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MECHANICAL VAPOUR COMPRESSION REFRIGERATION SYSTEM: REVIEW PART 1: ENVIRONMENT CHALLENGE

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In Australia and others developed countries, concerns about global warming have increased, and these concerns influence the use of refrigerants as working fluids in mechanical vapour compression refrigeration systems. One of the most important aspects of refrigerant selection is to reduce its impact on the environment and the ozone layer. This paper provides a comprehensive review of various theoretical and experimental studies which have been carried out on air conditioning and refrigeration applications to investigate the effect of refrigerants on the environment. The analysis in this paper reveals that alternative refrigerants are the most suitable working fluids that can be used in refrigeration systems to meet the needs of the environment. This study also suggests that natural types of refrigerants such as water, carbon dioxide, and hydrocarbon will play a significant role in protecting the environment and providing alternative friendly refrigerants to be used in refrigeration and air conditioning systems.

Key words: alternative refrigerants, mixture refrigerants, vapour compression refrigeration system, ozone depletion potential (ODP), global worming potential (GWP), R507A refrigerant, natural refrigerant, R-718 (water/steam).

1. Introduction

Both environmental concerns and energy costs have had repercussions across the globe. They have received much attention from researchers, encouraging the use of an alternative source of energy, one that must be a sustainable source to meet environmental and economic requirements. Hence, the following issues have been investigated by a number of researchers: conserving energy, the effect of refrigerants on the environment, reduction of energy running costs, and reduction in the emission of polluting substances [5, 6] and [7]. Natural refrigerants have been the focus of many researchers. Choudhari and Sapali [8] investigated the difference in performance using a natural refrigerant (R290) and Chlorodifluoromethane (R22). The study suggested R290 as a substitute to R22 because R290 has a low impact on the environment and

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excellent thermodynamic performance. Other studies have investigated tetrafluoroethane (R134a) and compared it with different refrigerants [9-11] and [12]. Vapour compression refrigeration systems can be used to provide a low temperature for a short time by using refrigerants that have positive effects on the environment [13-15] and [16]. From this point of view, many researchers have attempted to develop the vapour compression refrigeration system by investigating the different type of refrigerants, thermodynamic processes of the system, or adding new parts to the system which give the ability to obtain a high coefficient of performance. Some researchers have carried out experimental works while others such as Winandy and Lebrun [17], and Cho, Chung [18]. Sami and Aucoin [19] and Siva Reddy, Panwar [20] presented a theoretical evaluation of system performance to compare the performance a different refrigerants such as R134a, R143a, R404A, R407C, R410A, R502, and R507 Ain vapour compression systems and to reduce the refrigerant's impact on the environment. Fatouh, Ibrahim [21] investigated the performance of vapour compression systems experimentally using R407C as an R22 alternative. The study reported that the actual coefficient of performance of R407C is lower than that for R22 by *18.5*%. Kasera and Bhaduri [22] presented a review study to investigate alternative refrigerants in terms of their effect on ozone depletion potential (ODP) and global warming potential (GWP). The study reported that R410A is suitable for new designs. Mota-Babiloni, Haro-Ortuño [23] presented an analysis of the feasibility of R454C and R455A, two new low global warming potential (GWP) refrigerants, in vapour compression refrigeration systems as alternatives to R404A. The experimental results show that the cooling capacity of the replacements is slightly lower than R404A, demonstrating that the Coefficient of Performance (COP) of the new mixtures was *10–15*% higher than that of R404A, especially at higher condensation temperatures. Kalla, Arora [24] presented a review study to determine the best available alternativesto replace an existing refrigerant, R22, with minimum or no changes in the air conditioning system. El-Sayed, El Morsi [25] reported that an ideal refrigerant is the one having zero ozone depletion potential (ODP) and low global warming potential (GWP), is nontoxic, non-flammable, has appropriate thermodynamic and heat transfer properties and is compatible with any type of lubricating oil. Therefore, this paper provides an extensive review study to investigate and analyse the effect of refrigerants on the environment and their use in vapour compression systems to meet the needs of the environment and the user.

2. Refrigerants

There are many different types of refrigerants which can be used in the mechanical vapour compression refrigeration system. Some of these refrigerants are pure substances, whereas others are mixtures. Generally, refrigerants can be classified into Hydro chlorofluorocarbons HCFCs, Hydrofluorocarbons HFCs, Chlorofluorocarbons CFCs, and Hydrocarbons HCs [4]. However, some of these refrigerants have been phased out by the Montreal Protocol, which was signed in 1987, due to their effect on ozone depletion. As a result, in many developed countries, some refrigerants have been prohibited for use in new mechanical vapour compression systems since 2010 [26]. These prohibitions have taken a number of years to enact: in 1997 the Kyoto Protocol warned of global warming issues, including CFCs and HCFCs refrigerants which have a significant effect on the environment [27]. However, as a result of the Kyoto Protocol, nowadays CFCs are not used as working fluids in mechanical vapour compression refrigeration systems because of their significant effect on ozone depletion [28]. La Rocca and Panno [2] asserted that, because the HFC refrigerants do not cause damage to the ozone layer and they do not contain chlorine, HCFCs are being replaced with the HFC refrigerants. HFC refrigerants are now seen as the best choice to use in mechanical vapour compression refrigeration systems as a replacement for CFC and HCFC refrigerants [29]. As a result, in developed countries, 2030 will be the end of HCFC refrigerants, as presented in Tab.1 [30], while 2040 will be the end of HCFC refrigerants in developing countries.

