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Cooling Capacity and Energy Efficiency Studies Comparing Commercial Grade and Refrigerant Grade Propane (C_3H_8) used as "Drop-in" Refrigerant in a "Split Type" Air Conditioner

Zakaria, Z. and Koh, J. H.*
Oil & Gas Engineering Program, Faculty of Engineering, Universiti Malaysia Sabah, Jalan UMS, 88400 Kota Kinabalu, Sabah, Malaysia
*Corresponding author (e-mail: jhkoh@ums.edu.my)

This study compares the efficiencies and cooling capacities of commercial grade propane with refrigerant grade propane (C_3H_8) and chlorodifluoromethane ($CHClF_2$) (R 22) in a split unit air conditioner installed in a psychrometric chamber. "Tunnel Air Enthalpy" method in MS ISO 5151 was used to obtain the cooling load calculations. Results of experiments indicated that the commercial propane provided the highest efficiency but had 10% drop in refrigeration capacities. Refrigerant grade propane, R 290, and HC 22a however performed poorer in terms of efficiencies and cooling capacities. R 22 which was the original refrigerant used in the air conditioner unit has the highest cooling capacity, but the life cycle of carbon emissions was also the highest among all the refrigerants tested.

Keywords: Refrigerants; global warming potential; propane; cooling capacity

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Refrigerants used in air conditioning and refrigeration (ACR) industries were identified as one of the several hydrochlorofluorocarbons (HCFCs) that depletes the ozone layer and subsequently contributes to the global warming. Chlorodifluoromethane ($CHClF_2$), which is also known as refrigerant R 22 was being phased down since 2016 with a 10% reduction of its usage in the ACR industries in Malaysia. Under the Phase 1 of the HCFC Phaseout Management Plan (HPMP), the Department of Environment Malaysia (DOE) has implemented the banning of R 22 in air conditioning equipment with the range of 2.5 horsepower (hp), and below. Subsequently, the Phase 2 of the HPMP will be implemented in 2017, targeting 35% reduction in the use of HCFC [1]. The local manufacturers and importers of ACR equipment switched to refrigerant R 410A which comprises 50% mass of difluoromethane (CH_2F_2) and 50% mass of pentafluoroethane (CF_3CHF_2). Refrigerant R 410A is categorized as a hydrofluorocarbon (HFC) which is a potent global warming gas. The global warming potential (GWP) of R 410A was 2090, as compared to R 22 at 1810, making it more environmentally damaging than R 22, which it replaced [2]. The recent Kigali amendments to the Montreal Protocol, has listed these HFCs in the list of greenhouse gases subjected to a phasedown [3]. In industrialized countries, with the ratification of the Kigali Amendment to the Montreal Protocol, high GWP HFCs were currently being phasedown. HFC 32/ R 32 (difluoromethane) was offered by major air conditioner manufacturers as a replacement for R 410A.

According to the latest "Intergovernmental Panel on Climate Change, Assessment Report No. 6 (IPCC, AR6), R 32 has a GWP of 771 [4]. Hydrocarbons (HC) refrigerants such as propane (R 290) and butane (R 600a) were identified as potential replacements for these refrigerants [5]. The IPCC AR6 quoted the GWP for propane as 0.02 and butane as 0.022 [4].

Many researchers have conducted experiments and simulations of thermodynamic performances of HC refrigerants, comparing them with various other refrigerants currently in use today. Some of these works carried out were worth mentioning. It was concluded that in experiments conducted to compare the coefficient of performance (COP) of R 290 (refrigerant grade propane), R 22, R 407C (a blend of HFC) and R 410A in ambient temperature condition of 35º C to 55º C, R 290 has the highest COP [6]. In another experiment, using Indian Standard IS 1391, in a R 290 charged window unit, it was found to have 2.8 - 7.9% higher COP, as compared to R 22 [7]. Pandalkal *et al.*, [8] noted that the split unit air conditioner using R 290 has lower cooling capacity but higher COP despite 50% less charge. In an experiment conducted by Teng *et. al* [9], it was found that with only 50% of volume of refrigerant R 290 charged into a window type air conditioner as compared to refrigerant R 22 the coefficient of performance (COP) of the air conditioner has increased thus resulting in better efficiency. In current researches conducted around the world, results indicated that blends of HC refrigerants can be used to replace HFC 134a in a refrigerator [10], propane and isobutane blends with lowering the isobutane proportion

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of the blends can increase COP significantly [11] and recently Teng [12] concluded that with mass ratio of 1:1 of propane and isobutane (R 290 & R 600a), the energy efficiency, cooling and dehumidifying capacities of automobile air conditioner were increased as compared to using R 134a. Lastly using split unit air conditioner, it was concluded that with an increase of 20% compressor displacement, the performance of the air conditioner that uses HC to replace HCFC will be enhanced [13].

