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Review Paper

Propane (HC – 290) as an Alternative Refrigerant in the Food Transport Refrigeration Sector in Southern Africa – a Review

Thomas Kivevele[1,2,3]

[1]Department of Materials and Energy Science and Engineering, Nelson Mandela African Institution of Science and Technology (NM-AIST), P. O. Box 447, Arusha, Tanzania
[2]African Centre of Excellence for Water Infrastructure and Sustainable Energy Futures (WISE-Futures), NM-AIST, P. O. Box 447, Arusha, Tanzania
[3]Department of Mechanical Engineering, Mechatronics and Industrial Design, Tshwane University of Technology, Private Bag X680, Pretoria 0001, South Africa

kivevelethomas@gmail.com

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Abstract

Most of the food transport trucks in Sothern Africa are equipped with refrigeration and air conditioning systems filled with fluorocarbon refrigerants such as R404A to facilitate the heat transfer process. These refrigerants are synthetic chemicals and have high potential to cause global warming and damage to the ozone layer. Currently, natural refrigerants are considered as alternatives to these man-made refrigerants to mitigate some of the environmental risks. The natural refrigerants are the substances that occur in nature such as hydrocarbons (HC), ammonia, and carbon dioxide. These type of refrigerants have been in the market for many years, but in some applications such as domestic refrigerators, heat pumps, chillers, and air conditioners, whereas fluorocarbons are the mostly used in the food transport refrigeration systems. Natural refrigerants such as propane (HC – 290) are now penetrating the market in food transport refrigeration systems where previously fluorocarbons were the favoured option. Therefore, this work reports the possibilities of using non-fluorinated hydrocarbon/natural refrigerant (propane – R290) in the food transport refrigerated systems in Southern Africa; a case study of South Africa. R290 has the potential to lower greenhouse gases emissions compared to hydrofluorocarbons (HFCs) which are widely used in most of the existing food transport refrigeration systems in South Africa. R290 has negligible Global Warming Potential (GWP) of 3 which is well below the global threshold value of 150. The review revealed that refrigeration capacity of R290 is in the average of 10 – 30% higher than commonly used fluorocarbon refrigerants such as R404A and R134A. Since R290 is labeled as a flammable refrigerant, the present study also reviews its flammability safety measures.

Keywords: Propane; Refrigerant; Transport refrigeration system; Greenhouse gases; Hydrocarbons

1. Introduction

Food transport refrigeration systems are very important on food chain not only for preserving products being transported but also its influence on the greenhouse gas emissions and energy consumption [1]–[5]. The road transport refrigeration equipment works in harsh and uncontrolled environments hence exhibit lower efficiencies and flammability risks than domestic refrigeration systems [5]. Conventional diesel engine driven vapour compression refrigeration systems are commonly used in food transport. However, these systems have as high as 40% of greenhouse emissions mostly coming from vehicle's engines [5], [6].

The increase in demand of home delivery of refrigerated products and expectations of high quality of the products is placing substantial pressures on the food industry to reduce energy consumption and greenhouse emissions in the transport refrigeration systems. Therefore, the use of environmentally friendly refrigerants with good thermodynamic properties in the transport refrigeration systems is inevitable such as the use of naturally occurring and ecologically safe refrigerants sometimes called natural working fluids [7]. The open literature demonstrates that most of the existing transport refrigeration systems in Southern Africa use synthetic hydrofluorocarbons (HFCs) refrigerants such as R404A which are considered as non-eco-friendly refrigerants [8].

R404A is reported to have high global warming potential (GWP) with negligible effect on ozone layer depletion as depicted in **Table 1** [3], [6], [7], [9]. HFCs refrigerant does not have harm when are securely contained in refrigeration systems and transporting containers, however, leakages of the systems and improper recovery of refrigerants during repairs or at end of life it may result the greenhouse gases entering the atmosphere [6], [7]. Maina and Huan [7] also reported that harmful wastes are released to the environment during production of refrigerants causing pollution in water, air and land and the release of greenhouse gases to the atmosphere.

These man-made refrigerants have been widely used in many refrigeration systems because their environmental effects could only be seen in the long run [7], [10]. The use of R404A consume more energy than the use of natural occurring refrigerants such as R290 which has higher thermodynamic performance hence reduces energy consumption [6], [8], [11], [12]. In addition, major manufacturers of refrigerants have announced a significant increase of the price of R404A and several other refrigerants with high GWP values as part of discouraging the use of these refrigerants [6], [8] and some of the manufacturers are planning to stop selling R404A in the next few years. Hence looking for ideal alternative refrigerants to replace unfriendly halogenated refrigerants (HFCs) in the transport refrigeration system is imperative. Natural refrigerants/non-fluorinated hydrocarbon e.g. propane (R290), carbon dioxide (CO_2), ammonia, water, and air are currently considered as an ideal replacement of HFCs [7].

The proper selection of refrigerant is one of the key design decisions in designing mechanical parts of refrigeration systems. There various factors to be considered during selection of refrigerants such as safety, reliability, performance, cost, environmental acceptance. However, the primary requirements are safety and reliability though nowadays environmental friendly refrigerants in terms of global warming potential and ozone depletion are the key factors when selecting refrigerant to be used in any refrigeration system [2], [3], [7].

This study therefore, reviews previous works and findings on using hydrocarbons; propane (HC – 290 or R290) as an alternative refrigerant in the transport refrigeration systems, also ongoing researches in Southern Africa. However, application of R290 to replace the widely used R404A in Southern Africa is unfortunately in infancy stages. Most the reported studies in this field have been done in developed countries as compared to developing countries like South

Table 1. Environmental effect of different groups of refrigerants [6]

Refrigerant Group	Refrigerant Example	ODP	GWP (100 year)	Atmospheric life time (years)	Flammability	Comments
CFCs	R11, R12, R115	0.6–1	4750–14,400	45–1700	Non-flammable	Very high ODP and GWP
HCFCs	R22, R141b, R124	0.02–0.11	400–1800	1–20	Non-flammable	Medium ODP and GWP
HFCs	R404A, R32, R134a	0	140–11,700	1–300	Non-flammable	Zero ODP and medium GWP
HFOs	R1234yf, R123ze, R1234yz	0	< 0–12	--	Flammable	Zero ODP and low GWP
HCs	290, R600, R600a	0	0	Few days	Flammable	Zero ODP and zero GWP

*Note: CFCs: Chlorofluorocarbons; HCFCs: Hydrochlorofluorocarbons; HFCs: Hydrofluorocarbons; HCs: Hydrocarbons and HFOs: Hydrofluoroolefins; ODP: Ozone Depletion Potential

Africa. It is important to note that performance of refrigeration system is significally affected by climatic conditions because as the ambient temperature rises, the compressor runs more to maintain the storage temperature in the fresh-food and frozen-food compartments whereas as the ambient temperature falls, compressor operation decreases. Siang and Sharifian [13] demonstrated that the amount of refrigerant charge and performance of a portable propane air conditioner are affected by the evaporator's inlet pressure and ambient conditions such as wind speed. When the inlet pressure of the evaporator is changed from 0.8 MPa to 0.4 MPa, the cooling capacity of a portable air conditioner employing R290 increases from 0.956 kW to 4.319 kW. The accumulated refrigerant mass within the evaporator decreases from 176.846 g to 67.768 g under the same conditions. When the air speed over the evaporator is increased from 1.0 m/s to 3 m/s, the cooling capacity increases from 3.208 kW to 4.275 kW, while the refrigerant mass decreases from 110.307 g to 68.033 g. It's worth noting that when the evaporator's inlet pressure is low, frost forms quickly on the coils. With these findings, it is therefore important to investigate the performance of these emerging refrigerants using local climatic conditions.

