# VIABILITY OF COMMERCIAL LIQUEFIED PETROLEUM GAS AS DROP-IN REFRIGERANT IN AIR CONDITIONING SYSTEMS

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# DEDICATION

Dedicated to my beloved wife and daughters.

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## ABSTRACT

This study focuses on the use of commercial grade liquefied petroleum gas (LPG) namely, propane and butane to replace chlorodifluoromethane (HCFC-22) or commercially known as R-22. Malaysia being a signatory to the Montreal Protocol has committed to phaseout the use of HCFC and subsequently introduced hydrofluorocarbons (HFC) refrigerants as replacements. HFC is a global warming gas and is also subjected to phasedown in the future. A replacement refrigerant using hydrocarbons such as, propane and butane were available in the market where most of them were imported. It was the objective of this study to find out the suitability, efficiency and the safety of LPG, which are widely available in Malaysia to be used as replacement as refrigerant, for R-22. The scope of research included conducting the cooling capacities and energy efficiency tests with variations of outdoor temperatures using R-290 & HC 22a (both were refrigerant grade propane), variations of LPG compositions based on mass percentage and R-22. Tests were conducted in psychometric chamber to compare the cooling capacities and energy efficiencies of R-22, refrigerant grade propane and LPG using the ISO 5151 standard as a reference. To study the safety aspects, in the use of LPG as refrigerant, computational fluid dynamics (CFD) simulations using the 'fire dynamics simulator version 6" software was used to generate propane leak scenarios of an indoor unit of the 1.0 horsepower split air conditioner in an enclosed room. In cooling capacities tests, by comparing, commercial propane was comparable to R-22, losing out only by 10 % of the capacity as compared to R-22. A 20 % propane and 80 % butane LPG blend meanwhile was the highest in energy efficiency ratio (EER) ratings but losing out by 40 % cooling capacities. In simulation studies, leak hole with a diameter of above 2.40 mm posted hazards of forming combustible mixture when propane was leaking from the indoor unit. The leak holes diameters of 0.08 mm, 0.76 mm, 1.50 mm and 1.90 mm posted no hazards in forming the combustible gas mixture when entire content of refrigerant was leaked into the room. Areas inside and surrounding the cover of the air conditioner's indoor unit were susceptible to fire upon reaching the lower flammability limit of propane due to the leak of refrigerant from the air conditioner. This study also established that, commercial propane could be used as a "drop-in" to replace refrigerant R-22 without significant loss in refrigerant capacities and could achieve better EER ratings than R-22. A combustible leak detection system installed, capable of detecting propane leakage from the cover of the indoor unit of split unit air conditioner could enhance safety when utilizing commercial propane as a refrigerant.

# ABSTRAK

Kajian ini menumpukan kepada penggunaan gas petroleum cecair (LPG) gred komersial khususnya propana dan butana bagi menggantikan klorodifluorometana (HCFC-22) atau nama komersialnya R-22. Malaysia telah menandatangani Protokol Montreal telah komited untuk menamatkan penggunaan HCFC dan memperkenalkan bahan penyejuk hidrofluorokarbon (HFC) sebagai gantinya. HFC adalah gas yang menyebabkan pemanasan global dan akan digantikan pada masa depan. Bahan penyejuk gantian menggunakan hidrokarbon seperti propana dan butana telah pun berada di pasaran dan kebanyakkan adalah diimport. Maka adalah menjadi objektif kajian ini untuk menentukan dari segi kesesuaian, kapasiti penyejukan serta keselamatan LPG yang terdapat dengan meluasnya di Malaysia sebagai gantian untuk bahan penyejuk R-22. Skop kajian ini meliputi menjalankan ujian kapasiti penyejukan serta kecekapan tenaga menggunakan R-290 dan HC 22a (kedua-duanya merupakan propana gred bahan penyejuk), variasi komposisi LPG berpandukan kepada peratusan kandungan jisim serta R-22, dalam suhu persekitaran luar yang berbeza. Ujian telah dijalankan dalam bilik psikometrik untuk membandingkan kapasiti penyejukan serta kecekapan R-22, propana gred bahan penyejuk dan LPG menggunakan piawaian ISO 5151 sebagai rujukan. Untuk mengkaji penggunaan LPG sebagai bahan penyejuk dari segi keselamatan, simulasi pengkomputeran dinamik bendalir menggunakan aplikasi "*fire dynamics simulator version 6* " telah dijalankan untuk menjana senario kebocoran propana dari unit dalaman peralatan penyaman udara 1 kuasa kuda dalam bilik tertutup. Dalam ujian kapasiti penyejukan, dengan perbandingan, propana komersial adalah setanding dengan R-22 yang mana kapasiti penyejukan hanya turun 10 % berbanding dengan R-22. Manakala nisbah kecekapan tenaga (EER) pula, adunan dengan 20 % propana dan 80 % butana adalah yang tertinggi tetapi kapasiti penyejukan turun sebanyak 40 %. Kajian simulasi, saiz lubang yang bocor berdiameter 2.40 mm ke atas mengundang bahaya dengan menjana campuran gas mudah terbakar apabila propana bocor dari unit dalaman. Lubang bocor berdiameter 0.08 mm, 0.76 mm, 1.50 mm dan 1.90 mm mengeluarkan campuran gas mudah terbakar yang tidak berbahaya apabila keseluruhan kandungan bahan penyejuk yang bocor memenuhi ruang bilik. Ruangan dalam penutup dan sekitar unit dalaman peralatan penyaman udara adalah mudah terdedah kepada kebakaran apabila propana mula bocor dari peralatan tersebut serta mencapai had nyalaan terendah. Keputusan kajian ini mendapati propana komersial boleh dijadikan gantian bagi bahan penyejuk R-22 tanpa penurunan kapasiti penyejukan yang mendadak serta dapat juga mencapai EER yang lebih baik berbanding dengan R-22. Pemasangan sistem pengesan kebocoran gas mudah terbakar pada penutup unit dalaman peralatan penyaman udara jenis berasingan yang mampu mengesan kebocoran propana, dapat meningkatkan tahap keselamatan semasa menggunakan propana komersial sebagai bahan penyejuk.

