and Other Mixtures was developed at Ruhr-Universität Bochum and uses the Helmholtz energy equation to derive the hydrocarbon fluid properties. Gerg-2008 can be used to determine various fluid properties specific to natural gas and to calculate phase boundaries. The validity range of Gerg-2008 covers the following temperatures from 90 k to 450 k and pressure less than 35 MPa for normal range, while the extended range covers temperatures from 60 k to 700 k and pressure less than 70 MPa.

III. RESULTS AND DISCUSSION

The theoretical C.O.P. was computed using equation 1. The Coefficient of performance is defined as the rate of heat extracted by the refrigerator to the work done on the refrigerant.

$$\mathrm{C.O.P.} = \frac{Q}{W} \, (eqn.1)$$

Q is the heat extracted in the refrigerator (J)

W is the work done. (J)

P is the pressure (bar)

H is the Enthalpy (kJ/kg)

The refrigerating effect or amount of heat extracted during evaporation per kg of refrigerant is;

$$q_{evap} = h_1 - h_4 (\mathrm{kJ/kg}) \qquad (eqn.2)$$

q_{evap} is the refrigerating effect (kJ/kg)

$h_4$is the enthalpy of liquid refrigerant leaving the condenser

The work by condensing the refrigerant at constant temperature and pressure is given below

$$q_{cond} = h_2 - h_3 (eqn.3)$$

q_{cond} is the condenser heat loss (heat rejected by condenser)

$h_3$is the enthalpy of liquid refrigerant leaving the condenser

C.O.P. Calculation for Iso Butane at (-15°C, 40°C andto 70°C)

Enthalpy values are obtained using REFPROP

$$h_1 = 534.257 \frac{kJ}{kg} (\text{at } -15^\circ\text{C}, \text{saturatedstate})$$

$$h_2 = 628.320 \frac{kJ}{kg} (\text{compressed to } 70^\circ\text{C})$$

$$h_3 = 296.491 \frac{kJ}{kg} (\text{condensed to } 40^\circ\text{C})$$

$$h_4 = 296.491 \frac{kJ}{kg}$$

(expanded at constant enthalpy h3 = h4)

Heat rejected by condenser

$$q_{cond} = h_2 - h_3 = 331.829 \text{ kJ/kg}$$

Refrigerating effect

$$q_{evap} = h_1 - h_4 = 237.766 \text{ kJ/kg}$$

Compressor work

$$w = h_2 - h_1 = 94.063 \text{ kJ/kg}$$

C.O.P =Refrigerating effect / Compressor work

$$\mathrm{C.O.P} = \frac{q_{evap}}{w} = \frac{237.766}{94.063}$$

$$\mathrm{C.O.P}_{IsoButane} = 2.527$$

Flammability Calculations

$$LFL_{mix} = \frac{1}{\sum \frac{xi}{LFL_i}} \qquad (eqn.4)$$

$$UFL_{mix} = \frac{1}{\sum \frac{xi}{UFL_i}} (eqn.5)$$

Where:

UFL_{mix} Upper Flammability Limit Value of the Mixture

LFL_{mix} Lower Flammability Limit Value of the Mixture

xi Mole Fraction of Gas Component in the Mixture

UFL_i Upper Flammability Value of Single Gas Component in the Mixture

The chromatography calculation is analysed showing the presence of the following hydrocarbons; isobutane, normal butane, is pentane, normal pentane, ethane, methane and propane. Following the chromatography table for the first traces of methane is identified with a unique retention time (RT) and serial number (SN) which is the calculated with an area factor (AF). The table area factor (TAF), corrected area factor (CAF), specific gravity (SG) and relative vapourdensity is obtained using subsequent equations 3.6 – 3.10

$$\text{Moles}\% = \frac{CAF}{TCAF} * 100 \qquad (eqn.6)$$

$$SG = \text{mole}\% * SGF \quad (eqn.7)$$

$$\text{Molar mass} = \sum_{SN=13}^{19} SG_{SN} \, (eqn.8)$$

$$RVP = mole\% * RVPF (eqn.9)$$

$$RVPmixture1 = \frac{\sum_{SN=13}^{19} RVP_{SN}}{100} - 14.7 \, (eqn.10)$$

Where:

CAF	Corrected Area Factor
TCAF	Total Corrected Area Factor
SG	Specific Gravity
SGF	Specific Gravity Factor
SN	Serial Number
RVP	Relative Vapour Pressure

IV. DISCUSSION OF RESULTS

The results obtained shows that the use of hydrocarbon refrigerant with PAG, POE &MN as a substitute to conventional refrigerants is a suitable alternative in refrigerating systems. According to[4], the use of mineral and synthetic oils with R-290 (propane) and R-600a is confirmed its practicable. [5], showed the properties of R600a had the following values; the molecular weight 58.122 kg/kmol, Coefficient of performance of 2.527 and flammability limits (LFL of 1.8% and UFL of 8.4%). The properties of the four mixtures presented in (Table 5) showed Mixture 4 with the closest ranges of values similar to that of R600a. Mixture 4, exhibited the following values; molecular weight (54.611 kg/kmol), Coefficient of performance (2.159) and flammability limits (LFL of 1.8384% and UFL of 8.8492%). Table 5 further confirms the close performance of Mixture 4 to that of compared to R600a.