Table 1. Montreal protocol.

Date	**Control measure**	
1 July 1989	□	Freeze of annex A[a] CFCs
1 January 1992	□	Freeze of halons
1 January 1993	□ □	Annex B CFCs[b] reduced by *20*% from 1989 levels Freeze of methyl chloroform
1 January 1994	□ □ □ □	Annex B CFCs reduced by *75*% from 1989 levels Annex A CFCs reduced by *75*% from 1986 levels Halcon[a] phased-out[d] Methyl chloroform reduced by *50*%
1 January 1995	□ □	Methyl bromide frozen at 1991 levels Carbon tetrachloride reduced by *85*% from 1989 levels
1 January 1996	□ □ □ □ □	HBFCs[d] phased out[a] Carbon tetrachloride phased-out[d] Annex A and B CFCs phased-out[d] Methyl chloroform phased-out[d] HCFCs[f] frozen at 1989 levels of HCFC + *2.8*% of 1989 consumption
1 January 1999	□	Methyl bromide reduced by *25*% from 1991 levels
1 July 1999	•	Freeze of annex A CFCs at 1995-1997 average levels[g]
1 January 2001	□	Methyl bromide reduced by *50*% from 1991 levels
1 January 2002	• •	Freeze of halons at 1995-1997 average levels[g] Freeze of methyl bromide at 1995-1997 average levels
1 January 2003	□ • •	Methyl bromide reduced by *70*% from 1991 levels Annex B CFCs reduced by *20*% from 1998-2000 average consumption Freeze in methyl chloroform at 1998-2000 average levels
1 January 2004	□	HCFCs reduced by *35*% below base levels
1 January 2005	□ • • • •	Methyl chloroform phased out Annex A CFCs reduced by *50*% from 1995-1997 average levels[g] Halons reduced by *50*% from 1995-1997 average levels[g] Carbon tetrachloride reduced by *85*% from 1998-2000 average levels Methyl chloroform reduced by *30*% from 1998-2000 average levels
1 January 2007	• •	Annex A CFCs reduced by *85*% from 1995-1997 average levels[g] Annex B CFCs reduced by *85*% from 1995-1997 average levels[h]
1 January 2010	□ • •	HCFCs reduced by *65*% CFCs, halons, and carbon tetrachloride phased-out Methyl chloroform reduced by *70*% from 1998-2000 average levels
1 January 2015	□ • •	HCFCs reduced by *90*% 4 Methyl chloroform phased-out Methyl bromide phased-out
1 January 2016	•	Freeze of HCFCs at base line figure of year 2015 average levels
1 January 2020	□	HCFCs phased-out allowing for a service tail of up to *0.5*% until 2030 for existing refrigeration and air-conditioning equipment
1 January 2040	•	HCFCs phased-out

Developed countries (□), developing countries (•),
[a]Five CFCs is annex A: CFCs 11, 12, 113, 114 and 115
[b]Ten CFCs is annex B: CFCs 13, 111, 112, 211, 212, 213, 214, 215, 216 and 217.
[c]Halons 1211, 1301, and 2402.
[d]With exceptions for essential uses. Consult the Handbook on Essential Use Nominations prepared by the Technology and Economic Assessment Panel, 1994, UNEP, for more information.
[e]A 34 hydrobromofluorocarbons.
[f]A 34 hydrochlorofluorocarbons.
[g]Calculated level of production 0.3 kg per capita can also be used for calculation, if lower.
[h]Calculated level of production 0.2 kg per capita can also be used for calculation, if lower.

2.1. Type of refrigerants

As a result of the Montreal protocol of 1987 and regulation number 2037/200 of the European Parliament of 2000, the use of CFC and HCFC refrigerants was gradually reduced [4] and [2]. Consequently, an environmentally friendly refrigerant that provided good thermodynamic and physical properties became the most suitable solution to reduce environmental effects [31]. The mixed refrigerants area mixture of HC, HCFC, and HFC refrigerants with certain weight ratio, which could be safely used in mechanical vapour compression systems at different temperature applications. For example, to replace the refrigerants HCFC-22 (R22) and CFC-502 (R502), the refrigerant mixtures R507A (R125/ R143a, *50*% / *50*% wt%), R410A (R32/R125, *50*% / *50*%, wt%), R407C (R32 / R125 / R134a, *23*% / *25*% / *52*%, wt %), and R404A (R125 / R134a / R143a, *44*% / *4*% / *52*%, wt%) have been recommended to use in vapour compression systems as alternative refrigerants [32]. In addition, the refrigerant mixtures are harmless for the ozone layer. Hence the refrigerant mixtures can be classified as Zeotropic mixtures (non-azeotropic mixture), Azeotropic mixtures, and Near azeotropic mixtures[33].