Research carried out to evaluate the performances and thermodynamic analysis of commonly used HC refrigerants gave very promising results for, R 600a and R 290, as replacement refrigerants. Some of these experiments were not performed in a standardised environmental (climatic/psychrometric) chamber. Instead, they were carried out at ambient conditions, which varies during each experiment. [14-15]. The non-standardized conditions may generate different sets of results as compared to other researchers who perform at standardised climatic chamber (psychrometric chamber). Devotta *et al* [7] conducted experiments in accordance with the Indian Standard IS 1391 in a climatic chamber. Kim *et al.* [16] had also conducted a similar experiment using the Korean Standard KS 9305. These two experiments therefore yielded more accurate and standardised results as compared to other researchers. Besides these researchers there were others who have conducted experiments in a controlled environment such as, using a psychrometric chamber or using a controlled flow of chilled and heated water to simulate the standard ambient and load conditions for several types of refrigerants [17-20]. The experiments carried out to obtain thermodynamic analysis and performance evaluation on HC or HC blends, gave results which were very promising.

Current studies on HC refrigerants only compared performances of the HC refrigerants with HCFC and HFC. The objective of this research is to compare the performance of commercial grade propane with refrigerant grade propane using the R 22 as the initial refrigerant of the air conditioner unit as a baseline for comparing energy efficiencies and cooling capacities.

1. Methodology and Experimental Set Up

1.1. Methodology

Experiments were conducted in a psychrometric chamber using the "tunnel air enthalpy" method, in accordance with the *ISO Malaysian Standard 5151:2012: Non-ducted air conditioners and heat pumps- testing and rating for performance* (1^{st} revision). Chlorodifluoromethane (R 22) and 2 types of refrigerant grade propane (HC 22a & R 290) and commercial propane were used as refrigerant in a 1 hp (10,000 Btu/hr) split type of air conditioner to be tested for cooling capacities and energy efficiencies in cooling capacity rating conditions as specified by ISO Malaysian Standard 5151 :2012.

The tunnel air enthalpy test method practically involved the measurement of both the dry and wet bulb of air entering and leaving the indoor unit of the split air conditioner in a climatic chamber. These changes together with the airflow measured in the indoor unit provided the cooling capacity of the equipment that was being tested.

An "air flow measurement" apparatus in the psychrometric chamber was where all the air flow data were collected and used for the cooling capacities calculations. As per requirements of the MS ISO 5151: 2012, the air inlet to indoor unit of the air conditioner was set at 19°C wet bulb and 27°C dry bulb and outdoor air inlet condition was at 24°C wet bulb and 35°C dry bulb with maximum allowable tolerances of ± 0.3°C wet bulb and ± 0.5°C dry bulb.

Table 1 showed the specifications of the air conditioning equipment. All the results obtained from this test that used R 22 will be treated as the baseline of the studies. The air conditioner was installed using the set up as shown in Figures 1 and 2 in the psychrometric chamber. The chamber was separated into two sections, each for the indoor and outdoor unit under test.

The indoor unit of the split-type air conditioner was installed on a rack and connected to an air mixer unit via a short length of ducting/plenum. Inside the air mixer unit chamber, wet/dry bulb thermometers and manometer were installed to measure the wet bulb, dry bulb and differential pressure of air entering the indoor unit. Room conditioning equipment were installed at the indoor and outdoor sections of the psychrometric chamber to ensure the air entering the indoor and outdoor units were controlled to the standard rating for moderate climates stipulated in MS ISO 5151: 2012.