For compressor handling R600a refrigerants, POE low viscosity refrigeration oils VG8 and VG7 POE were considered with mineral oils (VG10 to VG22). The lubricants nomenclature shows the first letters to be the lubricant type; alkyl benzene (AB), polyalkylene glycol PAG, polyol ester POE, Poly-alfa olefin POA, Mineral oil MN and VG shows the viscosity while the number tells the ISO grade.

[6]used a mixture of R-600a and mineral oil at temperatures between -800 C and 1000C and found out that the best performance was obtained using mineral oil (MN). [4]reported an excellent performance of diesters, showing high viscosity, low solubility and good miscibility with hydrocarbon R-600a. This work therefore, confirms that the use of mineral oil in mixture 4 as the most effective, when compared to properties of R600a. Software application programmes is used to ascertain the experimental results of most properties. Two basic factors affect oil return in most refrigeration systems: physical design and mixing of refrigerant with oil. Generally, a well-designed system should involve the flow of refrigerant under gravity to get oil back to the compressor. Hence, the reason why the evaporator is located at a significant height to the compressor.

The molecular weight ratio between the oil and refrigerant is essential to predict the change of viscosity and pressure-viscosity coefficients when the refrigerant dilutes the oil as illustrated in Figures 3 to 5. [7]found that compressor with lighter refrigerant, such as ammonia, dilutes the oil by only 3-5%, while heavier refrigerants like R-22 and R-134a, are usually found at concentrations of 5 to 40 wt%, depending on the operating conditions. The refrigerator was tested and run for about two days to check it performance. By using 1 kg equivalent to three sachets of pure water in the refrigerating system. It was observed that it formed an ice block within five hour using (R600a) refrigerant. Whereas cooking gas took eight hours to form ice block when compared with the R600a.

Plotting the data from the thermodynamic properties of mixture 1 to mixture 4 and IsoButane in terms of temperature against pressure, density and viscosity, it can be seen that the properties of the mixtures are within the range of Isobutane with a slight deviation for mixture 3, (see Figure 3, 4, 5.) This proves that the mixtures can be handled by a refrigeration system designed for Isobutane and may be used in applications where Isobutane based refrigerants are applied.

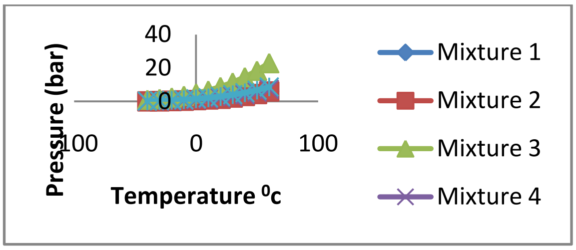

Figure 3: Plot of Pressure (dew) against Temperature.

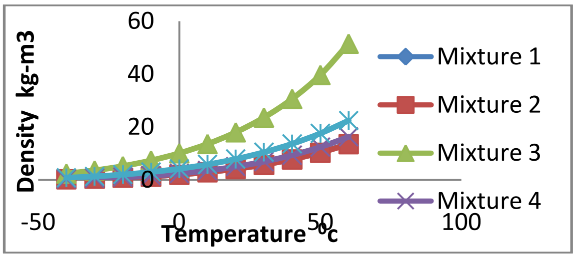

Figure 4: Plot of Density against Temperature

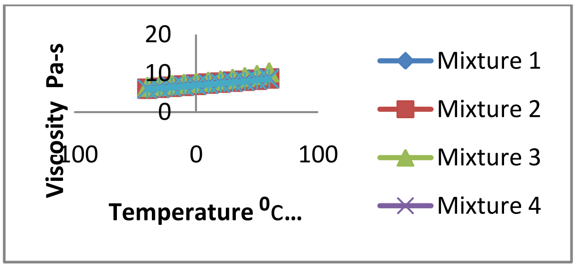

Figure 5: Plot of Viscosity against Temperature

The result from flammability calculations shown in Table 5 portrays the flammability chart and its flammable limits. The chart confirms that the mixtures are similar to isobutane in terms of flammability, thus any safety measures for flammability of R600a refrigerant will work well for the mixtures.