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| | | |
|---|---|---|
| ABS | - | Acrylonitrile-Butadiene-Styrene |
| AC&R | - | Air conditioning & refrigeration |
| AIRAH | - | Australian Institute of Refrigeration, Air conditioning and Heating |
| ASHRAE | - | American Society of Heating, Refrigeration and Air conditioning Engineers |
| ATEX | - | Appareils destines a etre utilizes en Atmosphere Explosibles |
| BS | - | British Standards |
| BTU | - | British Thermal Unit |
| $CCl_4$ | - | Carbon tetrachloride |
| CFC | - | Chlorofluorocarbon |
| CFD | - | Computational Fluid Dynamics |
| $CH_4$ | - | Methane |
| $C_3H_6$ | - | Propane |
| $C_4H_8$ | - | Butane |
| $CH_3Cl$ | - | Chloromethane |
| CIBSE | - | Chartered Institution of Building Services Engineers |
| $CO_2$ | - | Carbon dioxide |
| COP | - | Coefficient of Performance |
| DB | - | Dry bulb temperature |
| DOE | - | Department of Environment |
| DOT | - | Department of Transportation |
| DP | - | Differential Pressure |
| EER | - | Energy Efficiency Ratio |
| EN | - | European Norms (European standards) |
| EU | - | European Union |
| FDS | - | Fire Dynamics Simulator |
| GHG | - | Greenhouse Gas |
| GWP | - | Global Warming Potential |
| HC | - | Hydrocarbon |

| | | |
|---|---|---|
| HCFC | - | Hydrochlorofluorocarbon |
| HFC | - | Hydrofluorocarbon |
| HFO | - | Hydrofluoroolefin |
| $H_2O$ | - | Water |
| HPMP | - | Hydrochlorofluorocarbon Phaseout Management Plan |
| $H_2S$ | - | Hydrogen sulfide |
| HVAC | - | Heating ventilation and air conditioning |
| IEC | - | International Electrotechnical Commission |
| IPCC | - | Intergovernmental Panel on Climate Change |
| ISO | - | International Organization for Standardization |
| LCCP | - | Life Cycle Climate Performance |
| LFL | - | Lower Flammability Limit |
| LPG | - | Liquefied Petroleum Gas |
| MOM | - | Ministry of Manpower |
| MOX | - | Malaysian Oxygen Berhad |
| $NH_3$ | - | Ammonia |
| NIST | - | National Institute of Standards and Technology |
| NR | - | Natural Refrigerant |
| $N_2O$ | - | Nitrous oxide |
| ODP | - | Ozone Depletion Potential |
| PFC | - | Perfluorocarbons |
| R | - | Refrigerant |
| R & D | - | Research and Development |
| SCDF | - | Singapore Civil Defense Force |
| SEER | - | Seasonal Energy Efficiency Ratio |
| $SF_6$ | - | Sulfur hexafluoride |
| $SO_2$ | - | Sulfur dioxide |
| TUV | - | Technisher Uberwachungsverein |
| UNEP | - | United Nations Environment Programme |
| VOC | - | Volatile Organic Compound |

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# CHAPTER 1

# INTRODUCTION

## 1.1 Research Background

Ozone layer comprises of a gas made up of three atoms of oxygen and is a layer in the stratosphere which is 15- 50 km from the earth surface. Ozone layer provides a layer of protection against the harmful ultraviolet (UV) radiation from reaching the earth (UNEP, 2007, Langley, 1994). Without the ozone layer harmful UV in particular UVA and UVB causes skin cancer, cataracts and suppression of the human immune systems (UNEP, 2007). Depletion of the ozone was first recorded in the mid-1970s over Antarctica when what is not known as the "Ozone Hole". The "stratospheric ozone depletion caused by chlorofluorocarbons (CFCs)" were reported by Professor Sherwood Rowland and Dr Mario Molina at the annual meeting of the American Chemical Society and later published their findings in the Nature journal (Sekiya *et al*, 2006, Langley, 1994). The report in Nature journal sparked a worldwide ban on chlorine based compounds in CFCs and alternatives were sought to replace them. The United Nations Environment Programme (UNEP) initiated the Vienna Convention in 1985 to protect the ozone layer and two years later the "Montreal Protocol on Substances that Deplete the Ozone Layer" aimed at the reduction and phaseout of CFCs (UN, 1987).