Chlorodifluoromethane ($CHClF_2$) or commonly known as R 22 was used as base refrigerant. Two types of refrigerant grade propane which were commercially known as HC 22a and another refrigerant grade propane named as R 290. HC 22a was imported from the U.S.A. and R 290 was sourced from China. Meanwhile, the commercial grade propane was obtained from Petronas Gas export terminal, Cukai, Terengganu, Malaysia. Four samples were tested which include the baseline R 22, two different refrigerant grade propane and one commercial grade propane.

Table 1. Equipment Specifications

Item	Description
Type	Air cooled split unit
Brand	Kool Man
Made	Malaysia
Outdoor Model	KW-102FAO
Indoor Model	KC-102AA
Capacity based on 27ºC (DB) & 19ºC (WB) Indoor and 35ºC (DB) & 24ºC (WB) Outdoor	10,000 (Btu/h)
Refrigerant Type	R 22

1.2. Experimental Set Up

Before the commencement of any experiment the psychrometric chamber was turned "ON" for an hour to achieve the equilibrium temperature and cooling capacity rating conditions (MS ISO 5151:2012).

The indoor unit was installed on a rack above the floor level and outlet of this indoor unit was connected to the air mixer unit via a connected ducting. The air mixer was connected to the airflow measurement apparatus using a flexible duct. The indoor unit was connected to an outdoor unit in a separate room using a copper tubing for the refrigerant inlet and outlet.

The connection between the indoor and outdoor was pressurised with nitrogen at 1.5 times the maximum working pressure of 2620 kPa. If no leak was detected, the refrigerant piping system was then evacuated using a portable vacuum pump connected to a gauge manifold. The hose for the inlet and outlet of the gauge manifold was connected to the service valve for the refrigerant inlet and outlet located at the outdoor unit. The refrigerant piping system was then evacuated to a vacuum pressure of 29 inches mercury or 10014 mm water column.

After the evacuation process was completed, refrigerant was charged into the system. The first refrigerant to be tested in this experiment was R 22, followed by two types of refrigerant grade propane (HC 22a & R 290) and lastly commercial propane. The refrigerant container was set up on an electronic scale (accuracy of ± 1.0 g) to ensure that an accurate amount of refrigerant charged was based on manufacturer's recommendations. In the case of R 22, the manufacturer recommended 600 grams of R 22 for the 1 hp (10,000 Btu/h) split unit air conditioner. This was the amount of refrigerant charged into the system.

Manufacturers of refrigerant grade hydrocarbon have provided a simple chart which showed the correct amount of HC that needed to be charged into the split air conditioning system that have been converted to function from utilizing refrigerant R22 to HC refrigerants. From the chart it can be interpolated, and for a charge of 600 g of refrigerant R 22, 240 g of HC refrigerant would be sufficient. This was because the net refrigeration effect (kJ/kg) of propane was almost double that of R 22 [2]. This was the amount commercial and refrigerant grade propane was charged into the split air conditioner. Table 2 showed the total mass of R 22, commercial and refrigerant grade propane used for this experiment.

All the data used for these experiments were recorded at an interval of 5 minutes up to 7 times to ensure best average results.

Table 2. Types of refrigerants and charge amount

Test Run No.	Refrigerant	% of mass	Total charge amount (g)
1	R 22	100	600
2	HC 22a	100	240
3	R 290	100	240
4	Propane	100	240

