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Energy Efficiency Study, Comparing, Commercial Grade Propane/Butane Blend; Refrigerant Grade Propane and Chlorodifluoromethane ($CHClF_2$), Investigated in a Psychrometric Chamber

Z. Zakaria [1*], D. Veerasamy[2], J. H. Koh[3]

[1]School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia
[2]Suraaj Mahir Consultancy, 19, Jalan KE 4/9, Kota Emerald, 48000 Rawang, Selangor, Malaysia
[3]Kejuruteraan Muafakat Sdn Bhd, 30 Jalan Taiping off Jalan Pahang 50400, Kuala Lumpur, Malaysia
Corresponding Author: zainalz@petroleum.utm.my

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Abstract

The current use of hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) as refrigerants will be phaseout and phasedown. Hydrocarbon (HC) refrigerants were introduced as potential replacements. These refrigerant grade hydrocarbons namely propane (R 290) and isobutane (R 600a) were on sale at premium prices. As Malaysia has capabilities to produce LPG, a study was conducted to find out the suitability of commercial liquefied petroleum gas (LPG) to be used as refrigerant. This study compares the efficiencies and cooling capacities of commercial grade LPG to refrigerant grade propane (C_3H_8) and chlorodifluoromethane ($CHClF_2$) (R 22) in a split unit air conditioner installed in a psychrometric chamber. Results of experiments indicated that the commercial blends in the ratio of 80% propane and 20% butane provided the highest efficiency, but had the lowest cooling capacities; in contrast, the imported refrigerant grade propane despite value being purer, was not reflected in term of its efficiency; recorded the lowest. $CHClF_2$ provided the highest efficiency and cooling capacity. LPG has the potential to replace R22 in split air conditioners despite losing 10 % in cooling capacities but instead gained 2.6% in energy efficiencies.

Keywords: Refrigerants; global warming; propane; cooling capacity

1.0 INTRODUCTION

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 is 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 horse power (hp), and below. Subsequently, the Phase 2 of the HPMP will be implemented in 2017, targeting 35 % reduction in the use of HCFC [4]. 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 is 2090, as compared to R 22 which is at 1810, making it more environmentally damaging than R 22, which it replaces. The recent Kigali amendments to the Montreal Protocol, has listed these HFCs in the list of greenhouse gases subjected to a phasedown [17]. Hydrocarbons such as propane and butane were identified as potential replacements for these refrigerants [18].

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 are 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 [7]. In another experiment, using Indian Standard IS 1391, in a R 290 charged window unit, was found to have 2.8 - 7.9% higher COP, as compared to R 22 [3]. The split unit air conditioner using R 290 has lower cooling capacity but higher COP despite 50% less charge [11]. In an experiment conducted by Teng et. al. [16], 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. Lastly using split unit air conditioner, it was concluded that with an increase of 20% compressor displacement, the performance of the air conditioner will be enhanced [20].

Researches 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 [1, 14, 15]. The non-standardized conditions may generate different sets of results as compared to other researchers who perform at standardised climatic chamber. Devotta et al. [3] conducted experiments in accordance with the Indian Standard IS 1391 in a climatic chamber. Kim et al., [8] 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 [2, 19, 21, 22]. The experiments carried out to obtain thermodynamic analysis and performance evaluation on HC or HC blends, gave results which were very promising COPs [3, 6, 7, 8, 10, 11, 12, 13, 16].

Therefore, a study was carried out to compare the efficiencies of commercial grade propane and butane to that of refrigerant grade propane in a split air conditioner that uses chlorodifluoromethane (CHClF2) or commonly known as R 22 as its base refrigerant. Two types of refrigerant grade propane which were named commercially as HC 22A that was imported from the U.S.A. and another refrigerant grade propane named simply as R 290 imported from China. Meanwhile the commercial grade propane and butane were obtained from Petronas Gas export terminal, Cukai, Terengganu, Malaysia. Eight samples were tested which include the baseline R 22 and four different blends of commercial propane and butane with different percentage of mass ratios of propane and butane. This study was conducted in a psychrometric chamber using the tunnel air enthalpy method as described in ISO Malaysian Standard 5151 (2012).

2.0 METHODOLOGY AND EXPERIMENTAL SET UP

2.1 Methodology

Experiments were conducted in a psychrometric chamber using the "tunnel air enthalpy" method, in accordance to the ISO Malaysian Standard 5151 (2012): Non-ducted air conditioners and heat pumps- testing and rating for performance (1st revision). Chlorodifluoromethane (R 22) and 2 types of refrigerant grade propane (HC 22A & R 290) and blends of LPG were used as refrigerant in a 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.