In view of the phaseout of CFCs and hydrofluorochlorocarbons (HCFCs), alternative refrigerants were formulated in the form of hydrofluocarbons (HFCs) where the chlorine element was eliminated from this type of refrigerant, HFCs were one of the causes for global warming as these type of refrigerants were later found out to have global warming potential (GWP) of many times compared to carbon dioxide which is a naturally found global warming greenhouse gas found in nature. Global warming was a naturally phenomenon occurring in the earth's atmosphere but anthropogenic contributions to global warming are causes for concern as rising earth temperature leads to climate change. Carbon dioxide, methane and nitrous oxides are three main greenhouse gases and since the pre- industrial revolution these gases has increased 32%, 145% and 13% respectively. (AIRAH, 2003). Apart from the naturally occurring greenhouse gases, man-made fluorinated compounds such as HFCs, Perfluorocarbons (PFCs), sulphur hexafluoride ($SF_6$) and nitrogen trifluoride ($NF_3$) are potent greenhouse gases (UN, 1998). R-410A a type of hydrofluorocarbon currently used as a refrigerant in domestic air conditioning systems has a GWP of 2100 times as compared to carbon dioxide (ASHRAE, 2013).

With the impeding total phasing out of hydrochlorofluorocarbon (HCFC) based refrigerants used in the air conditioning and refrigeration industries in Malaysia by 2040, there is an urgent need to find an alternative solution to the current issue. By the year 2015, Malaysia as listed in the category of Article 5 nations has committed itself to the following timetable for phasing out the use of HCFC in industries (DOE, 2010). Table 1.1 defines the Article 5 and non-Article 5 nations according to the "Montreal Protocol on Substances that deplete the Ozone Layer" (UN, 1987).

Table 1.1 Article 5 according to Montreal Protocol (UN, 1987)

| **Article 5 and non-Article 5 according to Montreal Protocol** | **Definitions** |
|---|---|
| Article 5 | Any party that is a developing country and whose annual calculated level of consumption of the controlled substance (as listed in Annex A of the Montreal Protocol) is less than 0.3 kilograms per capita. |
| Non-Article 5 | All developed countries or nations not categorised as developing nations. |

Table 1.2 Comparison of the old and new commitments of HCFC phase out plans (UN, 1987, 1998)

| **Non-Article 5 Parties** | **Non-Article 5 Commitments** | **Article 5 Parties** | **Article 5 Commitments** |
|---|---|---|---|
| **Existing Commitments** | **Under 2007 Montreal adjustments** | **Existing Commitments** | **Under 2007 Montreal adjustments** |
| Baseline: 8% of 1989 CFC levels plus 100% of 1989 HCFC levels | Unchanged | Baseline: 2015 levels | Average of 2009 and 2010 production and consumption |
| Freeze in 1996 | Unchanged | Freeze by 2016 | Freeze by 2013 |
| 35% reduction by 2004 | Unchanged | No obligation | 10% reduction by 2015 |
| 65% reduction by 2010 | 75% reduction by 2010 | No obligation | 35% reduction by 2020 |
| | 90% reduction by 2015 | No obligation | 67.5 reduction by 2025 |
| 99.5% reduction by 2020 | Unchanged | No obligation | 97.5 reduction by 2030 |
| Phase out by 2030 | Unchanged | Phase out by 2040 | Unchanged |

The government of Malaysia under the directive of the Department of Environment (DOE), will oversee that industries that uses or produces HCFC, to freeze and stop importing and production of HCFC by 2013 and reduction of 10% by 2015, 35% reduction by 2020, 67.5% reduction by 2025, 97.5% reduction by 2030 allowing 2.5% to be used for the serving and maintenance of existing equipment (DOE, 2010). These dates were agreed upon by countries ratifying to the Montreal Protocol adjustment to the Montreal Protocol when the meeting of parties was held in September of 2007 (UNEP, 2007). The total phase out of ozone depleting substances (ODS) by the non- Article 5 countries was however not affected by the new agreements. The year 2030 will mark the year when ODS will be eliminated and banned in developed nations. Table 1.2 indicates the old and new commitments of the CFC phaseouts according to categories of developing and developed countries. Back to the air conditioning industries, as per directive of Department of Environment's (DOE), HCFC Phase-out Management Plan Phase 1 (HPMP), one of the key planned regulatory actions includes the "prohibition of manufacturing, assembling and importing of HCFC-based domestic air conditioners (2.5 horse power and lower) for use in Malaysia" (DOE, 2015).

With the target date set and with full commitments from countries ratifying the Montreal Protocol, the air conditioning and refrigeration industries throughout the world were looking and researching into the introduction of alternative methods and technology to continue providing air conditioning and much needed refrigeration to buildings and the food industries.

In the air conditioning industries, the introduction of zero ODS refrigerants were introduced in the early 90s in the form of hydrofluorocarbons (HFC). HFC 134a were widely adopted in the refrigeration sectors and HFC 410a, a near azeotrope blend of 50% R-32 and 50% R-125 were introduced as possible transitional refrigerants for the air conditioning industries (Calm, 2008). All HFCs introduced were advertised as '0 ODS' refrigerants. This claim however only short lived as it was soon discovered that these HFCs were more damaging to environment than the HCFCs that it replaced because of the Global Warming Potential (GWP) of these gases. GWP is an index to compare the value of the gases concerned (HFCs and HCFCs) to that of carbon dioxide ($CO_2$) for an iteration of a period of 20, 100 and 500 years (UNEP, 2007). The GWP of the base carbon dioxide is equals to 1 (UNEP, 2007). The GWP of these refrigerants were even higher that those inherited by HCFCs. For an instance, R- 410a that replaced the R-22 has a GWP of 2100 as compared to GWP of 1790 of R-22. R-410a is 2100 times more potent than of carbon dioxide in contributing to global warming. (GWP of carbon dioxide is =1) (ASHRAE, 2013). It is the target of refrigerant or air conditioners manufacturers to find an alternative refrigerant that have the lowest possible GWP ratings without the issues of toxicity and combustibility. And yet R-410a was proposed by the DOE and the air conditioner manufacturers to replace R-22, knowing that the GWP of this replacement refrigerant is higher than that it replaces.