Zeotropic mixture (Non-azeotropic mixture)

A zeotropic mixture consists of two or more refrigerant components. The behaviour of a zeotropic mixture refrigerant is not like the behaviour of a single refrigerant during the phase change process due to glide temperature [34]. The glide temperature can be defined as the temperature difference between the bubble and dew points at a given pressure and composition. Therefore, the glide temperature influences phase change processes such as condensation and evaporation processes, as shown in Fig.1 [4]. In addition, the glide temperature provides a reduction of entropy generation in both the condenser and the evaporator due to matching between the heat transfer and glide temperature of the zeotropic mixture refrigerant [35]. Mohanraj, Muraleedharan [36] reported that the glide temperature depended on the pressure drop in the condenser and evaporator in a temperature range from 4^oC to 7^oC, as the condensation and evaporation process are not isothermal processes. Guo, Pinzan [37] reported that near-azeotropic mixed refrigerant is environmentally friendly and it can be used in vapour compression refrigeration systems.

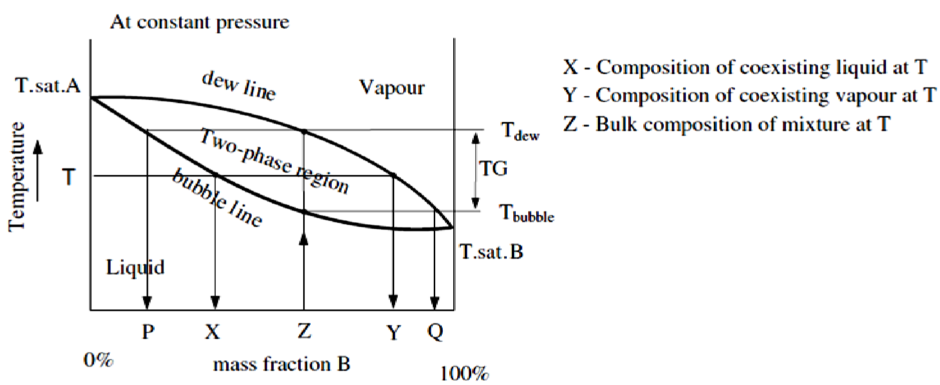

Fig.1. Phase changing of a binary mixture Leelananda [4].

Furthermore, Giuliani, Hewitt [38] stated that the behaviour of the zeotropic mixture refrigerant affected the vapour compression system performance and different parts of the system due to changes of circulation composition. Indeed, the zeotropic mixture refrigerants have a different behaviour as a result of composition changes in the vapour compression system which always matches the pressure drop in high- and low-pressure sides.

Azeotropic mixture

An azeotropic mixture consists of two or more pure refrigerants, and it cannot be separated or dissolved during the phase change processes. Therefore, the behaviour of azeotropic mixture refrigerants is similar to that of a single refrigerant; in addition, the boiling point temperature of the azeotropic mixture refrigerants is lower than their substances [34]. Further, the azeotropic mixture refrigerants can be used in different applications such as commercial refrigeration systems and domestic refrigeration systems.

Near azeotropic mixture

The behaviour of near azeotropic mixture refrigerants is similar to that of the azeotropic mixture refrigerants. Hence, the hardware of a vapour compression system does not need to be considered. However, the near azeotropic mixture refrigerants have a very low glide temperature range from 0.2^oC to 0.6^oC [34]. Therefore, there may be a change in the refrigerant composition during the phase change processes. Arora and Kaushik [39] reported that the exergetic efficiency of the azeotropic mixture refrigerants is better than that of near azeotropic mixture refrigerants. In addition, the coefficient of performance for the azeotropic mixture refrigerant in a vapour compression system is better than that of near azeotropic mixture refrigerants, especially when the pressure drops in the condenser and that in the evaporator increases.

2.2. Thermodynamic properties of refrigerant mixtures

The thermodynamic properties are the most important factors that should be considered to fulfil the requirements of system performance. The thermodynamic properties give reliability to the system. Because of the applications, the temperatures of mechanical vapour compression systems are different, as the refrigerants must have the ability to deal with a different range of application design temperatures. Therefore, to obtain a low discharge temperature and to operate a vapour compression system at low application temperature, the specific heat and the boiling temperature of the refrigerant should be low. In addition, to achieve the operating condition of a condenser in a vapour compression system far away from the critical point on the pressure and enthalpy diagram, the critical temperature of the refrigerant should be high. Furthermore, to obtain an effective refrigerant effect, the critical pressure should be low. Another thermodynamic property that should be considered is a molecular weight. Because of the direct proportion between the molecular weight and specific volume, the molecular weight will affect the compressor size. Table 2 shows the thermodynamic properties for some refrigerants [2]. Indeed, to provide an alternative refrigerant mixture that gives a suitable system performance the same as the existing halogenated refrigerant, the thermodynamic properties of these mixtures should cover the system operating temperature.