Propane is regarded as the best refrigerant because it is occurring naturally with zero ozone depletion potential, high performance due to excellent thermodynamic properties, good compatibility with system components and low refrigerant charges allowing smaller heat exchangers and piping [8], [11], [12], [14]–[18]. Propane can be used in commercial refrigeration systems, large air conditioning and chiller systems, chill cabinets/vending machines, cold storage and food processing, small air conditioning systems, heat pumps/water heaters, and transport and industrial refrigeration systems. The properties of R290 is somewhat different to that of fluorocarbon refrigerants and the main difference is its categorization as flammable refrigerant [6], [8], [11]. Therefore, the handling and use of propane (HC – 290) as a refrigerant requires adequate safety measures. It is for such reason that this study also reviews safety issues when R290 is used in food transport refrigeration units.

2. Transport Refrigeration Systems in South Africa

HFC – 404A is the widely used refrigerant in the food refrigeration transport sector in South Africa. However, as previously discussed this refrigerant has high global warming potential as compared to natural occurring refrigerant such as HC – 290 (see **Table 1**). South Africa is one of the major producers of greenhouse gases in Africa. The yearly per capita emission rate of the country is approximately 10 tons of carbon dioxide, 43% above the required global average. This is due to the country's dependency on coal in power generation. South Africa is among top 100 big producers of coal in the world and around 77% of electricity in the country is generated from coal [14]. South Africa is number one emitter of greenhouse gases in the African content and among 15 big emitters worldwide.

South Africa is vulnerable to climate change; the impacts of climate change affect almost every sector in the country, including health, agriculture, infrastructural development, water, trade, tourism, transportation and finance. South Africa like many countries signed the Kyoto Protocol and the United Nation's Framework Convention on Climate Change is keen in combating climate change. The target of the country is to reduce the emission by 34% in 2020 against business as usual (BAU) and by 42% in 2015 [14]. As a part of the country to meet this goal, the government aims to improve energy efficiency and use of renewable energy resources. These efforts also include possible measures in the transport and, consequently, the refrigerated transport sector (road vehicles, railway wagons, and sea containers). Thus, refrigerants with low-global warming potential (GWP) such as HC – 290 are expected to be the next generation of refrigerants in the country.

The use of R290 in the food transport refrigeration systems has not been well applied in Southern Africa. The most recent project on transport refrigeration systems was conducted jointly between Transfrig South Africa, a German federal enterprise which support the German Government in achieving its objectives in the field of international cooperation for sustainable development (GIZ – South Africa) and the Tshwane University of Technology (TUT). The aim of the project is improving energy efficiency and reducing greenhouse gas emissions in South Africa with the focus in the refrigerated transport sector.

The objective was to develop, demonstrate and deploy the use of a safe and efficient food transport refrigeration system with hydrocarbons (propane – R290). Specific objectives were to jointly develop a pilot food transport refrigeration system (conceptual and detailed design; prototype construction, testing and risk assessment) for a refrigerated truck with R290 as a refrigerant. The refrigeration unit be independent of the vehicle motor. Also, to experimentally investigate the thermal performance of the developed system and compare with theoretical and numerical results and also investigate the safety aspects related to the leakages and flammability of using R290. In addition, install the developed system in a truck and test the operating system in a truck for its safety and energy efficient operation. Finally, jointly place efforts for the market introduction and dissemination of the developed system.

The developed transport refrigeration system using R290 for small and large trucks as shown in **Figure 2** is showing convincing results based on local climatic conditions. Compared to the existing R404A system, the newly developed system using R290 consume lower amount of refrigerant with better performance in terms of energy efficiency [8], [11]. The developed transport refrigeration systems are electrically driven using a diesel engine and an alternator, the system also includes a variable speed drive (VSD) for capacity control. The main features addressed in the new design were circuit optimization and integration of safety measures. Circuit optimization included system simulations to select compressors and redesign of heat exchangers with the purpose of achieving the same cooling capacities as R404A while improving the coefficient of performance (COP) and reducing refrigerant charge as much as possible [8], [11]. **Figure 1** summarizes the main stages in the development of an R290 transport refrigeration system [8].

Conformity to refrigerating systems and heat pumps safety and environmental requirements standards such as EN 378 and SANS 10147 were established in this project. **Figure 2** and **Figure 3** depict the newly developed truck refrigeration system (model: MT480) by Transfrig South Africa and its circuit arrangement, respectively. **Table 2** summarizes technical details of MT450 and MT480 transport refrigeration systems, it can be seen that new design (MT480) using R290 have smaller heat exchanger tubes meaning that the sizes of condenser and evaporator for MT480 are smaller than MT450 and hence low charge of refrigerant. In addition, variable speed compressor reduces the energy consumption of the system.

South Africa supports the transition from high to low global warming potential (GWP) natural refrigerants. The transition to low GWP refrigerants has been addressed in the meeting of the G8 in the Petersburg declaration of 16th July 2006, also signed by South Africa; the ambition to phase down hydrofluorocarbons (HFCs) has been underlined. Also, it is important to point out that

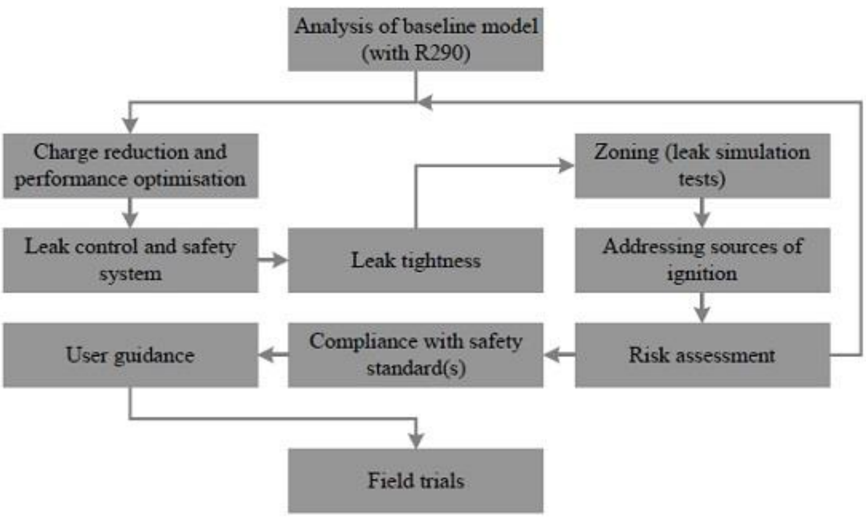

Figure 1. Summary of the main stages in the development of an R290 transport refrigeration system [8]

Table 2. Technical details of MT450 and MT480 [11]

Item	MT450	MT480
Refrigerant	HFC – 404A	HC – 290
Cooling capacity	7.95 kW for 0 °C 4.55 kW for -20 °C	7.95 kW for 0 °C 4.55 kW for -20 °C
Powered by	Open-type, driven by diesel engine	Semi-hermetic compressor, electrically driven, diesel-driven alternator
Expansion device	Thermostatic expansion valve	Electronic expansion valve
Compressor	Fixed speed	Variable speed (60 – 100%)
Condenser tubing	9.5 mm	5 mm
Evaporator tubing	9.5 mm	7 mm