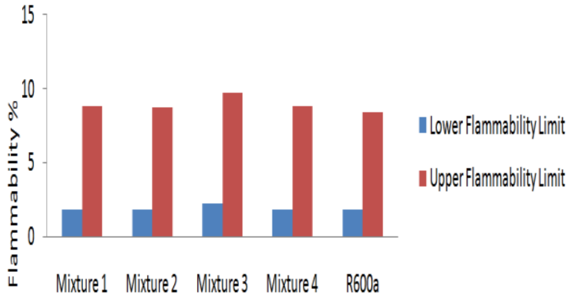

Figure 6: Flammability chart

Table 1: Chromatography Mixture 1							
Symbol	Name	Number	Formula	Mol%	Mole(xi)	SG	RVP
c1	Methane	R50	ch4	1.9	0.019	0.57	10054.8
c2	Ethane	R170	C2H6	14.2	0.142	5.311	9940
c3	Propane	R290	C3H8	12.1	0.121	6.15	2299
ic4	iso butane	R600a	C4H10	21.1	0.211	11.87	1523.42
nc4	normal butane	R600	C4H10	27.1	0.271	15.86	1398.36
ic5	iso pentane	R601a	C5H12	10	0.1	6.25	204.4
nc5	normal pentane	R601	C5H12	13.6	0.136	8.582	211.75
				100	1	54.60	256.3173

Table 2: Chromatography Mixture 2							
Symbol	Name	Number	Formula	Mole%	Mole(xi)	SG	RVP
c1	Methane	R50	ch4	0.6	0.006	0.18	3175.2
c2	Ethane	R170	C2H6	9.6	0.096	3.59	6720
c3	Propane	R290	C3H8	20.1	0.201	10.21	3819
ic4	iso butane	R600a	C4H10	18.4	0.184	10.36	1328.48
nc4	normal butane	R600	C4H10	26.7	0.267	15.59	1377.7
ic5	iso pentane	R601a	C5H12	10	0.1	6.25	204.4
nc5	normal pentane	R601	C5H12 o	14.6	0.146	9.21	227.3
				100	1	55.39	153.8208

Table 3: Chromatography Mixture 3							
Symbol	Name	Number	Formula	Mol%	Mole(x)	SG	RVP
c1	Methane	R50	ch4	4.7	0.047	1.41	24872.4
c2	Ethane	R170	C2H6	5.3	0.053	1.98	3710
c3	Propane	R290	C3H8	88.5	0.885	44.96	16815
ic4	iso butane	R600a	C4H10	0.3	0.003	0.169	21.66
nc4	normal butane	R600	C4H10	0.7	0.007	0.41	36.12
ic5	iso pentane	R601a	C5H12	0.3	0.003	0.188	6.132
nc5	normal pentane	R601	C5H12 o	0.2	0.002	0.126	3.114
				100	1	49.24	439.944

Table 4: Chromatography Mixture 4							
Symbol	Name	Number	Formula	Mole%	Mole(xi)	SG	RVP
c1	Methane	R50	ch4	0.5	0.005	0.15	2646
c2	Ethane	R170	C2H6	4.8	0.048	1.795	3360
c3	Propane	R290	C3H8	41.9	0.419	21.29	7961
ic4	iso butane	R600a	C4H10	13.5	0.135	7.6	974.7
nc4	normal butane	R600	C4H10	20.7	0.207	12.089	1068.12
ic5	iso pentane	R601a	C5H12	8.3	0.083	5.188	169.61
nc5	normal pentane	R601	C5H12 o	10.3	0.103	6.499	160.37
				100	1	54.611	148.698

Table 5 Summary of the Thermodynamic Properties of the Mixtures and R600a					
Name	Mixture 1	Mixture 2	Mixture 3	Mixture 4	R600a
Critical temperature [^oC]	141.508	144.13	91.204	135.16	134.66
Critical pressure [bar]	44.3704	42.884	47.293	43.637	35.815
Molecular weight [kg/kmol]	54.604	55.39	49.243	54.611	58.122
Normal boiling point [^oC] (1.01 bar)	5.4288	6.095	-40.783	0.16843	-11.749
Pressure [bar] (at -25 ^oC)	0.24741	0.24011	1.9943	0.31134	0.5842
Liquid Density [kg/m3] (at -25^oC)	651.96	652.24	577.87	648.74	608.27
Vapour Density [kg/mg] (at-25 ^oC)	0.66646	0.65738	4.3292	0.815	1.6934
Liquid volume (at -25 ^oC)	0.00153	0.00153	0.00173	0.00154	0.0016
Vapour volume (at -25^oC)	1.5005	1.5212	0.23099	1.227	0.5906
Liquid viscosity (at -25 ^oC)	230.89	328.66	180.47	320.34	268.27
Gas viscosity (at -25 ^oC)	8.2893	6.3642	6.9292	6.4735	6.26
Liquid thermal conductivity(25 ^oC)	122.86	126.97	122.22	126.4	108.71
Gas thermal conductivity (-25 ^oC)	20.231	12.249	13.727	12.454	12.011
Lower Flammable Limit (LFL) %	1.8162	1.7841	2.1844	1.8384	1.8
Upper Flammable Limit (UFL) %	8.8308	8.7251	9.7654	8.8492	8.4
Coefficientof Performance (COP)	2.04	2.051	2.760	2.159	2.527