Table 2. Thermodynamic properties [2].

Refrigerant	22	R417A R125/R134a/R600a 46.6/50.0/3.4 (% in mass)	R422A R125/R134a/R600a 85.1/11.5/3.4 (% in mass)	R422D R125/R134a/R600a 65.1/31.5/3.4 (% in mass)
Molar mass	*6.48*	*106.75*	*113.60*	*109.94*
Boiling temperature (°C)	*40.80*	*-39.12*	*-46.50*	*-43.20*
Critical temperature (°C)	*6.00*	*87.04*	*71.75*	*79.56*
Critical pressure (kPa)	*980*	*4036*	*3747*	*3903*
Critical density (kg/m^3)	*24.9*	*416.67*	*538.5*	*529.0*
Critical volume (m^3/kg)	*.0019*	*0.0024*	*0.0019*	*0.0019*
Certainty class	1	A1	A1	A1

2.3. Thermo-physical properties of refrigerant mixtures

To provide successful condensation and evaporation processes by using refrigerant mixtures in mechanical vapour compression systems, the thermo-physical properties should be considered. Thermal conductivity and viscosity are the most significant properties to achieve effective condensation and evaporation processes. At high values of thermal conductivity of both liquid and vapour phases of the refrigerant mixture, the condenser and evaporator will operate effectively due to the high value of the heat transfer coefficient [34]. Consequently, the power consumption will be reduced. Liquid density is another physical property which affects the refrigerant charge requirement. It can be used to calculate the thermal conductivity of superheated vapour and saturated liquid. As a result, to choose a refrigerant mixture as an alternative refrigerant the thermal conductivity, viscosity, and liquid density should be considered.

2.4. Refrigerant environment properties

Ethane and methane are essential gases to generate the halogenated refrigerants which are a chemical family derived from hydrocarbons. The majority of the halogenated refrigerants have chlorine and fluorine atoms; however, these atoms have an impact on the environment which can be evaluated by the ozone depletion potential ODP and global warming potential GWP [3].

Ozone depletion potential (ODP) and Global worming potential (GWP):

The most important factors that should be considered for selection of refrigerants are the ozone depletion potential ODP and global warming potential GWP. The ODP is a significant factor in saving people from the risk of ultraviolet (UV) rays from the sun because the ODP represents the ability of the refrigerants to destroy the stratospheric ozone layer, where the UV rays are filtered. Molina and Rowland [40] asserted that chlorine, which is the basic component in the refrigerants'ability to reach the stratosphere, has the ability to destroy the ozone layer. Therefore, the refrigerants should have zero ODP to save and protect the ozone layer from distortion by the chlorine which comprises halogenated gas. However, the GWP is an index that measures the energy balance between incoming energy from the sun that heats the earth and the amount of energy that radiates from the earth to space [41]. Mohanraj, Jayaraj [42] asserted that *30%* precent of the solar radiations which arrive at the earth at *5800K* and *13660* W/m^2 are reflected to space, but most of the arriving solar radiations passes through the atmosphere to reach the ground. Therefore, the temperature on the ground will increase. The impacts of the refrigerants on the environment alter the earth's temperature and distort the ozone layer, which causes climate change. Therefore, it remains challenging to select a refrigerant to satisfy both environmental needs and provide good system performance. Figure 2 shows the ODP and GWP for some refrigerant mixtures [3]. As can be seen from Fig.2, the ODP and GWP do not have zero values for the same refrigerant, when one of them has zero value the other has a significant value. However, La Rocca and Panno [2] and Mohanraj, Jayaraj [42] reported that the refrigerants which have zero ODP with zero or low values of GWP will not harm the environment. As a result, alternative refrigerants should have zero ODP and lower GWP to reduce the impact on the environment.

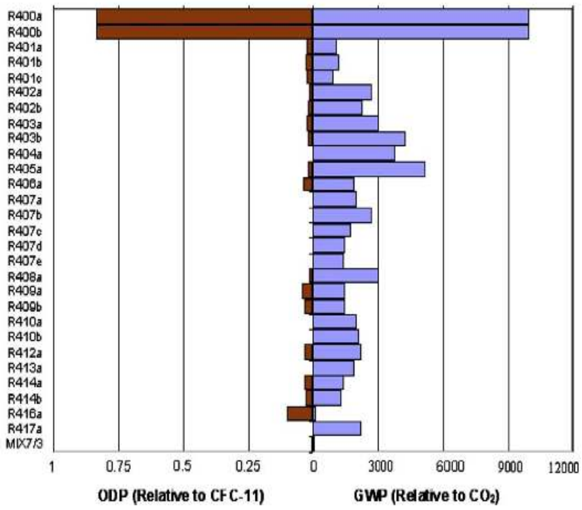

Fig.2. ODP and GWP for some refrigerants [3].

3. Mechanical vapour compression system

A mechanical vapour compression refrigeration system is one of the energy providers that can be used to provide energy where it is needed whether in heating or cooling applications. Most domestic and commercial applications use the mechanical vapour compression system which has different component sizes to match the system capacity to meet the demand of the application.