If the Montreal Protocol was to counter the ozone depletion issues of chlorofluorocarbon (CFC) and HCFC, then the Kyoto Protocol (effective 2005 and ended in 31 December 2012) was targeted to phase out the use of HFCs. (Kyoto

Protocol is an international agreement linked to the United Nations Framework Convention on Climate Change (UNFCCC) to target 6 greenhouse gas listed in Annex A of the protocol which includes carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride.) This has to be done because as HFCs contribute immensely to global warming. Due to this scenario, the HFCs, indeed will have a very short rein in its usage in the air - conditioning and refrigeration (AC&R) industries (DOE, 2018). Malaysia has since signed the agreement on curtailing HFCs usage in 1999 and subsequently ratified to the agreement on $4^{th}$ September 2002, thus paving the way for the reduction of greenhouse gases (GHGs) emissions. (DOE, 2015).

The air conditioning and refrigeration industries were left with very limited choice of using the transitional high GWP refrigerant, R-410a. Incidentally, one major player has imported equipment that uses R-32 which has lower GWP values as compared to R-410a but is classified as an A2L refrigerant. However, A2L is designation for mildly flammable refrigerant in accordance with the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 34. R-32 had a GWP value of 675 and possesses lower flammability value as compared to refrigerant classified as A3, which is a designation for highly flammable refrigerant in accordance with ASHRAE Standard 34. These classifications based on toxicity and flammability are found in many national and international standards. Namely the ASHRAE Standard 34 and 15, published by ASHRAE USA and ISO 817 (2014) Refrigerants – “Designations and Safety Classifications” published by the International Organization of Standardization (ISO). The European Union (EU) through its parliament has issued a regulation (Regulation 517) in 2014 prohibiting and reducing the use of fluorinated gases which includes HFCs (EU, 2014). This regulation was widely known as the “F-gas regulations” throughout its member states and was considered a regulation proper to reduce the use of the high global warming gases ahead of the targeted reductions specified in the Kyoto Protocol (EU Regulation 517, 2014). This regulation carries with it, very strict conditions for member states on the use fluorinated gases in industries. These include matters pertaining to the safety, release of fluorinated gases into the atmosphere and training of personnel in the use of fluorinated gases. It also imposed a strict ban on certain HFC that had values GWP of 2500 and above to be gradually phased out by 1st January 2020 for all refrigerators and freezers in the commercial use. Single split air conditioners functioning on less than 3 kg of HFC refrigerant of GWP of 750 and above will be prohibited in 1 January 2025 (EU Regulation 517, 2014).

Table 1.3 Article 2 parties according to Kyoto Protocol (UN, 1998)

| **Article 2 and Non- Article 2 parties according to Kyoto Protocol** | **Definitions** |
|---|---|
| Article 2 parties | All 43 parties included in Annex 1 of the Kyoto Protocol that must meet Kyoto Protocol targets in reduction of GHG emissions. Countries included in Annex 1 of the protocol includes most developed countries in the world and economies in transition. |
| Non-Article 2 parties | All parties not listed in annex 1 of the protocol which include most developing nations and least developed countries. These parties have no GHG reduction targets. |

The Article 2 countries which included countries in the European Union had embarked on a very drastic measure to implement the phase down and eventual phase out of the potentially harmful GWP refrigerants way ahead of the targeted dates set under the Kyoto agreement. Table 1.3 provided a brief explanation between article 2 and non-article 2 parties according to the Kyoto Protocol. The issue of global warming is surely more real and damaging to the environment as compared to the issue of the ozone depletion (UNEP, 2007). These developments soon will be followed and imposed upon those in the Article 5 countries since most manufacturers of these refrigerants are found in the developed nations with these strict regulations on manufacturing standards, taxes and other safety issues the supply of HFCs to the developing nations will eventually diminishes and cost of using the HFC will be higher since the short supply of HFC manufactured in developed nations and increased demand for HFC to replace HCFC in developing nations will eventually drive prices up.

We will eventually soon witness the double jeopardy of using HFC with its impact on global warming and future excessive costs. Since 2017, there is two-fold increase of price for the supply of HFC 410a in the Malaysian market. The 10 kgs HFC 410a was retailed at RM 180 per 10kgs cylinder on mid-year of 2016 to RM 380 at the end of 2017 These will make HFC as only a transitional medium, as an interim measure for use in the AC&R industries. In the next 10 to 15 years, depending on the market conditions and the most importantly the severity of climate change, that would entail the replacement of HFC.