Since indoor air enthalpy test method emphasizes on the temperature of wet and dry bulbs of air entering the indoor and outdoor associated with airflow rate, the correct method and equipment could perform these measurements accurately. The MS ISO 5151 provided methods and information of airflow measurement using the airflow measurement apparatus.

This airflow measurement apparatus and air mixer units were the main parts of the equipment used in the indoor air enthalpy method for measuring cooling capacities of split air conditioners. These apparatuses together with the air conditioning split unit under test was installed in a psychrometric chamber that operates at cooling capacity ratings "T1"as per Table 3 of MS ISO 5151 (2012). ("T1" states that the indoor unit inlet temperature at 19°C wet bulb and 27°C dry bulb and outdoor air inlet condition is 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.)

The main part of the research, which consists of tunnel air enthalpy setup, by using a 1 hp (10000 Btu/hr) split unit air conditioner installed in a psychometrics chamber. The air conditioning unit was designed to operate on refrigerant R 22. Table 1 shows the specifications of an air conditioning equipment. All the results obtained from this test that uses R 22 will be treated as the baseline of the studies. The air conditioner is installed using the set up as 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 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 "T1" standard rating for moderate climates.

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

Equation (1) to (3) were used for calculating the cooling capacity (watts) via the tunnel air enthalpy method. The total cooling capacity based on the indoor side test data, φ_{tci} was calculated using Equation (1), the sensible cooling is given as φ_{sci}, in Equation (2) and the latent cooling capacity is given as φ_{d}, in Equation (3) and (4), respectively.

$$\varphi_{tci} = \frac{q_{vi}(h_{a1} - h_{a2})}{v_n} = \frac{q_{v1}(h_{a1} - h_{a2})}{v'_n(1 + W_n)} \tag{1}$$

$$\varphi_{sci} = \frac{q_{vi}(c_{pa1}t_{a1} - C_{pa2}t_{a2})}{v_n} = \frac{q_{vi}(c_{pa1}t_{a1} - c_{pa2}t_{a2})}{v'_n(1 + W_n)} \tag{2}$$

$$\varphi_{d} = \frac{K_{1qvi}(W_{i1} - W_{i2})}{v_n} = \frac{K_{1qvi}(W_{i1} - W_{i2})}{v'_n(1 + W_n)} \tag{3}$$

$$\varphi_{d} = \varphi_{tci} - \varphi_{sci} \tag{4}$$

where,

q_{vi} = air- volume flow rate at inlet, (m^3/s)

h_{a1} = specific enthalpy of air entering indoor side, (J/kg of dry air)

h_{a2} = specific enthalpy of air leaving indoor side, (J/kg of dry air)

v_n = specific volume of dry air portion of mixture at nozzle, (m^3/kg)

v'_n = specific volume of air-water vapour mixture at nozzle, (m^3/kg)

w_n = specific humidity at nozzle inlet, (kg/kg of dry air)

c_{pa1} = specific heat of air entering indoor side, (J/kg °C)

c_{pa2} = specific heat of air leaving indoor side, (J/kg °C)

t_{a1} = temperature of air entering indoor side, dry bulb (°C)

t_{a2} = temperature of air leaving indoor side, dry bulb (°C)

K_1 = latent heat of vaporization of water, (J/kg)

W_{i1} = specific humidity of air entering indoor side, (kg/kg of dry air)

W_{i2} = specific humidity of air leaving indoor side, (kg/kg of dry air)

Total power consumed by the split air conditioner in the psychrometric chamber in the experiments were measured by the power meter installed and average power consumption were calculated for each cycle. The energy efficiency ratio (EER) of the air conditioner under testing was calculated using Equation (5).

$$EER = \frac{\text{Total cooling capacity (watts)}}{\text{Total power input (watts)}} \quad (5)$$

2.2 Experimental set up

Before the commencement of any experiment the psychrometric chamber was turned "ON" for an hour to achieve the equilibrium "T1" temperature and cooling capacity rating conditions [9].

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 is 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 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 by different proportions of LPG mixture. Figures 1 and 2 are the photos of the setup of split air conditioner indoor and outdoor in the test facility. The refrigerant container is 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 shows the correct amount of HC the need to be charged into the split air conditioning system that have been converted to function from utilizing refrigerant R 22 to HC. From the chart it can be seen, for a charge of 600 g of refrigerant R 22 needs 240 g of HC refrigerant. This was the amount of LPG blends charged into the split air conditioner that is being investigated for EER. Table 2 shows the total mass and mass fractions of different LPG components used for the EER experiments.