3.1. Single stage mechanical vapour compression system

The single stage mechanical vapour compression system consists of four main parts: compressor, expansion valve, condenser and evaporator. These four main parts are connected systematically to complete a closed cycle, as shown in Fig.3a. [1]. This closed cycle involves four thermodynamic processes: isentropic compression, isobaric heat rejection (condensation), isenthalpic expansion, and isobaric heat absorption (evaporation) as shown in Fig.3b. The function of the mechanical vapour compression system is to transfer heat from a low temperature zone to a high temperature zone. Indeed, the mechanical vapour compression system is a simple system that includes four essential parts to transfer the energy and meet the requirements of system design condition.

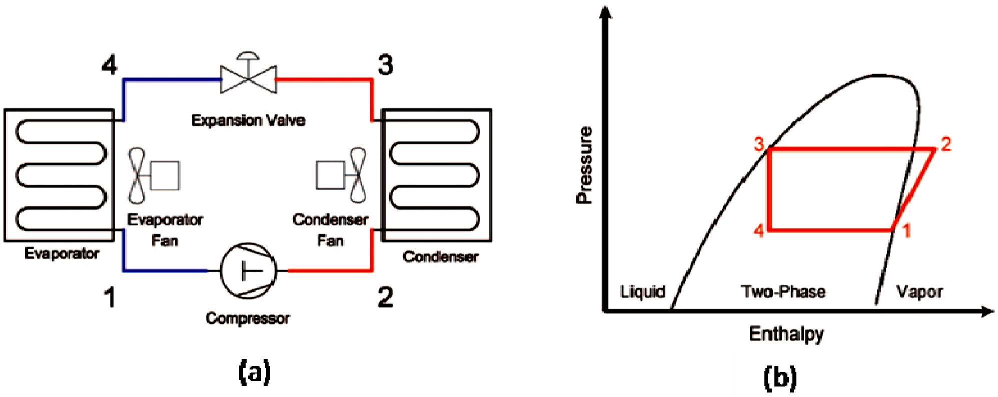

Fig.3. Compression vapour system [1].

3.2. Theoretical and experimental studies

Many different theoretical and experimental studies have been done; some of these studies have considered alternative refrigerants to solve environmental issues. Other studies which have been considered are system components and system modifications to obtain the best coefficient of performance with less energy cost. In the present work, only the studies which are carried out to investigate the refrigerant types and their effects on the environment will be presented and analysed.

Alternative refrigerant studies

The chlorofluorocarbons, CFC, and hydrochlorofluorocarbons, HCFC refrigerants are phased out because they have a high global warming potential (GWP) and ozone depletion potential (ODP) [3]and because the global warming concerns have increased in recent years [43]. Therefore, hydrofluorocarbons and HFC refrigerants have been increasingly used instead of using the CFC and HCFC refrigerants, and many different studies have been carried out propose an appropriate refrigerant as a working fluid in a mechanical vapour compression system.

Use of R507A mixture as an alternative refrigerant

The R507A mixture is one of the HFC refrigerants, and it is an azeotropic refrigerant. It is also a blend refrigerant, consisting of *50%* of pentafluoroethane (HFC-125) R125 and *50%* of trifluoroethane (HFC-143a) R143a[44]. The R507A mixture is one of the refrigerants used in a vapour compression refrigeration system due to its excellent thermo-physical and thermodynamic properties [34]. In addition, the R507A has zero ODP and low GWP which are essential factors for choosing an environmentally friendly refrigerant. La Rocca and Panno [2] reported that the refrigerants which have zero ODP with zero or low values of GWP will not harm the environment. Consequently, the R507A is classified as being in a safety group (A1) [39]. Furthermore, the R507A condenses and evaporates as a single substance, and it does not have the glide temperature problem which is the temperature difference between the dew point and bubble temperatures at a given pressure and composition (Leelananda [4], [45] and [46]). Table 3 presents some studies performed on R507A.

Table 3. Performed studies on R507A.

Authors	Type of study	Finding and results
Geller, Nemzer [32]	Experimental work to compare R404A, R410A and R407C with R507A	Thermal conductivity is affected by the density.
Sami and Aucoin [47]	Experimental work to replace R404A, R407C, R410A and R507 instead of R22	The liquid injection has a positive effect on compressor protection.
Arora and Kaushik [39]	Numerical analysis to replace R404A and R507A instead of R502.	The R507A is a good alternate to R502.
Llopis, Torrella [44]	Experimental investigation to study R404A and R507A.	The R404A is better than R507A at high evaporator temperature.
Bolaji [48]	Experimental work to replace R404A and R507 instead of R22	The COP of R507 is better than R404A as a substitute of R22.
Parekh and Tailor [45]	Numerical investigationto replace R507A and R23 instead of R13	The COP increased with increasing evaporator temperature and decreased with increasing condenser temperature.
Venkatarathnam, Mokashi [35]	Theoretical work to study R-134a, R407C, R410A, R404A, R507A, R290, and R600a as an alternative of R22	R410A can be considered as the prominent refrigerant to replace R22 in air conditioning systems
Siva Reddy, Panwar [20]	Theoretical investigationto study mixture R407C and R409A, R410A, and R507A.	R410A and R507C are assumed to be more appropriate refrigerants for use.
Aized and Hamza [49]	Numerical study to investigate thermodynamic analysis of R134a, R152a, R1234yf, R404A, R407C, R410A and R507A	The results revealed that R152a can be used in refrigeration system with minimum modification.
Kuczynski, Bohdal [50]	Theoretical work to investigate the influence of dynamic instabilities on the condensation phase change of R507.	The study reported that R507A is a good alternative refrigerant that can be used in vapour refrigeration system.