Developed countries had since reverted to the “ancient” medium of naturally available refrigerants. These gases (carbon dioxide, ammonia, water and hydrocarbons) were bypassed at one time, presumed wrongly regarding the danger posed by their inherent properties of toxicity and flammability. Nevertheless, during the recent time, the ever popular and safe chlorofluorocarbon has been finally replaced. This was due to the discovery by Dr Molina & Rowland, when the ‘Nature’ carried their hypothesis which is related to the connection that exists between stratospheric ozone depletion and the use of CFC in industries (Calm and Didion, 1998). It is an irony that instead of Thomas Midgley Jr, the co-inventor of CFC being looked up as a saviour of the AC&R for creating the world’s first safe and non-flammable refrigerant CFC 11, he is now being chastised for misleading them to utilise an environmentally damaging substance for almost 60 years (Calm and Didion, 1998). Over the years lots of resources have been wasted in the research and development on AC&R equipment to use CFC efficiently. Instead, if the same amount of resources were invested on the R&D activities, surely safer and more efficient AC&R equipment would have been able to run on natural refrigerants (NRs) now. Due to their short sightedness, we are in this predicament now, to reinvent the wheel after almost 60 years of neglecting them.

NRs that were out of favour then, found new lease of life after all these years, These NRs include carbon dioxide, ammonia, water and hydrocarbons. The use of carbon dioxide in AC&R has been limited to refrigeration equipment in cold rooms and has limited applications in air conditioning system due to the high operating pressures in ranges of 80 to 100 bar, (Lorentzen, 1994, ASHRAE, 2018). Ammonia had been widely used in industrial refrigeration and in ice making factories due to the low cost and the only disadvantage being its high toxicity (Lorentzen, 1994, ASHRAE, 2018). In addition, the current refrigerant piping which were made of copper is not compatible to ammonia, as drop in or replacement. This is due to the corrosion that occurs when ammonia reacts with copper. Water as refrigerant in absorption chillers necessitates the use waste heat to operate. However, the need to operate in deep vacuum and the use of multistage axial turbo- compressors makes it a very expensive option as a refrigerant (Calm, 2008). Water is also not suitable in vapour compression systems. That leaves hydrocarbon, as the only suitable drop in media or suitable alternative for existing AC&R equipment that uses HCFC or HFC. This is due to the similarities of their thermodynamic values and compatibilities with copper pipes and the refrigerant oils that are in use.

Hydrocarbon (HC) refrigerants especially R-290 (propane) has close thermodynamic properties and performance factors to HCFC 22 (ASHRAE, 2013). This was because in the 1920s CFCs were synthesized to mimic/imitate the performances of the HC that they were supposedly to replace (Calm and Didion, 1998). HC were reintroduced more recently due to the gap in finding a suitable replacement for R-22 used in small air conditioning systems and R-134a that replaces CFC 12 in domestic refrigeration equipment. Safety factors with the flammability issues remain the hardest hurdle to overcome for its full implementation of HC as refrigerant (Lorentzen, 1995).

Hydrocarbon (HC) refrigerants were extensively used in the EU and the Scandinavian countries which include Denmark, Norway and Sweden. Greenpeace first introduced the concept of HC in refrigerators when they took over the management and production of a manufacturer in East Germany and began converting its facilities to produce HC refrigerant based refrigerators and marketed them to Europe. Acknowledging the fact that these refrigerators were both energy efficient and environmentally friendly, other manufactures in other countries followed suite (Greenpeace, 2004). Most domestic refrigerators sold in the EU are mostly charged with R-600 (butane) or R-600a (iso butane). As a safety measure, due to flammability issues, the maximum charge allowable for these refrigerators was limited to 150 g as per International Electro Technical Commission which are (IEC) Standards IEC 60335-2-24 and IEC 60335-2-89, respectively (BS EN 378-1, 2013). Because of the EU's initiation, major air conditioner manufacturers in China have already started to manufacture and exporting HC based small split system air conditioners to EU in 2013 (GIZ, 2014). These factories and manufacturing practices have already been quality certified by the Technischer Überwachungs-Verein (TUV) of Germany. TUV is an independent quality certification agency in Germany (GIZ, 2014).

The needs of industries have pointed to HC as the current best alternative as replacement for HCFCs or HFCs. HCs such as propane is now offered in pure and refined form in the guise of trademark such as "CARE 40" as marketed by Linde Group which is a German multinational chemical company and is the world's largest industrial gas company by market share. It is being claimed that the refined and purified propane refrigerant R-290 is more than 97.5% pure propane with very minimal impurities with the content of sulphur to be less than 2 ppm with less than 10 ppm moisture and aromatics (DOE, 2010)). With all these comes a price, each kilogram of pure and refined HC cost around RM 50 - RM 90 depending on the manufacturers and the importers. These entire refrigerant grade HCs were imported.

Marketers and proponents of purified HCs often condemn the usage of commercially available HCs which were commonly used in cooking and generally addressed as liquefied petroleum gas (LPG) as not suitable for use as a refrigerant. It was claimed that LPG has purity levels of only 60 % - 65 % with sulphur content were more than 200 ppm - 300 ppm, respectively. Aromatics are also in excess; more than 20 ppm. These impure HC would impact the refrigeration system through thermo-physical properties of the working fluid, internal stability of the system, structure and behaviour of components and materials and toxicity implications if released from system.