Table 2: Types of refrigerant 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
5	Propane: butane	80: 20	240
6	Propane: butane	60: 40	240
7	Propane: butane	40: 60	240
8	Propane: butane	20: 80	240

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

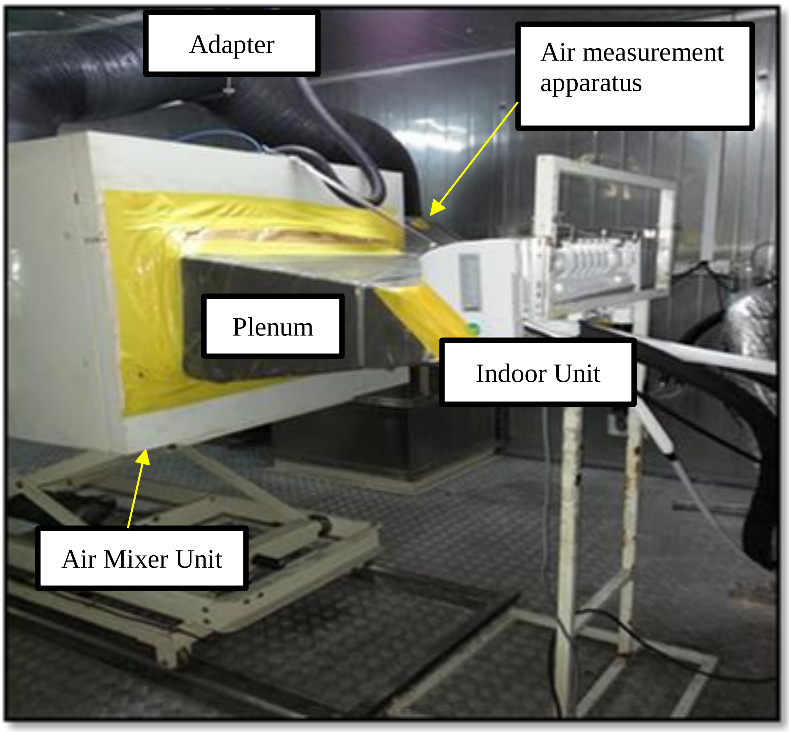

Figure 1: Indoor unit undergoing “Tunnel air test” in psychrometric chamber

Figure 2: Outdoor unit undergoing test in psychrometric chamber.

3.0 RESULTS AND DISCUSSION

Figures 3-5 show the results of the experiments obtained, with different refrigerants charged into the same air conditioner unit.

In Figure 3, the baseline of R 22 which is the actual working fluid for the air conditioner which recorded the highest cooling capacity. For alternative refrigerants, 100% commercial grade propane provided the highest cooling capacity as compared to others with refrigerant grade propane R 290 coming in second. The blend of 20% propane and 80% butane has the lowest cooling capacity in this test. Butane has a normal boiling point of -0.5º C as compared to propane at -42º C. At pressures higher than atmospheric in the refrigeration circuit butane may remain mostly as a liquid unable to boil off hence little enthalpy change occur other than that of the propane in the blend. 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 closer 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 uses R 22 and no other types of alternative despite some refrigerant grade propane and commercial grade propane having similar thermophysical properties [20]. 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. Most of the power used in an air conditioner was when the compressor works to compress the low-pressure gas phase refrigerant into high pressure gas. Lower power consumed by the air conditioner when blends of propane and butane were used as refrigerants in the study. The lowering power consumption corresponds with the increased mass of butane in the blends. Butane was mostly in liquid phase during the entire refrigeration cycle. Only gas phase propane was compressed, and butane remained mostly as liquid and compressor performed less work thus the lower power consumed when blends of commercial propane and butane were used as refrigerants in this study. The higher the mass percentage of butane content in the blends the lower the power consumption of the compressor.

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 blends of commercial propane and butane were because the blends comprising of different ratios of commercial propane and butane despite having lower cooling capacities had also lower power consumption.