Natural and alternative refrigerants

To provide environmentally friendly refrigerants which cover many different applications of mechanical vapour compression systems, different studies have been proposed that provide some information about the behaviour of natural and alternative refrigerants when they act as a working fluid in mechanical vapour compression systems. Table 4 presents these studies and their outcome.

Table 4. Performed studies on alternative refrigerants.

Authors	Type of study	Finding and results
Sato, Kagawa [51]	Theoretical work to calculate the thermodynamic properties of pure refrigerants R23, R125, and R134a	Some recommendations about R134a were presented.
Aprea and Greco [52]	Experimental work using reciprocating compressor in a vapour compression refrigeration system to compare R22 with R407.	The results revealed that R22 are better than R407C.
Cabello, Torrella [28]	Experimental work of single stage vapour compression system using R407C and R134a	The coefficient of performance of R407C at a higher compression ratio was higher than that of R22.
Kumar and Rajagopal [3]	Experimental and computational analysis work using R123 and R290.	The results revealed that the discharge temperature of R290 at the outlet of the compressor is lower than that of R12.
Bertsch and Groll [53]	Theoretical work to simulate three models (intercooler, economizer, and cascade system models) of an air source heat pump system using R410A.	The worst efficiency values are obtained at intercooler system mode.
Jung [54]	Theoretical work to compare HFC with CFC and HCFC refrigerants in terms of its effects on the environment.	The study suggested using HFC as working fluids instead of the CFC and HCFC to save the environment.
Aprea and Maiorino [55]	Experimental work to evaluate the energy performance of mechanical cooling system by using an internal heat exchanger with carbon dioxide as working fluid.	The using of internal heat exchanger in the cooling system enhanced the COP by 10%.
Mastrullo, Mauro [56]	Experimental work to compare the heat transfer coefficient of R744 with that of R134a.	R744 has heat transfer coefficients higher than that of R134a.
Fernández-Seara, Uhía [29]	Experimental work to measur a heat transfer coefficient of R22 and its retrofit substitutes such as R417A, R422A, and R422D.	The heat transfer coefficient for vapours R417A, R422A, and R422D are lower by 65-76%, 24-31%, and 60-67% than the heat transfer coefficient for R22 respectively.
Llopis, Cabello [41]	Experimental comparison by using a double stage vapour compression system using R22, R422A, and R417B.	The COP of refrigeration system when R422A and R417B were used was smaller than that of R22.
Mohanraj, Muraleedharan [34]	Theoretical work that involved an extensive study on refrigeration, air conditioning, and heat pump units using Azeotropic, Near azeotropic, and Zeotropic mixtures.	R430A is a good substitute for replacing R12 and R134a in the domestic small units. R430A and R152a are are good replacement in an automobile system instead of R12 and R134a. In the low evaporator temperature application, R507 is found to be the best substitute for replacing R502.
La Rocca and Panno [2]	Experimental work on a vapour compression refrigeration system to compare R22, R123, and R124 with R422A, R422D, and R417A.	The discharge temperature of R417A, R422A, and R422D that leave the compressor outlet in the system is smaller than that of R22. It leads to subject the compressor to less thermal stress