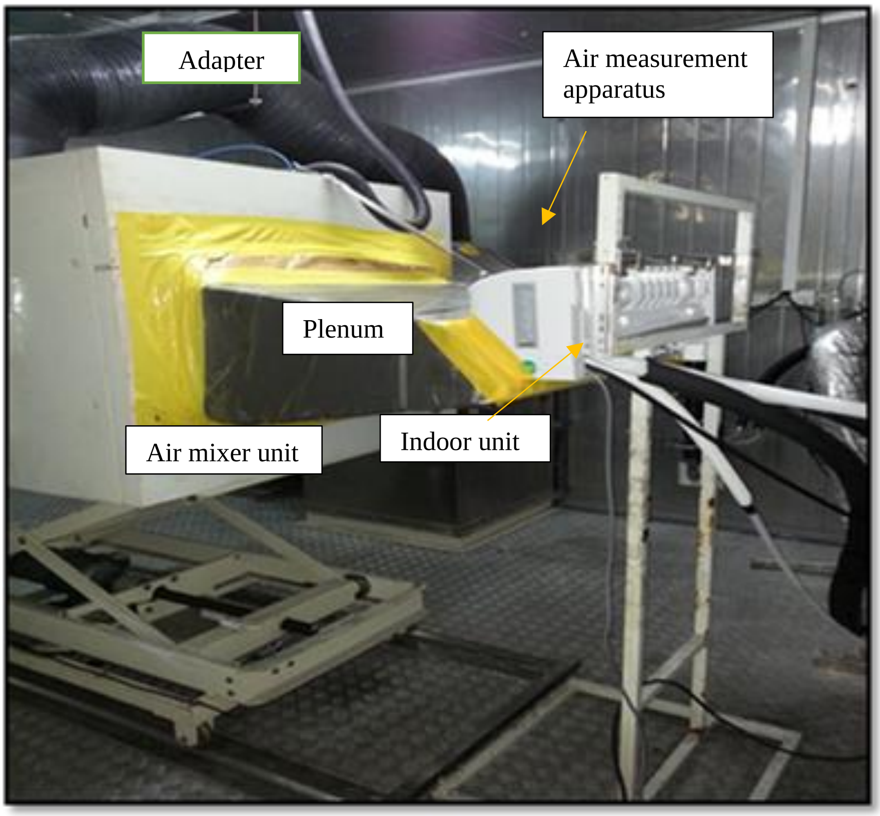

Figure 1. Indoor unit undergoing "Tunnel air test" in psychrometric chamber

Figure 2. Outdoor unit undergoing test in psychrometric chamber.

EXPERIMENTAL RESULTS AND DISCUSSION

In Figure 3, the baseline of R 22 which was the actual working fluid for the air conditioner recorded the highest cooling capacity. For alternative refrigerants, commercial grade propane provided the highest cooling capacity as compared to others, with refrigerant grade propane R 290 coming in second. The R 22, baseline refrigerant has a normal boiling point of -41º C. The thermophysical properties of both the R 22 and propane were very close thus showing very close cooling capacities. Lower cooling capacities of other refrigerants as compared to baseline refrigerant R 22 may be also due to the initial design of the air conditioner that used R 22 and no other types of alternatives despite some refrigerant grade propane and commercial grade propane having similar thermophysical properties. Yang *et. al*., [13] have concluded by changing the compressor of the air conditioner that initially used R 22 into one that has 20% more displacement capacity, both the EER and cooling capacities of the air conditioner will increase. In this study however, no replacement of other components of the air conditioner other than the refrigerants were conducted.

Figure 4 shows the power consumed by the air conditioning unit using R 22 as baseline and other refrigerants as comparison. Refrigerant grade HC 22a has the highest power consumption value as compared to others. This may be due to impurities or suspected incondensable gases that comes with the product. The material data safety sheet (MSDS) of HC 22a, states that the product contains more than 98% of propyl hydride (propane) with 2% as "Non-Hazardous Ingredients". This 2% may have contributed to the lesser performance of HC 22a in terms of cooling capacity and higher power consumption. The compressor of the air conditioner charged with HC 22a was compressing a small amount of non - condensable gas in the refrigerant. With the experiments conducted to check the effects of non - condensable gases in household refrigerators it was concluded that air with a mass of 0.6 g injected into a refrigerator using 40 g of refrigerant or just 1.5 % of non- condensable gas, energy consumption increased by 3.5 % per day in a test chamber with 25 °C ambient temperature [21].

Most of the power used in an air conditioner was when the compressor worked to compress the low-pressure gas phase refrigerant into high pressure gas. Lower power was consumed by the air conditioner when refrigerant and commercial grade propane were used as refrigerants in the study. The mass of HC charged into the air conditioner unit was significantly less as compared to R 22.

In Figure 5, HC 22a has the lowest energy efficiency ratio (EER) due to the combination of low cooling capacity and higher power consumption. The higher EER rating for the commercial propane was because the commercial propane despite having lower cooling capacities as compared to R22 had also lower power consumption.