Figure 2. Truck refrigeration system using R290 (model: MT480) [11]

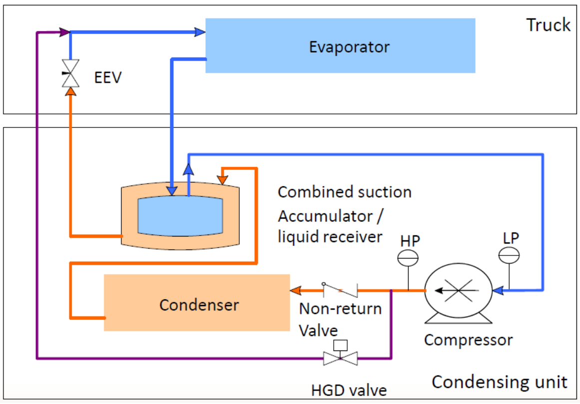

Figure 3. Circuit arrangement of new transport refrigeration system (model: MT480) [11]

South Africa seeks to support domestic manufacturers of transport refrigerated systems to pilot and demonstrate the use of low-GWP refrigerants such as natural refrigerants e.g. R290.

3. Performance of Refrigeration Systems using HC–290

Various research works have been reported in the literature when R290 was used as an alternative refrigerant to replace the widely used synthetic refrigerants such as R22, R404A, and R134A. Li et al. [18] used R290 into a split room air-conditioner designed for using R22. They investigated the influence of capillary length, outdoor temperature, and refrigerant charge on the performance of an air conditioner. The distribution of R290 along the loop in the heat exchangers was also analyzed. It was observed that, the cooling capacity of the R290 air conditioner was 99% that of the R22 air conditioner while the Energy Efficiency Ratio (EER) of the former increased by10% – 15% when compared to the latter, also lower refrigerant charge was used when R290 was added in the system compared to R22.

Colbourne et al. [8] reported the development of R290 transport refrigeration system for use in medium-sized Refrigerated Road Vehicles (RRVs) under actual South African weather conditions. The starting point for the development was a baseline R404A system and it involved a number of stages as depicted in Figure 1. The primary function of the study was overcoming the flammability hazard of R290 whereby the majority of the steps addressed the risk minimization. This involved reduction of refrigerant charge while maintain same cooling capacity at rating conditions as the baseline R404A model, development of a leak control and safety system, improving leak tightness, identification of potentially flammable zones and subsequently addressing possible sources of ignition within those zones.

Furthermore, Colbourne et al. [8] demonstrated that the model output with the R290 porotype exhibits better performance over a range of ambient conditions compared to the baseline R404A model for medium temperature (MT) and low temperature (LT) applications. For both MT and LT conditions, the R290 displayed consistently better COP (about 15 – 25% at MT and 10–30% at LT) and in fact, at the lowest and highest ambient temperatures, it tends to exhibit a greater improvement over R404A than at the rating conditions. The cooling capacity of the R290 model showed a "flatter" performance curve, i.e., the variation across a wide range of temperature was less than with R404A. At higher ambient temperatures the cooling capacity of R290 was greater than R404A (for about 15 – 20%), whereas at lower ambient temperatures R290 tends to exhibit lower cooling capacity than R404A for about 5%; this behavior was possibly attributed by the small diameter tubes in the R290 model leading to greater condenser pressure drop at higher capacity conditions. A broader parametric assessment was conducted and indicated that greater improvement in the COP could be achieved with the use of R290 model with an alternate design of heat exchangers, but these require greater charge of refrigerant in the system and thus at the expense of increase in flammability risk.

Ramaube and Huan [16] tested and evaluated thermal performance of a transport refrigeration system depicted in **Figure 2** using R290. The facility/system installed at Tshwane University of Technology, Pretoria – South Africa was originally designed to use R404A. The experiments were conducted without any modification when the system is retrofitted with R290 at various refrigerant charge. Baseline tests were conducted using R404A for performance comparison purposes. The results revealed that the refrigerant charge of R290 was significantly reduced to 40% of the system's full charge (3000 g). The hydrocarbon refrigerant (R290) exhibited higher refrigeration capacity (28.2%) against that of R404A. The measured COP was higher for R290 by approximately 28.6% as compared to R404A. R290 exhibited comparable measured power consumption though R404A recorded slightly higher by 4.4%. Good results exhibited by R290 over R404A could be attributed by high thermal conductivity of propane [17]. These findings and environmental friendliness of R290 reveals that it can be used as a drop-in substitute to R404A considering no system modification was done.

Table 3 summarizes other studies on HC – 290 and HC mixtures as alternative refrigerants. It can be seen that most the studies have been conducted using domestic refrigerators, heat pumps and chillers as compared to transport refrigeration systems. However, the results for HC – 290 and HC mixtures are promising to be used as an alternative for HFCs. The only challenge is flammability which must be carefully considered at design stages of the systems. This is very important for the road transport refrigeration equipment because the systems are working in harsh and uncontrolled road environments hence the risk of flammability is high as compared to stationary domestic refrigeration systems [5].

Table 3. Summary of studies on R290 and its HC mixtures as an alternative refrigerant

Refrigerant	Alternative	Ref.	Findings and conclusions
R134a	R290/R600/R600a	[18]	A mixture of R290, R600 and R600a to replace R134a was experimentally investigated in a 3.5 kW automotive air conditioner. The COP of every ratio of R290/R600/R600a was higher against that of R134a in similar working conditions such as temperature and pressure. The ratio of 50:40:10 for R290, R600 and R600a, respectively exhibited the best results among other investigated mixtures. The optimal mixture of 50%R290, 40%R600 and 10%R600a recorded a higher COP of 1.55 against 1.33 of R134a at the same evaporation temperature of 4 to 6 °C and engine speed of 1500 rpm. However, COP is not the only factor in selecting alternative refrigerants, it is also important to understand their thermodynamic properties because most of automotive air conditioning systems (e.g. compressor and expansion valve) are designed to work on R134a. The working temperature and pressure must therefore be similar to that of R134a or even better. In this study, the best ratio of 50:40:10 for R290, R600 and R600a recorded similar range of discharge pressure to that of R134a and the reduced discharge temperature, this means the compressor is not affected. The higher the suction pressure of refrigerant affects the opening of the expansion valve and reduces the discharge refrigerant. However, fluctuation of suction pressure was not detected in this study making the mixture of 50%R290, 40%R600 and 10%R600a as the best substitute in automotive air conditioning systems originally designed to use R134a.
R134a	R152a, R290, R600a, and R270	[19]	A mixture of R152a and selected hydrocarbons (R290, R600a, and R270) was theoretically investigated as an alternative substitute to R134a in an automobile air conditioner. The mixture of R152a and hydrocarbons displayed better performance results as compared to R134a. This is in good agreement with other studies that natural refrigerants have better heat transfer characteristics, and thermodynamic and transport properties.