		and offers long life time.
Aprea, Maiorino [26]	Experimental work on a vapour compression refrigeration system to compare R-22 and its substitute R422D.	The COP by using R22 was higher than that of R422D. The discharge temperature of refrigerant R422D at the compressor outlet was lower than that of R22; therefore, the R422D offers longer compressor life.
Wang, Wang [57]	Experimental study to operate an inverter heat pump system using R125.	The values of COP decrease when the hot water temperature increase at any compressor frequency value. The heating capacity increase when the frequency is changed from 50 to 110 Hz.
Han, Qiu [58]	Experimental work to investigate the coefficient of performance, volumetric refrigerating effect, and specific refrigerating effect, using R161, R125, and R134a and compare system performanceby using R404A and R502	The COP for first case is 5.19% higher than that when R404A was used. The specific refrigerant effect and volumetric refrigerant effect are 15.48% and 2.33% respectively higher than that of R404A.
Han, Qiu [59]	Experimental work to investigatethe coefficient of performance, volumetric refrigerating effect, and specific refrigerating effect using R404A and R502.	The COP of system when R502 was usedwas 5.19% higher than that of R404A. The specific refrigerant effect and volumetric refrigerant effect are 15.48% and 2.33% of R502 respectively higher than that of R404A.
Siva Reddy, Panwar [20]	Theoretical studyto consider an exergy analysis of a vapour refrigeration system using R134a, R404A, R407C, and R507A.	The results showed that the best values of COP and exergy efficiency were recorded when R134a was used.
Šarevski and Šarevski [60]	Theoretical investigations of R718 refrigeration cycles with two-phase ejector as a compression device.	Novel R718 refrigeration/heat pump systems are proposed: simple two-phase ejector cooling cycle, two-phase ejector heat pump cycle applied in evaporators–concentrators, and combined compact R718 centrifugal compressor–two-phase ejector water chiller for air conditioning application, and their thermal and performance characteristics are estimate
Moon, Choi [61]	Investigate the performance characteristics of vapour injection refrigeration system with an economizer at an intermediate pressure by using R404A as a refrigerant.	The results revealed that The coefficient of performance (COP) increased and then decreased with respect to the intermediate pressures under all the experiment conditions.
Heller, Rausch [62]	Experimental study to measure the thermophysical properties of mixture R417A and R417B.	The results are discussed in detail in comparison with literature data and with various prediction methods.
Kılıç [63]	Theoretical study for exergy analyses of vapor compression refrigeration cycle with two-stage and intercooler using refrigerants R507, R407c, and R404a.	The results showed that the irreversibility in evaporator is based on pressure drop arising from phase change, the temperature difference between refrigerants and refrigerated environment, heat transfer and frictions.
Agrawal, Patil [6]	Experimental studyof a domestic refrigerator using R290/R600a zeotropic blends.	The results reported that the R290/R600a zeotropic blend is a good option as substitute of R134a.

Shaik and Babu [7]	Theoretical study to investigate the performance of vapour compression refrigeration system using HFC and HC refrigerant mixtures as alternatives to replace R22.	Overall the thermodynamic performance of refrigerant mixture R134a/R1270/R290 is better than that of R22 hence it is an appropriate alternative refrigerant to substitute R22.
Choudhari and Sapali [8]	Conducted a study to investigate performance of natural refrigerant R290 as a substitute to R22.	The result revealed that the R290 can be a better substitute to R22 in real applications.
Samuel, Govindarajulu [10]	Conducted an experimental investigation and performance evaluation of 1.5 TR window air-conditioner by using R22, R407C and R410A.	From the results it is evident that the refrigerant R410A gave the best coefficient of performance.
Fatouh, Ibrahim [21]	Performed a study to assess the performance of a direct expansion air conditioner working with R407C as an R22 alternative.	The average input electric power of a machine uses R407C is lower than that for R22 by about 13.2%.
Kasera and Bhaduri [22]	Presented a review study to investigate the performance of R407C as an Alternate to R22.	The study revealed that the R410A is suitable for new design.
Ersoy and Sag [64]	Presented an experimental study to investigate the employment of the ejector as an expansion device using R134a.	The results showed that the COP is increased by 14.5% when the ejector used as an expansion device using R134a.
Gill and Singh [65]	Reported an experimental work to investigate the performance of mixture of R134a with LPG as an alternative of R134a.	The results revealed that the mixture of R134a and LPG van be used as alternative refrigerant.
Abdulqadir, Salim [66]	Provided an experimental study to investigate the use of R407C as a replacement of R22.	The study reported that the R407C can be used as substitute for R22.

Water

Water is the ultimate natural refrigerant (working fluid) that can be used in refrigeration and air conditioning systems. Water is an environmentally friendly refrigerant because it has zero ozone depletion potential (ODP), zero global warming potential (GWP), non-toxicity, and non-flammability [67]. Therefore, water is classified a safe refrigerant, falling into the A1 group as a refrigerant code (R718) [68], [69]. Water also has excellent chemical and thermodynamic properties, so it can be used both below and above its freezing point [68], [70] and [71]. However, at the below freezing application, water needs to be coupled with a protective solution such as propylene or ethylene glycol to prevent freezing during the operation.

Water (R718) has been used in many different applications of air conditioning and refrigeration systems and received attention as a natural refrigerant after the signing of the Montreal Protocol to reduce environmental concerns [67] and [72]. Agrawal, Mali [73] stated that R718 can be used as a refrigerant in a vapour compression system. Earlier, water had been used in adsorption, absorption, and desiccant air conditioning systems as mentioned in the studies of Dimotakis, Cal [74], Pope and Fry [75], and Dai, Wang [76]. Mahmood, Buttsworth [77] Mahmood, Buttsworth [77] used water to investigate the two-phase separation performance of a vertical gravity flash tank. Mahmood [78] investigated the use of water as an ultimate refrigerant in refrigeration systems. Mahmood, Buttsworth [79] investigated the performance of a vertical flash tank using water as a refrigerant. However, since some industries face difficulties in providing a powerful and efficient compressor (due to blade production, which should overcome radial stress), many different studies have been undertaken to use water as a natural refrigerant to solve obstacles for utilizing water in refrigeration and air conditioning systems [80]. Recently, water (R718) has been used as a natural refrigerant in mechanical compression refrigeration, turbo compression, and ejector air conditioning and refrigeration systems as mentioned in studies undertaken by Li, Piechna [80], Šarevski and Šarevski [69], and Chen, Omer [81]. These studies have revealed that among the refrigerants such as R717, R12, R22, R134a and R290, water (R718) showed the highest coefficient of performance (COP) at high evaporator temperature. Table 5 presents studies that have used water as a refrigerant.