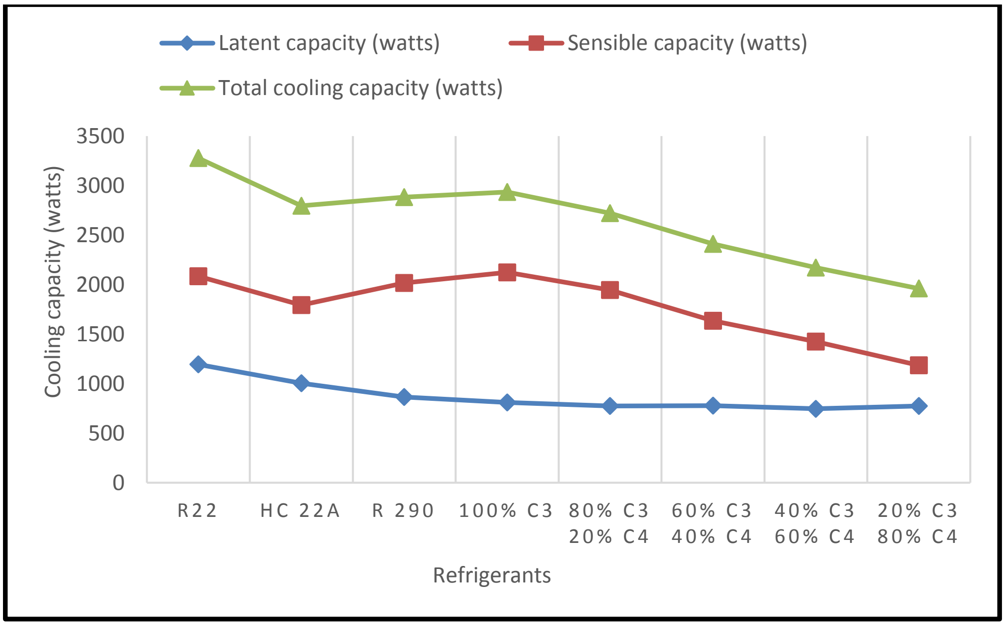

Figure 3. Latent, Sensible and Total Cooling Capacities

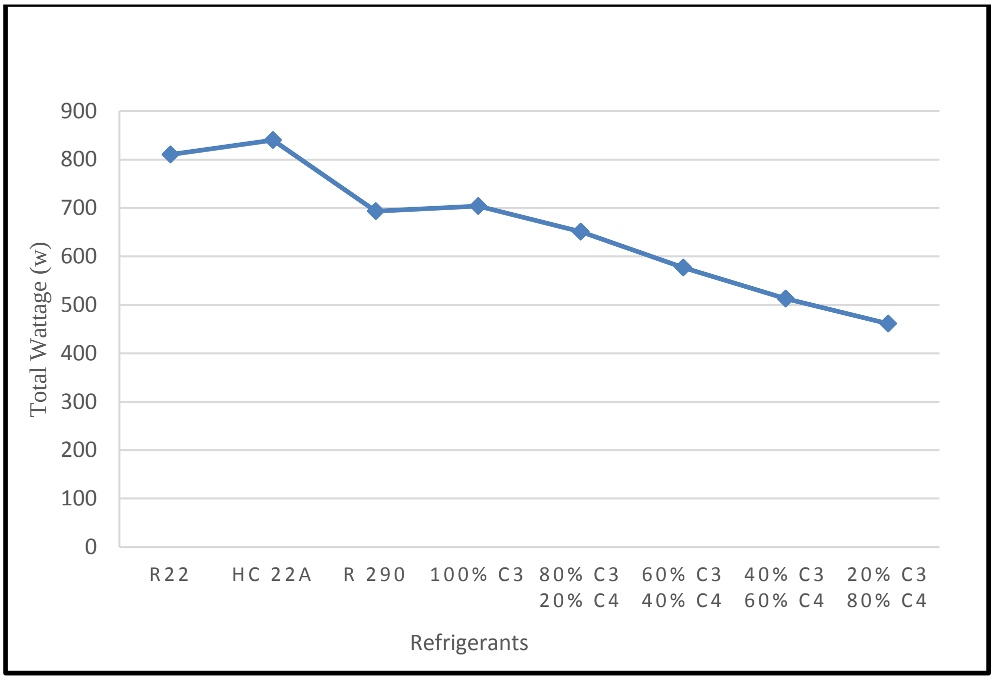

Figure 4. Total Power Consumption (watts)