Refrigerant	Alternative	Ref.	Findings and conclusions
R12	R290, 401A and R134A	[20]	A traditional domestic refrigeration system was used to investigate the performance of various HC and HFC refrigerants (R290, R134a and R404A) as alternative replacement of chlorofluorocarbon refrigerant (R12). The performance of R134a was found to be comparable to that of R12. HC-290 demonstrated higher cooling capacity and COP against R12 and the other tested HFC refrigerants (R134a and R404A) in their study.
R22	R290/R600a	[21]	Performance of R12 and R290/R600a mixtures was compared when used in the domestic refrigerator by varying the refrigerant charge and the length of capillary tube. The temperature in the food compartment and the freezer was higher when the refrigerator was retrofitted with a mixture of R290/R600a as compared to R12. The time of ice making were approximately the same for both the refrigerants.
R22	R290	[22]	The possibility of replacing R22 with the near-azeotropic refrigerant mixture of R290/R1234ze(E) (55%:45%) was investigated in a domestic refrigerator. One of shortcomings of R290 is classified as A3 (flammable and explosive) refrigerant, R1234ze was therefore R1234ze(E) as flame retardant. The mixture of R290/R1234ze(E) (55%:45%) displayed better thermodynamic cycle performances and thermo-physical properties against that of R22 and was recommended as technically feasible to substitute R22.
R22	R290	[23]	A 2 horse power split air conditioner was retrofitted with R290 as drop-in substitute to R22. A comparative performance analysis it terms of energy consumption, COP, and cooling capacity was conducted. R290 recorded low energy consumption whereas R22 exhibited slightly better COP and cooling capacity. R290's effectiveness as an air-conditioning refrigerant could be improved further with improvements in thermal conductivity and viscosity of the lubricant. This can be accomplished by utilizing the capabilities of metallic and non-metallic nanoparticles to improve the lubricant's thermal and physical properties, and hence the thermodynamic system.
R134a	R290/R600a (45/55)	[9]	A mixture of R290 and R600a at the ratio of 45:55 by weight was investigated as an alternative substitute to R134a in a domestic refrigerator. The energy efficiency and discharge temperature of the system retrofitted by R134a and hydrocarbons mixture (R290/R600a) was evaluated. The mixture of R290 and R600a displayed lower energy consumption to nearby 11.1% and higher COP of about 3.25–3.6%. A mixture of R290/R600a (45/55) also exhibited lower discharge temperature (8.5 to 13.4 K) as compared to R134a. It was concluded that a hydrocarbons mixture tested in this study could be used as an ideal alternative to R134a in a long run. According to Kyoto protocol R134a need to be phased out soon because of its high global warming potential of about 1300 which is too high to the recommended global threshold value of 150.
R22	R290	[12]	HC – 290 was experimentally and theoretically investigated as a drop-in substitute to HCFC – 22 using a window air conditioner. Generally, HC – 290 demonstrated better results than HCFC – 22. The energy consumption of R290 was lower by 12.4 – 13.5% and the cooling capacity was higher by 6.6 – 9.7% as compared to R22. The COP of R290 was also higher by the range of 2.8% – 7.9% against that of HCFC – 22. Additionally, HC – 290 displayed lower discharge pressure (13.7 – 18.2%) and pressure drop in the evaporator and condenser as compared to HCFC – 22. However, the capacity of condenser for HC – 290 was lower by 12.3 – 18.7% against that of HCFC – 22. The agreement between experimental and theoretical results was within ±4% for both refrigerants in terms of cooling capacities. Safety issues of HC – 290 which is classified as flammable natural refrigerant was not reported.
R12	R123/R290	[24]	The performance of a mixture of HCFC –123 and the natural refrigerant (HC – 290) in a chiller was investigated in terms of COP, discharge temperature and operating pressure. HCFC –123 was opted because it has very low GWP and ODP values, however, it has a challenge of high boiling point and specific volume being the reason why it is not considered as a substitute to CFC – 12. To overcome these issues, HCFC –123 was mixed with HC – 290 to form a suitable refrigerant mixture. The performance results of a mixture of R123/R290 at the ratio of 70:30 was comparable to that of R12. The discharge temperature for the mixture of R123/R290 was lower by 5 – 22 °C against that of R12. The mixture of R123/R290 (70/30) recorded higher COP with respect to R12, however, the operating pressure of the mixture (R123/R290) was slightly higher as compared to R12 but within acceptable range. Operating pressure of the system should not be too high in order to avert extensive manufacturing costs of the heat exchangers.

Refrigerant	Alternative	Ref.	Findings and conclusions
R22	R290 and R1270	[1]	A small R22 wall air conditioner with the cooling capacity of 2.4 kW was retrofitted with R290 and R1270 and experimentally investigated its performance. A compressor with larger displacement (20% large) was used for the experiments. R290 exhibited an increased cooling capacity and energy efficiency ratio (EER). Under normal conditions, R1270 recorded higher cooling capacity and EER by 2.4% and 0.8%, respectively against that of R22. The refrigerant charge was also reported to be reduced. Safety experiments were not conducted, this could be due to small size of the air conditioner and refrigerant charge hence minimal risks of flammability.
R13a	R290 and R600	[25], [26]	HC refrigerants (R290 and R600a) were tested as an alternative to a small refrigerator with a capacity of 240 L originally using R134a. Different mixtures of R290 and R600a (65:35, 50:50 and 0:100) by mass fraction were tested and the refrigerant charge was also varied at 30%, 40%, 50%, and 60%. At no load, the optimal refrigerant charge for the hydrocarbons was 40% of the R134a. Due to the increased energy consumption and freezer temperature as compared to R134a at the optimal charge, the capillary tubes were re-sized to 2.77, 5.05, 5.34, and 5.60 m for R134a, R290/R600a (65/35), R290/R600a (50/50), and R290/R600a (0/100), respectively. The HC mixtures with their respective capillary tubes recorded considerable decreased freezer temperature and energy consumption against that of R134a for the 24-hour on-load cycling test, this could be attributed to the high latent heat of the HC mixtures as compared to R134a. The mixtures can be used as a substitute to a small domestic R134a refrigerator provided the capillary tube lengths are changed in line with the mixture used.
R12	R290/R600/R600a	[27]	R-12 domestic refrigerator with the capacity of 320 L was used to test the performance of mixtures of three HC refrigerants namely, propane (R290), butane (R600) and isobutene (R600a) without any modifications. The mixture of 100:0:0, 75:19.1:5.9, and 50:38.3:11.7 by weight for R290, R600 and R600a, respectively were tested in terms of energy consumption, COP, cooling rate characteristics and evaporator capacity. The mixture of 50:38.3:11.7 recorded the best performance among the tested mixtures and was recommended as a substitute of R-12. The COP was 3.7 at the evaporator and condenser temperatures of −16 °C and 27 °C, respectively whereas R-12 recorded COP of 3.6 at the same operating temperatures.
R12	R290/R600a	[28]	The performance of R290 and R600a mixture was carried out in the R12 domestic refrigerators with the capacity of 299 and 465 Liters. An increase of up to 2.3% of COP as compared to R12 was recorded for the R290/R600a mixture when the composition range of R290 is 0.2 – 0.6 mas fraction. A mixture of R290/R600a with 0.6 mass fraction of R290 displaced an increased energy efficiency by 3 to 4 % and improved cooling rate than R12.
R134a	R290/R600A	[29]	A small-capacity directly cooled refrigerator was investigated its performance using a mixture of R290 and R600A at the ratio of 55:45 as alternative replacements of R134a. The displacement volume of the R134a compressor was modified to match the refrigeration capacity and the system was then optimized by varying the capillary tube length and the refrigerant charge. The results indicated that the refrigerant charge was 50% less for the optimized R290/R600A system as compared to the optimized R134a. R290/R600A exhibited the same mass flow rate as that of R134 regardless of its low charge, this is because R290/R600a (55/45) has larger specific volume (approximately two times) to that of R134a. The optimized R134a system exhibited higher power consumption (12.3%) as compared to the optimized R290/R600A system, this could be attributed to the improved heat transfer coefficient of R290/R600a against that of R134a [30]. The optimized R290/R600A (55/45) displayed an improved cooling speed by 28.8% over that of the optimized R134a at the setting temperature of −15 °C. In addition, the lengths of capillary tube for the optimized R290/R600a were 500 mm longer for each evaporator against those of optimized R134a.
R22	R290	[31]	The performance of R22 and R290 was experimentally investigated using two commercial compressors (scroll and reciprocating compressor). Similar mineral oil was used as a lubricant in the two compressors. R290 displayed better performance than R22. The COP of R290 was increased by 1 to 3% against that of R22 under the same operating conditions.
R22	R290, R407C and R410A	[32]	Residential air conditioning (split units type 1 and 2 TR) were used to experimentally investigate the performance of three refrigerants namely, R290, R410A and R407C as an alternative to R22. The experiments were conducted under high condensing temperatures due to hot climate of Iraq. The working ambient air temperature was