Table 5. Performed studies using water as a refrigerant.

Authors	Type of study	Finding and results
Kilicarslan and Müller [68]	Theoretical investigation using R718, R22, R134a, R12, and R290	The high value of the COP was recorded when R718 was used.
Wang and Li [82]	Theoretical study to investigate using natural working fluid (water and dioxide) in air conditioning and refrigeration system.	The natural refrigerants have zero effect on the environment.
Srisomba, Mahian [83]	CFD numerical approach was used to predict the thermodynamic capacity system using water and R134a.	The COP of the vapour compression system by using water increased at least 30% at full load compared to a conventional refrigerant such as R134a.
Šarevski and Šarevski [69]	Theoretical study to estimate performance characteristics, fluid flow characteristic, and parameters of the centrifugal compressor using water (R718).	Water can be used with centrifugal compressor as natural refrigerant in refrigeration and air conditioning.
Wang, Wang [57]	Experimental and theoretical study to investigate the use of water as a refrigerant.	The integrated compressor with the new design of impeller can be used in refrigeration and air conditioning systems by using water as natural refrigerant.
Do and Chan [84]	Study to investigate the use of alternative refrigerants and their effect of the environment.	The result showed that it is possible to reduce the energy consumption up to 5% by using an alternative refrigerant. The impact on the environment of the alternative refrigerant is comparable to isobutane.
Sun, Wang [85]	A study to explore the technical alternatives of refrigerant substitution and analyse the application of low GWP refrigerant.	The results showed that R718 can be used as alternative refrigerants in addition to R1150, R41, R717, R1150, R41 and R152a.

4. Future vision

The future vision for the use of natural and alternative refrigerants in refrigeration and air conditioning systems was obtained after intensive investigation and analyses of the literature. The future refrigerants must satisfy environmental requirements and needs in terms of protecting the ozone layer, and should provide a sustainable system which can be used without any negative effects on the environment. From the environmental point of view, the type of refrigerant should be considered and selected according to the values of ODP and GWP. According to the Montreal Protocol of 1 January 2016 the HCFC refrigerants were banned and on January 1 2020 the HCFC refrigerant will be phased out but up to *0.5*% will be allowed to remain in service until 2030, using the existing refrigeration and air conditioning equipment in developed countries; however, on 1 January 2040 the HCFC refrigerant will be phased out completely in developing countries. Therefore, natural refrigerant types such as water, carbon dioxide, hydrocarbon, and ammonia will play a significant role in protecting the environment and providing alternative friendly refrigerants to be used in refrigeration and air conditioning systems. The present study has offered some suggestions for the future research:

- Investigate the suitability of water to be used as the ultimate friendly working fluid in mechanical refrigeration systems.
- Investigate the natural refrigerant and its compatibility to be used as an effective refrigerant in mechanical refrigeration systems.
- Use alternative refrigerants in the computational fluid dynamic (CFD) to predict the flow characteristics and two-phase flow development in a refrigeration system.
- Create new generations of air conditioning and refrigeration systems by using vacuum operating conditions with water as a working fluid.

5. Conclusion

The effects of refrigerants and refrigerant types on the environment were presented and reviewed. Experimental and theoretical studies which considered alternative refrigerants to obtain environmentally friendly refrigeration systems were analysed. Refrigerant types, thermodynamics, and thermo-physical properties were discussed. According to the previous studies and the Montreal Protocol of 1987 and the regulation number 2037/200 of the European Parliaments of 2000 the HCFC, CFC refrigerants are forbidden to be used in refrigeration and air conditioning systems in developed countries due to their negative effects on the environment. The HCFCs and CFCs were found to be harmful to the ozone layer which is the protective layer for the earth. Therefore, their production has been prohibited by the Montreal Protocol and other international agreements. Alternative refrigerants such as HFC refrigerants are currently the leading replacement for CFC and HCFC refrigerants in refrigeration and air-conditioning systems. This paper presented a review study of the previous experimental and theoretical work to provide a strong basis for establishing the need to embrace the use of natural refrigerants as a replacement for halocarbon refrigerants. Hence, some refrigerants such as R123, R290, and R407Cwere presented as suitable alternativesto use instead of R22 refrigerant and refrigerant mixture of *70*%. In addition, R129-*30*% R290 is a substitute for replacing R12 refrigerant. Further, according to the literature, a refrigerant mixture such as R507A and natural refrigerants play crucial roles in reducing the environmental impacts of CFC and HCFC refrigerants. They are also efficient refrigerants to be used in air conditioning and refrigeration systems. Water can also be used as an ultimate friendly refrigerant, however; there is more need to investigate its operating conditions and system design.

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