The data presented in Figure 6 shows the flammability of the refrigerant selected.

According To Fire Safety Science– Proceedings of The Ninth International Symposium, the range of flammable compositions for a fuel/air/additive mixture is bounded by an upper and a lower limit is within the range of (1.8 – 8.4), which corresponds to those of the chosen R600a[8]. The upper

flammability limit (UFL) is the highest fuel concentration where a mixture will be flammable (for a given fuel, air and additive composition). By contrast, the lower flammability limit (LFL) gives the lowest fuel concentration that will give a flammable mixture. A potential hazard arising from the use of flammable refrigerants is the scenario where the entire refrigerant charge escapes from the refrigerator unit due to a malfunction or accidental rupture. This work has evaluated the performance in the worst case scenario and further concretized possible solutions for the usage of the alternative refrigerants in a domestic refrigerator. The lower flammability limit is therefore the parameter of most value for assessing the safety merits of flammable refrigerant mixtures.

The current safety discussion understudies the following risk associated with; flammability of the refrigerant (LFL and UFL) and the toxicity data available for each refrigerant. The assessment includes checking the worst case scenario in event of an accidental refrigerant release. The following remedies were purported to be put into place so as to avoid any situation of mishap.

Remedies for Flammability

1. The addition of the lubricant oil alters the mixture composition thereby increasing the heavier ends of the hydrocarbon constituent and further improves the flammability tendencies of the mixture. This act profers the central solution to the goal of this research in the area of flammability and miscibility concerns.
2. The addition of relatively small amounts of CBr_2F_2, CH_2Br_2, CF_3I, C_4F_{10}, SF_6 and C_3F_8 can decrease the lower flammability limit of propane/isobutene (LPG) gas. This research is tailored on retrofits of lubricating oils which has the potential of reducing risk.
3. Fans can be installed to complement the refrigeration safety guidelines.
4. For all instances, electric connection must be made safe to avoid any event of a spark resulting from a short circuit. The replacement of any such equipment must be done with precautions, assuring the safety and prevention of explosion risk.

V. CONCLUSION

The quest for improvement of environmental friendly refrigerant has been a continuous one and the need to meet this demand was the goal of this research work. The research showed different samples analysed using chromatography machine and found mixture 4 to have the most appropriate properties for refrigeration purpose. Mixture 4 sample have the following constituents: Methane (0.5%), Ethane (4.8%), Propane (41.9%), iso butane (13.5%), normal butane (20.7%), iso pentane (8.3%). Upon further evaluation using Prode properties software, the mixtures were found to exhibit the flammability data which were close to that of R600a with the Lower Flammable Limit (LFL) of Mixture 4 having a value of 1.8384%, while R600a gave 1.8% and the Upper Flammable Limit (UFL) of Mixture 4 yielded 8.8492% as compared to R600a which resulted in 8.4%.

Furthermore Refrpop software was used to determine other properties showing the; Critical temperature Mixture 4- 135.160C, R600a- 134.660C and Molecular weight Mixture 4- 54.611 kg/kmol, R600a- 58.122 kg/kmol . The results showed that the properties of Mixture 4 are close to those of R600a and were found to be the most suitable alternative. The fabricated facility had a 1/6 hp capacity compressor which was used to determine the performance of the refrigerant mixture by testing it. The COP result produced the following outcome as R600a (2.527) cooled 1kg of water in 5hours, whereas Mixture 4 (with COP of 2.127) cooled 1kg of water in 8hours.

Upon evaluation of this work, the results showed the viability of using cooking gas in place of R600a which also further confirms its economic viability and the suitability of using cooking gas as a potential alternative for domestic refrigerators. Form the experimental results, Mixture 4 is seen to have close values as compared to that of isobutane. Hence, the mixture was optimized with the mineral oil lubricant. Mixture 3 had the highest deflection in all reading, exhibiting the highest value of COP. However, cooking gas without any lubricating oil would not function for a long time, due to the damages it may likely cause to the compressor. The use of cooking gas as refrigerant presents less danger provided that the safety measures are strictly adhered to.

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