Refrigerant	Alternative	Ref.	Findings and conclusions
			varied from 35 to 55 °C at intervals of 5 °C. Among the tested refrigerants, R410A exhibited the highest power consumption and cooling capacity whereas reduced refrigerant charge and energy consumption was recorded when R290 was used. R290 was therefore recommended as the best candidate to substitute R22 when operated in high ambient conditions.
R22	R32 and R290	[33]	The experiments were carried out in a small air conditioning system using R290 and R32. The system was originally designed to use R22. The R290 and R32 were analyzed as possible candidates to replace R22 and R404A. In cooling mode: at the rated conditions the results depicted that, R290 and R32 recorded higher COP than R22 by 20.4% and 26.8%, respectively and by 2.1% and 7.3% against that of R404A. In the heating mode: both R290 and R32 recorded higher COP by 11% compared to that of R22, and when compared with R410A, the values of COP for R290 and R32 increased by 5.3%. With this results, R290 and R32 were recommended as possible candidates to replace R22 in split units, though, a comprehensive thermodynamic performance analysis of these refrigerants in split air conditioners is necessary.
R22	R290	[34]	A numerical model was developed to analyze the performance of R22 and R290 in a split air conditioner equipped with coiled adiabatic capillary tubes. The results demonstrated that, when R290 was used instead of R22, the power consumption and cooling capacity were slightly reduced. R290 exhibited lower cooling capacity by 12.1 to 12.3% against that of R22 whereas energy efficiency ratio of R290 was higher by 8.5% as compared to that of R22.
R222	R717, R744, R290, R600, R600a and R1270	[35]	The solar boosted heat pump was used to test thermodynamic performance of various natural refrigerants namely, R290, R717, R600a, R600, R744 and R1270 to replace the commonly used R22. R744 displayed high working pressures and low critical temperature hence recorded low COP as compared to other refrigerants whereas R600 and R600a exhibited low operating pressures. These refrigerants were therefore disqualified to be used as direct replacement of R22. On the other hand, R290 and R1270 recorded COP similar to that of R22 and were recommended as ideal R22 substitutes.
R407C	R290	[36]	R407C water to water heat pump system was used in the performance testing of R290 without any modification of the unit. The charge in the system was optimized. The results revealed that R290 had lower heating capacity in the range of 9 to 13% against that of R407C whereas the cooling capacity was also slightly reduced by 3%. However, COP of heating and cooling of the system were higher for R290 by 9–15% and 27%, respectively as compared to that of R407C. The differences in COP could be attributed by the best thermodynamic properties of R290 against that of R407C and much lower density of R290 influenced the difference in heating and cooling capacities.
R22	R290	[37]	The influence of refrigerant charge and ambient air temperatures on a window air conditioner was carried out using a hydrocarbon refrigerant (HC – 290) as a drop-in substitute to R22. The refrigerant charge was varied from 25 to 70% and the system was tested at various ambient air temperatures (26, 29, 32 °C). The optimal refrigerant charge of R290 to be directly used as a replacement of R22 is about 50 – 55% of R22 at any of the tested ambient air temperatures.

4. Safety Measures

The flammability and high working pressures are the main two concerns when R290 is used in the food transport refrigeration systems [8], [38], [39]. These are the important parameters to be taken into consideration when developing a new system with regards to safety. There is always a risk of leakage of refrigerant into a room or atmosphere that the refrigeration and air conditioning equipment is installed [38]–[40]. Reducing the build-up of flammable concentrations from refrigerant leakage through proper equipment construction and installation criteria minimizes the possibility of fire/ignition [38], [39]. There various research works on safety issues of R290 and its mixtures when used in refrigeration systems. However, most of the studies concentrated on stationary systems such as domestic freezers/refrigerators, industrial chillers, supermarket cold chain, and air-conditioning and a few have reported on food transport refrigeration systems [37]–[39], [41]–[46].

Refrigerants are classified as flammable or non-flammable, R290 is categorized as flammable refrigerant. However, the degree of flammability differs, for example, according to the American

Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE 34) and ISO 817 simplified model, R290 is classified as high flammable refrigerant (A3) as seen in **Figure 4**, therefore safety measures on use of R290 are mandatory [47]. The first letter in the classification of refrigerants according to ASHRAE 34 indicates the toxicity and the number (with or without a letter) shows the flammability. Most of the researched hydrocarbon refrigerants either in pure form or as a mixture with halogenated refrigerants are from low flammable refrigerants with ASHRAE safety code B2, A2, B2L and A2L. The B2L and A2L refrigerants have lower flammability and toxicity than B2 or A2 (**Figure 4**). The refrigerants that are classified in group "A" have occupational exposure limit (OEL) of 400 ppm or greater whereas group "B" have OEL of less than 400 ppm.

Colbourne et al., [8] reported the development of R290 transport refrigeration system in South Africa which originally used R404A as a refrigerant. They investigated safety issues when R290 was used in the modified R404A transport refrigeration system. It was reported that to increase safety with regard to the flammability of R290, the baseline R404A transport refrigeration system developed by Transfrig South Africa was modified by reducing charge size. The key changes for reducing charge size included reduction of the condenser (from 10 mm to 5 mm) and the evaporator (from 10 mm to 7 mm) tube size and in particular modification of their circuitry, smaller liquid line diameter and approximately halving the volume of the liquid receiver and accumulator in the system. Thus, the modified design used actual charge of 0.62 kg R290, which was about 20% of the original R404A charge size. Other main changes to the R404A refrigeration system were to remove potential sources of ignition or apply pre-ventilation to remove any build-up of potentially flammable mixtures.

Colbourne et al. [8] also described Active leak limiting response safety system (ALLRSS), leak tightness and zoning while performing safety measures for the modified R290 transport refrigeration system. It was recommended that in the event of a leak occurring within the refrigerated space, it is necessary to minimize the quantity of refrigerant released and further activate additional measures to mitigate the possibility of ignition. This kind of approach can be divided into sensing and mitigation, the application of such measures for R290 refrigeration systems is reported in detail elsewhere in the literature [38]–[40], [45], [48].