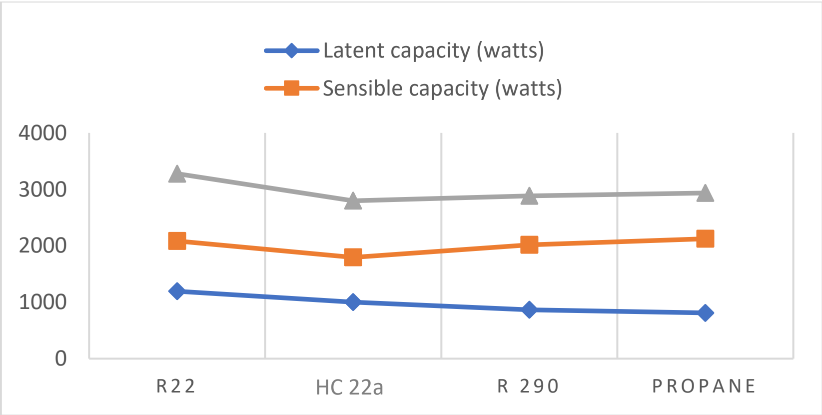

Figure 3. Latent, Sensible and Total Cooling Capacities

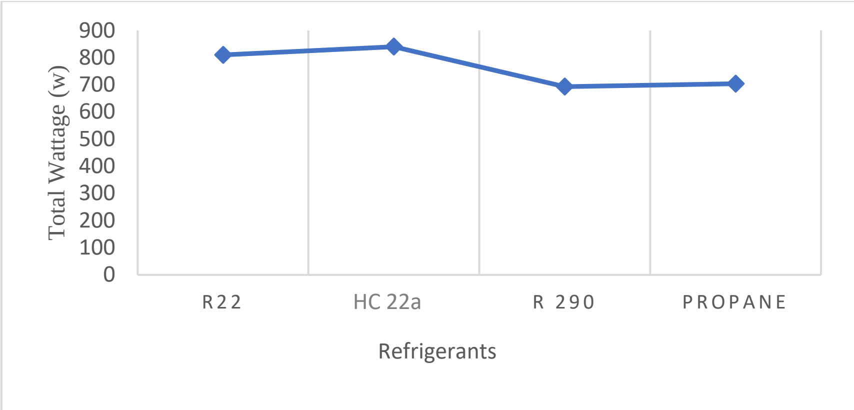

Figure 4. Total Power Consumption (watts)