These factors were factored in to prevent the use of commercial LPG as refrigerant. Research conducted by various researchers, however have concluded that commercial LPG was indeed able to be used as replacement despite its so called "inherent impurities". Research conducted by UTM using samples collected from various sources (Singapore, Thailand & Malaysia) and different companies (Shell, Petronas, BP, ESSO, Petronas Gas, KELOIL, Summit etc.) have concluded that these samples had hydrogen sulphide contents of less than 4.245 ppm. This is in line with 'clause 2.6.2.4'of the Malaysian Standard Code of Practice 930. This is to ensure that the LPG used in Malaysia is compatible with copper piping used in the reticulation. The presence of minimal amount of hydrogen sulphide ($H_2S$) will not corrode the copper pipes internally. The researchers had also concluded that hydrogen sulphide content in commercially available LPG was less than 2.62 ppm (Majid, *et al*., 2002). Based on the research results, LPG with this low range of sulphur content value available in Malaysia enables it to be safely used in the refrigeration system. It will have no corrosion issues when used in copper piping as refrigerant and as medium for heat exchangers and compressor windings made from copper cables.

The search for the replacement for HCFC and HFC is an ongoing process. R-410a being a type of hydrofluorocarbon will eventually be phasedown and phaseout. The current refrigerant of choice to replace R-410a is R-32 (difluoromethane) and is also a type of HFC. It is listed in the 'Group 1' controlled substance of the Kigali amendment to the Montreal Protocol, which will be phasedown and phase out eventually (UNEP, 2016).

Hence, by introducing locally available LPG which has a GWP of 3 as compared to R-32 with a GWP of 675 or R- 410a with GWP of 2100. These are 675 and 2100 times more potent than that of carbon dioxide as a global warming gas.

## 1.2 Problem Statement

Despite the agreement to start imposed the reduction of 10 % of HCFC beginning of 2015, the air conditioning and refrigeration (ACR) industries and other stakeholders involved with the industry were not ready at least in economic sense to start the process of imposing this reduction. With the current economic downturn, many importers and manufacturers found it difficult to reduce the stocks of household air conditioning units of 2.5 hp and below which still uses the R-22 as its main refrigerant. The stakeholders have voiced out their grievances through many representatives, one of these was the Malaysian Air- Conditioning and Refrigeration Association (MACRA) (DOE, 2015).

After much deliberation and rounds of meeting with the ACR industries and key players in the manufacturing of air conditioning units, the DOE issued a circular to inform the industries and public of the extension of time to ban the use of R-22 in household air conditioning of capacities 2.5 hp and below (DOE, 2015). The new timetable to ban R- 22 in air conditioning units of 2.5 hp and below was extended from the initial date set at 1st July of 2015 to 31st December 2015 (DOE, 2015). Several reasons were provided for this sudden turn around. The first would probably be the economic reason where unsold units that do not meet the July deadline must be disposed. Second reason being the issue of the replacement refrigerant of R-22 which is, R- 410A having a higher working pressure (with high side reaching to pressures of between 2000 kPa – 2400 kPa)since the refrigerant was still new in the market, cost of this refrigerant will be higher, and the third reason would be the environmental concern of replacing one refrigerant which has impact on the ozone depletion and global warming with another HFC with no impact on ozone but a higher GWP values. Another very fundamental issue that concern everyday users of the domestic air conditioning units were the inabilities of current air conditioning units that operated on R-22 to directly use R-410A as a “drop in” when the HCFCs were no more available in the market, as these units were not compatible in components and oil used to lubricate the compressors (ASHRAE, 2015).

On the other hand, suitable refrigerants (NRs such as carbon dioxide, ammonia, water and hydrocarbons) that can replace the HCFC were already being used and marketed in Europe, parts of Australia and even in India (Colbourne *et al*., 2015). The HC refrigerants were used successfully in Europe and the Scandinavian countries like Norway, Finland and Sweden. Domestic refrigerators that have less than 150 grams of R-600a (iso butane) is a norm in Europe. R-600a had been proven as a very well qualified and thermodynamically suitable replacement for R-134a found in most domestic refrigerators used today (Colbourne and Suen, 2015). It is also noted here that any new purchase of domestic refrigerator in our local Malaysian markets would have compressors running on R-600a instead of R-134a unknowingly by end users.

In Malaysia, there are companies that currently aggressively marketing the R-290 as replacements for R-22. Claims and counterclaims have been made on its suitability to replace the R-22 both in terms of thermodynamic qualities and components of existing systems that uses R-22. This is a good move as a suitable replacement have already been found to replace the environmentally damaging refrigerant R-22, but at a higher cost (177 % - 400 %) and risk of explosion. All the refrigerant grade propane and butane marketed are imported from Australia, Korea, United Kingdom and some are even blended in the neighbouring Thailand. None are in fact produce locally. The cost of these refrigerant grade propane and butane or its blend are in the range or RM 50 to RM 90 per kilogram (Ener- Save S.B, 2016). Malaysia is oil and gas producing country and petroleum products from our oilfields are light, sweet and cleaner having less sulphur content (0.08 % sulphur by weight) than those imported from the middle-east (0.5 % sulphur) (MPC, 2016). The cost per kilogram without the subsidies from the government is RM 3.10. The vast difference in the cost of imported refrigerant grade HCs and local commercial LPG will be a major factor in determining its success as a drop-in refrigerant for use in domestic split type air conditioner. The HC refrigerants introduced locally are the purified form of ethane, propane, butane and blends of the mixture of these hydrocarbons. The purified forms of hydrocarbons are often sold at premium prices and the cost of conversion of existing AC& R equipment to use the HCs will be determining factor on its success in replacing R-22.