In addition, from safety measures performed by Colbourne et al., [8] for the developed R290 transport refrigeration unit, the following general observations were reported:

a) The flammable concentrations were measured throughout the majority of the space when the condensing unit and fans are off (and the RRV is indoors and stationary). The result showed that when condenser fans are on, all positions had very low concentrations.
b) Concentrations at positions below the condensing unit (such as the truck air intake or external switch) are very low with or without fans running.
c) The concentrations of leaks within evaporating unit (at the fan motor) can exceed the LFL (Lower flammability Limit which is 0.038 kg/m^3 for R290) but are typically less than LFL when the unit is under operation.
d) The concentrations at the ceiling never exceeded the LFL.
e) The concentrations at the floor level (particularly directly below the evaporator) can exceed the LFL when the space is empty and can reach up to three times the LFL when the space is loaded with products.
f) However, when the fans are ON the concentration on both the floor and ceiling is always close to the average (homogenous) concentration on account of the high airspeed causing rapid mixing.
g) The concentrations at positions beyond the rear door (trail lift or smoking worker) while the doors are closed were almost no values recorded, although the highest values occurred once the doors are opened but still never approached the LFL.
h) When the doors were opened and the worker placed hands on the sill, on the occasion that the evaporator fans were off and the space was loaded with product, one test yielded a concentration just above the LFL.

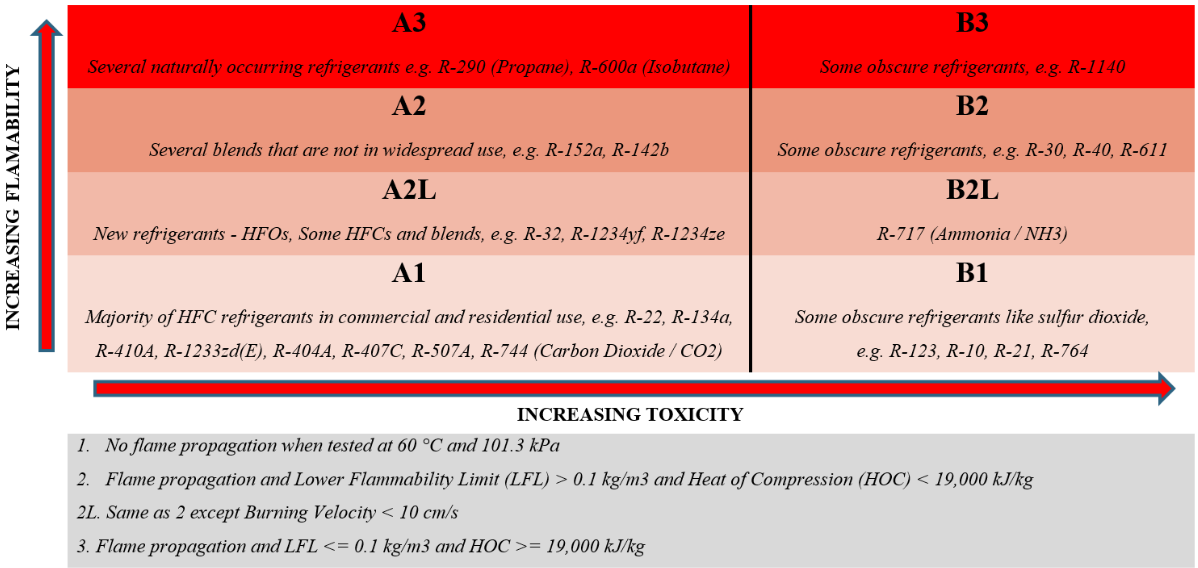

Figure 4. Refrigerants safety codes by ASHRAE 34

Colbourne et al., [8] indicated that the major aspects of the development were the significant reduction of refrigerant charge and adoption of the ALLRSS. In the risk assessments study, the results indicated that the level of flammability safety of the developed prototype should not present any concerns to the users such as when the trucks being involved with accidents and other comparable situations [45]. Now the R290 transport refrigeration porotype has been developed and tested, further studies are undergoing especially field trials under real conditions. As per the existing regulations such as EN 378: 2016 and SANS 10147: 2009, the flammability risk can be avoided if the HC – 290 charges in the systems are less than 20% of the LFL. In addition, if the quantity of refrigerant can be kept under 150 grams, according to European safety regulations, systems installed and used even inside private homes will not require special safety devices, assuming that the system is "hermetic" and provided that there is no ignition source in the vicinity of the system [45].

Findings by Colbourne et al., [8] are in good agreement with the results reported by Grzebielec et al. [17] who performed safety aspects of propane (R290) when used as a working medium in a small air conditioner. They concluded that it is safe to use a refrigerant like propane in small air conditioners because even if the full amount of gas leaks, there is no risk of an explosion. Similar observations were reported by Maclaine-Cross [43] who investigated the usage and ignition risks of HC refrigerants in motor cars for USA and Australia. However, because there is always the potential of the gas igniting locally during service or disposal, only qualified persons should execute these tasks. On the other hand, Zhang et al. [49] investigated different leakage conditions and concentration distribution of flammable refrigerant R290 in an automobile air conditioning (engine and passenger compartments). The results revealed that the most dangerous circumstance in the system, according to their findings, was evaporator leakage. When R290 gas seeped into the passenger compartment, the concentration in the atmosphere exceeded the LFL. The leak pressure, leak hole size, and wind speed were identified as the three key elements causing leakage in the engine compartment. To lessen ignition risks of R290 in automobile air conditioning, mitigation techniques such as the second loop (SL) system [50] or the installation of R290 concentration sensors can be used. The SL method can dramatically reduce both the peak concentration of R290 and the time spent over the LFL level.

5. Conclusion

HC – 290 can be used as a best alternative refrigerant to replace R404A which has been widely used in the food transport refrigeration systems in South Africa. From various studies reported in the present paper, R290 has proven to have the better thermal performance with lower refrigerant charge when compared to R404A. R290 was found to exhibit higher refrigeration capacity (10 – 30%) against that of R404A. The measured COP was found to be higher for R290 in the range of 3 – 30% as compared to R404A. The review revealed that the refrigerant charge of R290 was significantly reduced to approximately 40% of the system's full charge. However, as seen from the literature most of the studies investigated the use of HCs in domestic refrigerators, air conditioners, heat pumps, and chillers. Hence there is a need for further research on the use of HCs especially R290 in the transport refrigeration systems. Moreover, most the reported studies have been done in developed countries as compared to developing countries which has different climatic conditions. It is therefore important to locally investigate the performance of these emerging refrigerants using local environmental conditions. The only challenge with most of HCs like R290 is safety issues because it is categorized as a flammable refrigerant and few studies have reported this. Thus, proper sizing of R290 is imperative to accommodate appropriate refrigerant charge and reduce risk of flammability. In general, in spite of highly flammable characteristics of R290, it has been concluded in various studies that it can offer proper alternative to the halogenated refrigerants such as R404A from the standpoint of environmental impact, COP, refrigerant charge, energy efficiency and compressor discharge temperatures.

Author's Declaration

Authors' contributions and responsibilities

The author made substantial contributions to the conception and design of the study. The author took responsibility for data analysis, interpretation and discussion of results. The author read and approved the final manuscript.

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References

[1] J. H. Wu, L. D. Yang, and J. Hou, "Experimental performance study of a small wall room air conditioner retrofitted with R290 and R1270," *Int. J. Refrig.*, vol. 35, no. 7, pp. 1860–1868, 2012, doi: 10.1016/j.ijrefrig.2012.06.004.