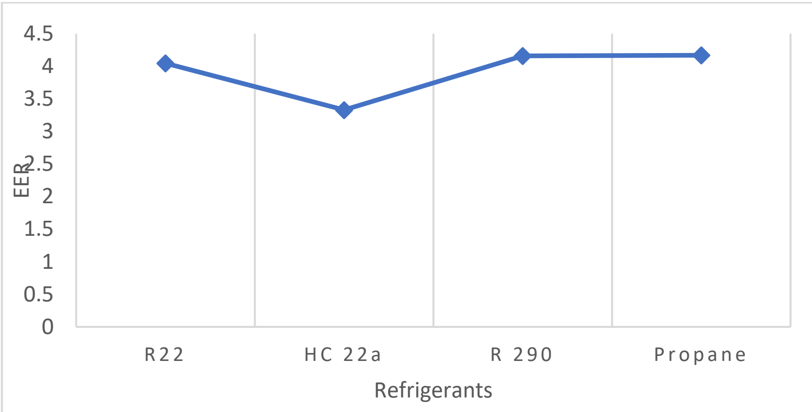

Figure 5. EER of R 22, Refrigerant and Commercial Grade Propane

Table 3 summarises the results obtained for all the experiments. The overall best performer is the 100% commercial propane as it has the lowest difference in cooling capacity as compared to the baseline refrigerant and a better EER as compared to R 22. Propane has a global warming potential (GWP) of 0.02 as compared to R 22 at 1960 making it a viable replacement for R 22 [4]. It was also noted here that despite the claims of refrigerant grade propane having higher purity thus better performance than commercial grade propane, did not show in this experiment. Results also indicated that the locally available commercial grade propane performed better than the imported refrigerant grade propane. However, the air conditioner unit tested still performed best in terms of having the highest cooling capacity with R 22 as the designated refrigerant to be used. Taking the impact of leakage and recovery losses coupled with annual energy consumption of the air conditioning unit the “Total Equivalent Warming Impact” (TEWI) as shown in Equation 1, was a better comparison of the refrigerants tested than looking at the EER alone. The “Life Cycle Climate Performance” (LCCP) illustrated by Equation 2 made the calculations of carbon emissions to more precise level by taking into considerations, the residual refrigerant in the retired equipment, the embodied and fugitive emissions of the refrigerants into the final tally for the calculations of total carbon emissions. Table 4 has listed the EER, TEWI and LCCP calculations of R 22, refrigerant grade propane and commercial grade propane. TEWI and LCCP values were in metric tonnes of CO_2 equivalent. The refrigerant grade and commercial grade propane all have lower TEWI and LCCP as compared to R 22. From Table 4, commercial propane has recorded almost the lowest TEWI and LCCP but losses only 10% of total cooling capacities as compared to R 22.

$$\mathrm{TEWI} = \mathrm{GWP} \times \mathrm{L} \times \mathrm{n} + \{\mathrm{GWP} \times \mathrm{m} \times (1-\alpha\,\mathrm{recovery})\} + \mathrm{n} \times \mathrm{E_{annual}} \times \beta \qquad \text{(Equation 1)}$$

where,

$(\mathrm{GWP} \times \mathrm{L} \times \mathrm{n})$ = Impact of leakage losses

$\{GWP \times m \times (1 - \alpha\ recovery)\}$ = Impact of recovery losses

$E_{annual} \times \beta$ = Impact of energy consumption

where,

L = Leakage, in kg per year;

n = System operating time, in years;

m = Refrigerant charge, in kg;

α recovery = Recovery/recycling factor, 0-1

E annual = Energy consumption, in kWh per year;

ß = CO_2 emission, in kgs^{-1} per kWh.

$$LCCP = \{L_{annual} \times n + R \times (1 - \alpha)\} \times (GWP + E + F) + n \times E_{annual} \times \beta \quad \text{(Equation 2)}$$

where,

R = Residual amount of refrigerant in retired equipment, kg

E = Embodied energy emissions

F = Fugitive emissions

Table 3. Difference in cooling capacity, power consumption and energy efficiency ratio of refrigerants tested in psychrometric chamber.

Refrigerant	Total Cooling Capacity (watts)	Diff (%)	Power consumption (watts)	Diff (%)	Energy efficiency ratio (EER)	Diff (%)
R 22	3277	-	810	-	4.040	-
HC 22a	2797	-14.6	840	3.7	3.330	-18.1
R 290	2882	-12.1	693	-14.4	4.159	2.3
Propane	2935	-10.4	704	-13.1	4.169	2.6

Table 4. TEWI, LCCP, EER and Total Cooling Capacities (TCC) of Refrigerants

Refrigerant	**TEWI**	**%TEWI of baseline**	**LCCP**	**%LCCP of baseline**	**EER (W/W)**	**%EER of baseline**	**Total Cooling Capacity (TCC) (W)**	**%TCC of baseline**
R-22 (Baseline)	14.572	100	14.735	100	4.04	100	3,277	100
HC-22a	13.781	95	14.076	96	3.33	82	2,797	85
R-290	11.370	78	11.666	79	4.16	103	2,882	88
Propane	11.550	79	11.845	80	4.17	103	2,935	90

*Values of TEWI & LCCP in tonnes of CO_2 equivalent.

CONCLUSIONS

This study may support the conclusion that with an air conditioner designed to use R 22, other alternative refrigerants if used, will not provide the similar cooling capacity the unit was designed to provide. EER may be higher for almost all alternative refrigerants used in this study mostly since the net refrigeration effect (kJ/kg) of HCs were better as compared to R 22 hence also the reduction in the charge amount. In this study we also concluded that the use of refrigerant grade propane did not provide any additional advantages as compared to locally commercially available propane. In fact, locally available commercial propane performed better in terms of cooling capacity, EER, TEWI and LCCP. The changing of higher displacement compressor and higher viscosity compressor oil can be adopted in the next phase of the study to compare the cooling capacity and energy efficiency between refrigerant grade propane and commercial grade propane.

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