There are currently no researches conducted in Malaysia on the viability of using the commercial LPG (ethane, propane, butane) as a substitute for HCFC 22 in a split type air conditioner. This is the research gap that needed to be conducted to ascertain on its viability of using commercial LPG as a substitute for refrigerant R-22 in a split type air- conditioner. Experiments conducted on using commercial LPG as a substitute to R-12 in a domestic refrigerator in ambient conditions results in lower COP of LPG as compared to the banned R-12 (Alsaad and Hammad, 1998). Some compared COPs of LPG, R-22, R-290, R-22 and R-404a in a domestic refrigerator (Meyer, 1999). It was noted that the COPs of R-22, LPG and R-290 are higher that R-404A. Most researchers had conducted experiments with domestic refrigerators and heat pumps with most using refrigerant grade propane (R-290) or butane as refrigerants to replace the currently used (R-134a and R-22). An experiment was recently conducted experiments using split type air conditioning units to compare the COP of R-290 with R-22 (Pandalkar *et al*., 2014). Findings were very positive when results indicated even with lower cooling capacities R-290 have higher energy efficiency ratio (EER) and needed only half of the volume as compared to R-22. No research was conducted so far to compare commercial grade LPG, refrigerant grade propane (R-290) and R-22 in an enclosed psychrometric chamber at conditions stated in the ISO 5151 methodology. (ISO 5151 – "Non-ducted air conditioners and heat pump- Testing and rating for performance" is an international standard published by the ISO and is used by manufacturers of air conditioners and heat pumps worldwide to ascertain the performances of air conditioners and heat pumps based on its energy efficiencies).

As shown by research conducted on the LPG, its $H_2S$ contents were within the limits of less than 4.245 ppm as required by the MS 930 for it to be used in copper piping. 4.245 ppm of sulphur content is much lower than the figure of 200 ppm provided by suppliers and manufacturers of purified HC refrigerant when comparing their products with LPG. The answers to the question of the performances of LPG as a refrigerant to be used as drop in or as a replacement with minimal conversion in small domestic air conditioning units up to 2.5 hp are needed to ensure that a cheap and safe suitable alternative will be made available to consumers when the eventual phase out of HCFC is imposed.

Another issue need to be considered is the combustibility of LPG as refrigerant that must be also researched upon. There are many researches being conducted on this issue. Researchers conducted actual leak test using $CO_2$ to simulate the scenario of leaking of R-290 in an enclosed chamber, they have concluded that small and low volume refrigerant charge, high air velocities coupled with high installation height will improve the concentrations of flammable refrigerants to reach lower flammability limits (LFL) (Colbourne and Suen, 2003). Other uses gas detectors set up in various locations in a room to detect leaking R-290 from a split air conditioner installed at a height of 1.8 metres above floor level with total refrigerant charge of 0.38 kilogrammes. The refrigerant was leaked at a rate of 13 g/min to 100 g/min. It was generally concluded that in any leak rate conditions the concentrations of flammable refrigerants in the room was in the ranges of one-third of LFL and maximum concentrations never exceeded two-third of LFL levels (Li, 2014). Several other researchers went a step further by igniting the R-290 released from a split type air conditioner in an enclosed chamber. The team found out that the flammable range of the leaking R-290 is within the close locality of the indoor unit and indoor unit was recommended to be installed away from any known source of ignition (Chang *et al.,* 2013). There are also simulation experiments conducted by other researchers using different software applications such as ANSYS FLUENT and Open FOAM (Nagaosa, 2014 and Liu *et al*., 2013). By using the Open FOAM open sourced software, it was concluded that gas flow velocities depended strongly on the gas densities. It further confirmed that the spread velocities are intensified by the density difference of the leaked gas and ambient air (Nagaosa, 2014). Using the ANSYS FLUENT Version 12, simulation was conducted to determine the ratio of dangerous area volume of a leaking propane scenario. It was concluded that propane leaking at a rate not larger than 2.84 g/s, the ratio of dangerous area volume of 30 % will be maintained and with a ventilation rate of 0.125 $m^3$/s the ratio of dangerous area volume will not reach 30 % which is considered critical hazardous value. (Liu *et al.,* 2013). The researchers have clearly defined the rate leak that can fill a room to reach the dangerous area volume of 30 % and the need to maintain good ventilation in an enclosed room so that dangerous area volume will not reach the value of 30%. These values were dependent on the volume of the room under investigations.

The question on the behaviour of commercial propane, butane and LPG leaking from a wall mounted air conditioning unit installed in a typical room in Malaysia may provide us with different results as those conducted by researchers stated above, as Malaysia being a tropical climate country have different ambient conditions as compared to those in temperate climates. The scenarios of leaking LPG from a wall mounted air conditioning unit in a room with a hot and humid condition may not be the same as the scenario found in temperate climates. It must also be noted here that as this research is being conducted there are no legislations or standards in Malaysia to allow the use of HCs as refrigerants in domestic air conditioning systems.

## 1.3 Objectives of Research

Based on the highlighted problem statement and the need of suitable alternative to replace HCFC as well as HFCs, therefore the main objectives of this study are:

1) To evaluate the suitability of LPG to replace HCFC 22 as drop in refrigerant in a 1.0 horse-power domestic air conditioner.
2) To verify and compare the energy efficiency ratio of LPG to HCFC 22 (R-22) and propane refrigerant (R-290 and HC-22a) in a 1.0 horse-power domestic air conditioner.
3) To perform a simulation study on LPG leakage in a 3 meters (width) by 3 meters (length) and 3 meters (height) room without any ventilation and window.