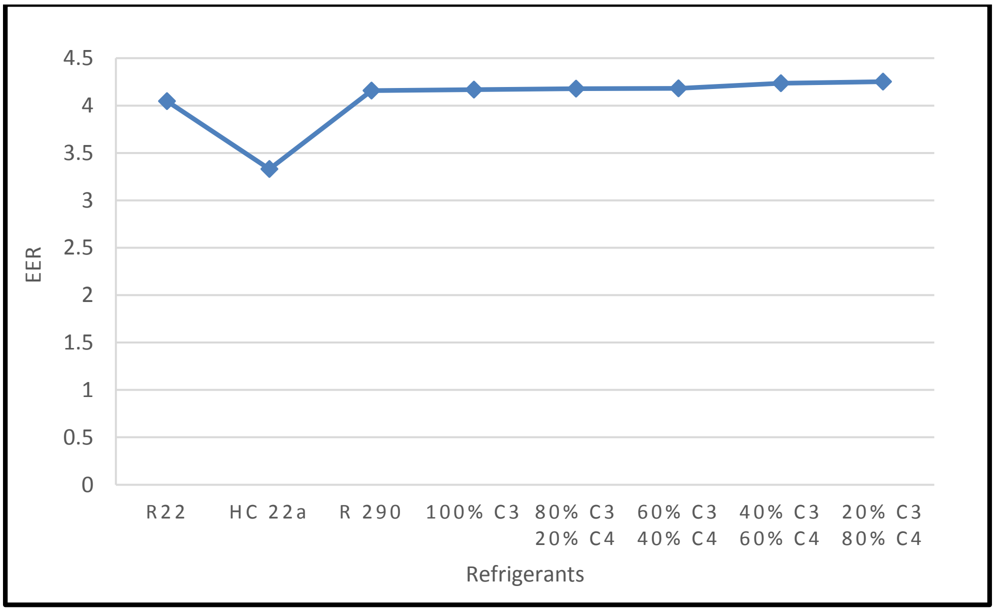

Figure 5. EER of Different Refrigerants and LPG Blends

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. This result was similar to experiments conducted on a split unit air conditioner that was replaced with 50% less charge with propane (R 290) as compared to the initially charged R 22 [11, 16]. Other researchers that replaced HFC refrigerant with propane in domestic refrigerators also reported results that were similar to this finding [10, 21], [19]. Propane has a global warming potential (GWP) of 4 as compared to R 22 at 1810 making it a viable replacement for R 22. It is 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.

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	-	4.064	-
HC 22A	2797	-14.6	840	3.7	3.330	-18.1
R 290	2882	-12.1	693	-14.4	4.159	2.3
100% propane	2935	-10.4	704	-13.1	4.169	2.6
80% propane 20% butane	2720	-17.0	651	-19.6	4.178	2.8
60% propane 40% butane	2412	-26.4	577	-28.8	4.180	2.9
40% propane 60% butane	2173	-33.7	513	-36.7	4.236	4.2
20% propane 60% butane	1960	-40.2	461	-43.1	4.252	4.6

4.0 CONCLUSION

After this study it can be concluded that with an air conditioner designed to use R 22, other alternatives refrigerants if used, will not provide the similar cooling capacity the unit is designed to provide. EER may be lower for almost all alternative refrigerants used in this study mostly due to the fact that the thermodynamic properties of HCs were better as compared to R 22 hence also the reduction in the charge amount. The results of the study were similar to those reported by Granryd [5]. The use of refrigerant grade propane has no advantages as compared to commercially available propane. In fact, commercial propane performed better in terms of cooling capacity and EER. It was also concluded that blends of commercial propane and butane have poor cooling performance with cooling capacity dropping with the gradual increase of butane in the blend. Lastly, it is worth mentioning here that Wu et al., [20], which performed a similar study have concluded that by increasing the compressor displacement by 20% and changing the compressor oil to a higher viscosity type but without changing other components such as capillary tubes and heat exchangers, using HC refrigerants to replace R 22 would increase both the cooling capacity and also EER.

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References

[1] Alsaad, M.A. and Hammad, M.A. (1998). The Application of Propane/Butane Mixture for Domestic Refrigerator. *Applied Thermal Engineering*. 18, 911-918.

[2] Dalkilic, A.S. and Wongwises, S. (2010). A Performance Comparison of Vapour- Compression Refrigeration System Using Various Refrigerants. *International Communications in Heat and Mass Transfer*. 37, 1340-1349.

[3] Devotta, S., Padalkar, A.S., and Sane, N.K., (2005). Performance Assessment of HC-290 as a Drop- In Substitute to HCFC-22 in a Window Air-Conditioner. *International Journal of Refrigeration*. 28, 594-604.