[2] M. Mohanraj, S. Jayaraj, and C. Muraleedharan, "Environment friendly alternatives to halogenated refrigerants-A review," *Int. J. Greenh. Gas Control*, vol. 3, no. 1, pp. 108–119, 2009, doi: 10.1016/j.ijggc.2008.07.003.

[3] J. H. Koh, Z. Zakaria, and D. Veerasamy, "Hydrocarbons as Refrigerants — A Review," *ASEAN J. Sci. Technol. Dev*, vol. 34, no. 1, pp. 35–50, 2016.

[4] B. Palm, "Hydrocarbons as refrigerants in small heat pump and refrigeration systems - A review," *Int. J. Refrig.*, vol. 31, no. 4, pp. 552–563, 2008, doi: 10.1016/j.ijrefrig.2007.11.016.

[5] S. A. Tassou, G. De-Lille, and Y. T. Ge, "Food transport refrigeration – Approaches to reduce energy consumption and environmental impacts of road transport," *Appl. Therm. Eng.*, vol. 29, no. 8, pp. 1467–1477, 2009, doi: https://doi.org/10.1016/j.applthermaleng.2008.06.027.

[6] K. Harby, "Hydrocarbons and their mixtures as alternatives to environmental unfriendly halogenated refrigerants: An updated overview," *Renew. Sustain. Energy Rev.*, vol. 73, no. Supplement C, pp. 1247–1264, 2017, doi: https://doi.org/10.1016/j.rser.2017.02.039.

[7] P. Maina and Z. Huan, "A review of carbon dioxide as a refrigerant in refrigeration technology," *S. Afr. J. Sci.*, vol. 111, no. 9/10, pp. 1–10, 2015.

[8] D. Colbourne, P. Solomon, R. Wilson, L. de Swardt, R. Nosbers, and M. Schuster, "Development of R290 Transport Refrigeration System," in *Presented before the IOR on 2nd March 2017*, 2017.

[9] M. Mohanraj, S. Jayaraj, C. Muraleedharan, and P. Chandrasekar, "Experimental investigation of R290/R600a mixture as an alternative to R134a in a domestic refrigerator," *Int. J. Therm. Sci.*, vol. 48, no. 5, pp. 1036–1042, 2009, doi: https://doi.org/10.1016/j.ijthermalsci.2008.08.001.

[10] T. Kivevele and Z. Huan, "A review on

opportunities for the development of heat pump drying systems in South Africa. South African Journal of Science," *South African J. Sci.*, vol. 110, no. 5/6, pp. 37–47, 2014.
[11] B. Wilson, D. Colbourne, and M. Schuster, "Development of climate friendlier truck refrigeration systems with R290 in South Africa," in *Side Event MOP Dubai 2015*, 2015.
[12] S. Devotta, A. S. Padalkar, and N. K. Sane, "Performance assessment of HC-290 as a drop-in substitute to HCFC-22 in a window air conditioner," *Int. J. Refrig.*, vol. 28, no. 4, pp. 594–604, 2005, doi: https://doi.org/10.1016/j.ijrefrig.2004.09.013.
[13] J. T. Siang and A. Sharifian, "Effect of Inlet Pressure, Size and Wind Speed of an Evaporator on Amount of Refrigerant Charge and Performance of a Portable Propane Air Conditioner," in *4th International Conference on Science and Technology (ICST), Yogyakarta, Indonesia, 7 – 8th August 2018.*, 2018, p. DOI: 10.1109/ICSTC.2018.8528623.
[14] M.-Y. Lee, D.-Y. Lee, and Y. Kim, "Performance characteristics of a small-capacity directly cooled refrigerator using R290/R600a (55/45)," *Int. J. Refrig.*, vol. 31, no. 4, pp. 734–741, 2008, doi: https://doi.org/10.1016/j.ijrefrig.2007.11.014.
[15] A. S. Padalkar, K. V Mali, and S. Devotta, "Simulated and experimental performance of split packaged air conditioner using refrigerant HC-290 as a substitute for HCFC-22," *Appl. Therm. Eng.*, vol. 62, no. 1, pp. 277–284, 2014, doi: https://doi.org/10.1016/j.applthermaleng.2013.09.017.
[16] G. Zhou, Y. Zhang, Y. Yang, and X. Wang, "Numerical model for matching of coiled adiabatic capillary tubes in a split air conditioner using HCFC22 and HC290," *Appl. Therm. Eng.*, vol. 30, no. 11, pp. 1477–1487, 2010, doi: https://doi.org/10.1016/j.applthermaleng.2010.03.009.
[17] J. F. Urchueguia, J. M. Corberan, J. Gonzalvez, and J. M. Diaz, "Experimental characterization of a commercial–size scroll and reciprocating compressor working with R22 and propane (R290) as refrigerant," *Ecobibrium J. AIRAH*, pp. 23–25, 2004.
[18] L. Tingxun, Y. Jiumin, Z. Zhaoshun, and Z. Zhang, "Experiment on R290 Substituting for R22 in A Room Air-conditioner," *J. Refrig.*, pp. 2010–04, 2010.
[19] S. Jain and P. K. Jain, "The rise of Renewable Energy implementation in South Africa," *Energy Procedia*, vol. 143, pp. 721–726, 2017, doi: https://doi.org/10.1016/j.egypro.2017.12.752.
[20] M. Ramaube and Z. Huan, "Testing and Performance Evaluation of a R404A Transport Refrigeration System Retrofitted With R290," in *AIUE Proceedings of the 17th Industrial and Commercial Use of Energy (ICUE) Conference, Cape Town - South Africa*, 2019, p. http://dx.doi.org/10.2139/ssrn.3658977.
[21] A. Grzebielec, A. Rusowicz, and A. Szelagowski, "Safety aspects for the R290 (propane) as working medium in small air conditioning installations," *Saf. Eng. Anthropog. Objects*, vol. 2, pp. 22–29, 2021, doi: https://doi.org/10.37105/iboa.110.
[22] S. Wongwises, A. Kamboon, and B. Orachon, "Experimental investigation of hydrocarbon mixtures to replace HFC-134a in an automotive air conditioning system," *Energy Convers. Manag.*, vol. 47, no. 11, pp. 1644–1659, 2006, doi: https://doi.org/10.1016/j.enconman.2005.04.013.
[23] G. Mahmoud, "An investigation of R152a and hydrocarbon refrigerants in mobile air conditioning.," *SAE Int.*, p. paper no. 01-0874, 1999.
[24] E. Halimic, D. Ross, B. Agnew, A. Anderson, and I. Potts, "A comparison of the operating performance of alternative refrigerants," *Appl. Therm. Eng.*, vol. 23, no. 12, pp. 1441–1451, 2003, doi: https://doi.org/10.1016/S1359-4311(03)00081-4.
[25] S. Devotta and M. . Kulkarni, "Use of hydrocarbon blends in Indian Household Refrigerators," in *International Conference on Ozone Protection Technologies, Washington DC, USA*, 1996, pp. 367–376.
[26] L. Wang, H. Li, J. Wu, and K. Qiu, "Feasibility of using near-azeotropic refrigerant mixture R290/R1234ze(E) as substitute for R22," *Env. Prog Sustain. Energy*, vol. 2021;40:e1, 2021, doi: https://doi.org/10.1002/ep.13574.
[27] T. Okolo and O. . Ajayi, "Thermal Performance and Energy Consumption