## 1.4 Scope of Research

The scope of the research will be by testing a 1.0 horse-power (hp) split type air conditioner in a psychrometric (environment) chamber with full load condition with set indoor and different ambient outdoor temperature to verify and compare the energy efficiency ratio (EER) of different refrigerants namely R-290, HC-22a, LPG and R-22.

Psychometric chambers have the abilities to pre-set the room temperature and the humidity levels of the indoor section and outdoor sections with the built in air conditioning units (to reduce the room temperature), humidifier (to increase the humidity), de- humidifier (to decrease humidity) and heaters (to increase the room temperature). A pre- set indoor and outdoor section dry bulb and wet bulb conditions can be adjusted according to the required conditions by a control panel.

The ambient outdoor temperature settings will be firstly set to T1 conditions (35 ºC dry bulb & 24 ºC). This is to obtain the EER of the air conditioner under testing to fulfil the ISO 5151 standards. Variations of dry bulb temperatures of 30 ºC, 32 ºC, 34 °C, and 38 °C with wet bulb at 24 ºC will be set using the controller panel of the psychrometric chamber to obtain the EER of the air conditioner under testing. Total LPG mass charged into the air conditioner is 240 grams and mass percentage of propane and butane will be charge with firstly 100 % mass of commercial propane and secondly the mass ratio will be changed to 80 % propane and 20 % butane which corresponds to 192 grams of commercial propane and 48 grams of commercial butane. Commercial propane will be reduced at a rate of 20 % and commercial butane will be increase by a rate of 20 % on the next phase of the experiment in the psychrometric chamber. The final mass will consist of 89 % commercial butane and 20 % commercial propane.

The following variables will be used to ascertain the suitability, EER and safety of LPG as a “drop in” refrigerant. They are:

1. Variations of outdoor temperature conditions ranging from 30 ºC to 38 °C dry bulb will be set to obtain the differences in EER based on these variations.
2. Variations of LPG composition of propane and butane based on percent of mass ratio

On the issue of safety, simulation using Fire Dynamics Simulator Version 6.5.3 (FDS) will be used to evaluate the leaking LPG in a typical enclosed room size of 300 cm x 300 cm x 300 cm, which is a common room size in dwellings in Malaysia. The leak will be simulated from a height of 200 cm from finished floor level which is the level most suitable to provide the airflow to the room at this height ease of maintenance of the air conditioner unit will be met. Variations of 7 out of 10 different leak rates studied by several researchers (Colbourne and Espersen, 2013, Colbourne and Suen, 2015) will be used as basis to simulate leaking propane over a period of 4 minutes as per requirements set by the IEC 60335-2-40 (2005) standard.

## 1.5 Significance of Study

This research is very much into finding a possible solution in providing a safe and efficient refrigerant available in abundance locally to replace the high global warming potential (GWP) currently in used.

Although the refrigerant grade propane has been utilised in developed countries, not much was made available in developing countries as the quantities of split air conditioning using R-290 were in limited numbers. Hence, by importing them, the cost for R-290 will be very expensive. This research will provide an answer to the question of whether the locally available LPG can be used and perform as well as those imported. By doing so, the cost factor in using LPG to replace imported R-290 will be very significant economic factor and will prevent the outflow of money to import refrigerant that we already produced in our backyard. The local air conditioning manufacturing industry will have a replacement made in Malaysia refrigerant and overall cost of manufacturing an air conditioner will be lower by using the LPG as compared to the imported R-290.

If local air conditioner manufacturers embark on the idea of manufacturing dedicated split air conditioners that uses LPG instead of HFC, then it will contribute to the effort to reduce the global warming menace. Using naturally available LPG in dedicated split air conditioners designed for LPG will be greener and an eco-friendly option.

With this research in finding a method to prevent flammable LPG from forming a combustible mixed when leaked in an enclosed environment, it further assures end users that have installed LPG split air conditioners to safely use them without the worries of combustion or secondary fires resulting from leaked LPG in the room. Coupled with this, and with the use of safety standards, statutes and trained personnel to handle LPG, split air conditioners filled with LPG as a refrigerant can be safely and efficiently used by the masses.

## 1.6 Limitation of Study

This research is limited to the use of commercial LPG and R-290 as drop in 1.0 hp residential air conditioner initially designed to use R-22. The air conditioner uses the vapour compression refrigeration cycle. The study of the azeotrope and zeotropic properties and the temperature glide of the LPG blends will not be included in this research.

The testing chamber used in this study consist of the "air enthalpy method" type of installation in determining the energy efficiency ratio (EER) of split types air conditioner using the MS ISO 5151:2012 "Non-ducted air conditioner and heat pumps- testing and rating performance ($1^{st}$ revision)". Since the split air conditioner used in this test consist of a unit without "inverter controller" that controls partial loads of the compressor, it will be tested at full load conditions only. This is in accordance with the requirements of MS ISO 5151.

The simulation of leaking LPG in an enclosed space is limited to a low Mach "Large Eddy Simulation" (LES) turbulence model. 729,000 purely hexahedral cells will be used for meshes and time step size is limited to 0.1s. Run time is limited to 240 seconds which is corresponding to 4 minutes of total leak time.

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