[4] Department of Environment (DOE) Malaysia, 2010, Consultative Workshop on *“HCFC Phaseout Management Plan (HPMP) for Malaysia, 4 October 2010.”* DOE Malaysia.

[5] Granryd, E. (2001). Hydrocarbons as Refrigerants- An overview. *International Journal of Refrigeration*. 24, 15-24.

[6] Hwang, Y., Jin, D.H. and Rademacher, R. (2007). Comparison of R-290 and Two HFC Blends for Walk- In Refrigeration Systems. *International Journal of Refrigeration*. 30, 633-641.

[7] Joudi, K.A. and Al Amir, Q.R. (2014). Experimental Assessment of Residential Split Type Air Conditioning Systems Using Alternative Refrigerants to R22 at High Ambient Temperature. Energy Conversion and Management. 86, 496-506.

[8] Kim, M.H., Lim, B.H. and Chu, E.S. (1998). The Performance Analysis of a Hydrocarbon Refrigerant R-600a in a Household Refrigerator/Freezer. KSME International Journal. 12(4), 753-760.

[9] M. S. ISO 5151, (2010). *Non-Ducted Air Conditioners and Heat Pumps- Testing and Rating for Performance,* Department of Standards Malaysia, 11.

[10] Mohanraj, M., Jayaraj, S. and Muraleedharan, C. (2007). Improved Energy Efficiency for HFC134a Domestic Refrigerator Retrofitted with Hydrocarbon Mixture *(HC290/HC600a) as Drop- In Substitute. Energy* for Sustainable Development. 11(4), 29-33.

[11] Padalkar, A.S., Mali, K.V. and Devotta, S. (2014). Simulated and Experimental Performance of Split Packaged Air Conditioner Using Refrigerant HC-290 as a substitute for HCFC 22. *Applied Thermal Engineering*. 62, 277-284.

[12] Park, K.J., Shim, Y.B. and Jung, D. (2009). A Drop In Refrigerant 431a for Replacing HCFC 22 in Residential Air Conditioners and Heat Pumps. *Energy Conversion and Management*. 50, 1671-1675.

[13] Purkayastha, B. and Bansal, P.K. (1998). An Experimental Study on HC290 and a Commercial Liquefied Petroleum Gas (LPG) Mix as Suitable Replacements for HCFC 22. *International Journal of Refrigeration*. 21(1), 3-17.

[14] Tashtoush, B., Tahat, M. and Shudeifat, M.A. (2002). Experimental Study of New Refrigerant Mixtures to replace R 12 in Domestic Refrigerators. Applied Thermal Engineering. 22, 495-496

[15] Thangavel, SP. and Somasundram, P. (2013). Part Load Performance Analysis of Vapour Compression Refrigeration System with Hydrocarbon Refrigerants. *Journal of Scientific and Industrial Research*. 72, 454-460.

[16] Teng, P.T., Mo, H.E., Lin, H., Tseng, Y.H., Liu, R.H. and Long, Y.F. (2012). Retrofit Assessment of Window Air- Conditioner. *Applied Thermal Engineering*. 32, 100-107.

[17] UNEP, 2016, Frequently asked questions relating to the Kigali Amendment to the Montreal Protocol. Viewed 3 April 2017 http://ec.europa.eu/clima/sites/clima/files/faq_kigali-amendment_en.pdf

[18] U.S, EPA, 2015, Significant New Alternative Policy (SNAP) Report, viewed 26 September 2016 <http://www.epa.gov/ozone/snap/index.html>.

[19] Wongwises, S. and Chimres, N. (2005). Experimental Study of Hydrocarbon Mixtures to Replace HFC 134a in a Domestic Refrigerator. *Energy Conversion and Management*. 46, 85-100.

[20] Wu, J.H., Yang, L.D. and Hou, J. (2012). Experimental Performance Study of a Small Wall Room Air Conditioner Retrofitted with R290 and R1270. *International Journal of Refrigeration*. 35, 1860-1868.

[21] Yu, C.C. and Teng, T.P. (2014). Retrofit Assessment Using Hydrocarbon Refrigerants. *Applied Thermal Engineering*. 66, 507-518.

[22] Yu, J., Xu, Z. and Tian, G. (2010). A Thermodynamic Analysis of a Transcritical Cycle with Refrigerant Mixture R-32/R-290 for a Small Heat Pump Water Heater. *Energy and Buildings*. 42, 2431-2436.