Analyses of R290 and R22 Refrigerants in Air-conditioning System," in *IOP Conf. Series: Materials Science and Engineering*, 2018, p. 413:012072, doi: doi:10.1088/1757-899X/413/1/012072.
[28] K. S. Kumar and K. Rajagopal, "Computational and experimental investigation of low ODP and low GWP HCFC-123 and HC-290 refrigerant mixture alternate to CFC-12," *Energy Convers. Manag.*, vol. 48, no. 12, pp. 3053–3062, 2007, doi: https://doi.org/10.1016/j.enconman.2007.05.021.
[29] C.-C. Yu and T.-P. Teng, "Retrofit assessment of refrigerator using hydrocarbon refrigerants," *Appl. Therm. Eng.*, vol. 66, no. 1, pp. 507–518, 2014, doi: https://doi.org/10.1016/j.applthermaleng.2014.02.050.
[30] S. Wongwises and N. Chimres, "Experimental study of hydrocarbon mixtures to replace HFC-134a in a domestic refrigerator," *Energy Convers. Manag.*, vol. 46, no. 1, pp. 85–100, 2005, doi: https://doi.org/10.1016/j.enconman.2004.02.011.
[31] M. A. Hammad and M. A. Alsaad, "The use of hydrocarbon mixtures as refrigerants in domestic refrigerators," *Appl. Therm. Eng.*, vol. 19, no. 11, pp. 1181–1189, 1999, doi: https://doi.org/10.1016/S1359-4311(98)00116-1.
[32] D. Jung, C.-B. Kim, K. Song, and B. Park, "Testing of propane/isobutane mixture in domestic refrigerators," *Int. J. Refrig.*, vol. 23, no. 7, pp. 517–527, 2000, doi: https://doi.org/10.1016/S0140-7007(99)00084-5.
[33] W. . Yun, "Performance Characteristics of Propane/Isobutane Mixtures in a Small Refrigeration System," Korea University, 2001.
[34] K. A. Joudi and Q. R. Al-Amir, "Experimental Assessment of residential split type air-conditioning systems using alternative refrigerants to R-22 at high ambient temperatures," *Energy Convers. Manag.*, vol. 86, no. Supplement C, pp. 496–506, 2014, doi: https://doi.org/10.1016/j.enconman.2014.05.036.
[35] S. Cheng, S. Wang, and Z. Liu, "Cycle performance of alternative refrigerants for domestic air-conditioning system based on a small finned tube heat exchanger," *Appl. Therm. Eng.*, vol. 64, no. 1, pp. 83–92, 2014, doi: https://doi.org/10.1016/j.applthermaleng.2013.12.022.
[36] C. Chaichana, L. Aye, and W. W. S. Charters, "Natural working fluids for solar-boosted heat pumps," *Int. J. Refrig.*, vol. 26, no. 6, pp. 637–643, 2003, doi: https://doi.org/10.1016/S0140-7007(03)00046-X.
[37] J. M. Corberán, I. O. Martínez, and J. Gonzálvez, "Charge optimisation study of a reversible water-to-water propane heat pump," *Int. J. Refrig.*, vol. 31, no. 4, pp. 716–726, 2008, doi: https://doi.org/10.1016/j.ijrefrig.2007.12.011.
[38] T.-P. Teng, H.-E. Mo, H. Lin, Y.-H. Tseng, R.-H. Liu, and Y.-F. Long, "Retrofit assessment of window air conditioner," *Appl. Therm. Eng.*, vol. 32, no. Supplement C, pp. 100–107, 2012, doi: https://doi.org/10.1016/j.applthermaleng.2011.08.036.
[39] D. Colbourne and K. O. Suen, "Appraising the flammability hazards of hydrocarbon refrigerants using quantitative risk assessment model. Part II. Model evaluation and analysis," *Int. J. Refrig.*, vol. 27, no. 7, pp. 784–793, 2004, doi: https://doi.org/10.1016/j.ijrefrig.2004.07.002.
[40] D. Colbourne and L. Espersen, "Quantitative risk assessment of R290 in ice cream cabinets," *Int. J. Refrig.*, vol. 36, no. 4, pp. 1208–1219, 2013, doi: https://doi.org/10.1016/j.ijrefrig.2012.10.036.
[41] D. Colbourne, R. Hühren, and A. Vonsild, "Safety concept for hydrocarbon refrigerants in split air conditioner," in *10th IIR-Gustav Lorentzen Conference on Natural Working Fluids (GL2012). Delft, The Netherlands*, 2012.
[42] W. Zhang, Z. Yang, X. Zhang, D. Lv, and N. Jiang, "Experimental research on the explosion characteristics in the indoor and outdoor units of a split air conditioner using the R290 refrigerant," *Int. J. Refrig.*, vol. 67, no. Supplement C, pp. 408–417, 2016, doi: https://doi.org/10.1016/j.ijrefrig.2016.03.018.
[43] W. Tang, G. He, D. Cai, Y. Zhu, A. Zhang, and

Q. Tian, "The experimental investigation of refrigerant distribution and leaking characteristics of R290 in split type household air conditioner," *Appl. Therm. Eng.*, vol. 115, no. Supplement C, pp. 72–80, 2017, doi: https://doi.org/10.1016/j.applthermaleng.2016.12.083.

[44] I. L. Maclaine-cross, "Usage and risk of hydrocarbon refrigerants in motor cars for Australia and the United States," *Int. J. Refrig.*, vol. 27, no. 4, pp. 339–345, 2004, doi: https://doi.org/10.1016/j.ijrefrig.2004.01.003.

[45] K. A. Joudi, A. S. K. Mohammed, and M. K. Aljanabi, "Experimental and computer performance study of an automotive air conditioning system with alternative refrigerants," *Energy Convers. Manag.*, vol. 44, no. 18, pp. 2959–2976, 2003, doi: https://doi.org/10.1016/S0196-8904(03)00051-7.

[46] D. Colbourne and K. O. Suen, "Comparative evaluation of risk of a split air conditioner and refrigerator using hydrocarbon refrigerants," *Int. J. Refrig.*, vol. 59, no. Supplement C, pp. 295–303, 2015, doi: https://doi.org/10.1016/j.ijrefrig.2015.06.026.

[47] L. Jia, W. Jin, and Y. Zhang, "Experimental study on R32 leakage and diffusion characteristic of wall-mounted air conditioners under different operating conditions," *Appl. Energy*, vol. 185, no. Part 2, pp. 2127–2133, 2017, doi: https://doi.org/10.1016/j.apenergy.2016.01.041.

[48] Z. Roy and G. Halder, "Replacement of halogenated refrigerants towards sustainable cooling system: A review," *Chem. Eng. J. Adv.*, vol. 3, p. 100027, 2020, doi: https://doi.org/10.1016/j.ceja.2020.100027.

[49] D. Colbourne, R. Hühren, and D. Rajadhyaksha, "Refrigerant leakage control for R-290 in split type refrigeration and air conditioning systems," in *8th IIF-IIR International Conference on Compressors and Coolants, Častá - Papiernička*, 2013.

[50] Y. Zhang *et al.*, "Leakage analysis and concentration distribution of flammable refrigerant R290 in the automobile air conditioner system," *Int. J. Refrig.*, vol. 110, pp. 286–294, 2020, doi: https://doi.org/10.1016/j.ijrefrig.2019.11.001.

[51] T. Li, "Indoor leakage test for safety of R-290 split type room air conditioner," *Int. J. Refrig.*, vol. 40, pp. 380–389, 2014, doi: https://doi.org/10.1016/j.ijrefrig.2013.11.023.