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Applications of eco-friendly refrigerants and nanorefrigerants: A review

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ABSTRACT

Usage of eco-friendly refrigerants could be an effective solution to the global warming problem. However, a comprehensive assessment is necessary when selecting new refrigerants. Any substance should be evaluated for its overall impact on the global environment, energy efficiency, cost-effectiveness, and safety. This paper reviews the experimental and theoretical studies that have been carried out with environmentally friendly refrigerants such as hydrocarbons, hydrofluorocarbons, R744 (carbon dioxide), hydrofluoro olefin, and nanorefrigerants. The article's main aims are to evaluate the potential of all refrigerants used in the refrigeration and air conditioning industries and to present the primary applications of environmentally friendly refrigerants and nanorefrigerants. The paper also identifies the gaps in the literature and introduces opportunities for future work.

1. Introduction

The Kyoto Protocol gave significant prominence to carbon dioxide, which is listed as the most perilous greenhouse gas because of its contributions to global warming. A large proportion of human-made carbon dioxide emissions are the direct result of burning fossil fuels [1]. Moreover, fossil fuels still are the predominant source of energy for power plants, and renewable energies' share of electricity generation is still low, even in most of the countries that signed the Energy Charter Treaty. Therefore, there is an urgent need to improve electrical appliances' energy efficiency and environmental impacts, particularly their refrigeration cycles, which play a prominent role in these devices' energy consumption and environmental impact.

Ozone-layer depletion is one of the most critical environmental problems. This problem is engendered by the interaction of destructive chemical substances, such as bromine and chlorine gases, with stratospheric ozone. The presence and stability of harmful substances such as volatile organic compounds, chlorofluorocarbons (CFCs), and hydrochlorofluorocarbons (HCFCs) in the lower atmosphere has increasingly threatened the environment, as well as people's health and safety, over the last two centuries. This ecological catastrophe is mainly the result of the leakage of refrigerants, industrial and vehicular exhaust gases, and aerosols into the atmosphere. Refrigerants' role is of primary importance, insofar as refrigerant management placed first on Hawken's list of 80 strategies for global-warming mitigation [2]. In 1987, the Montreal Protocol was adopted; it restricted the production, utilization, and commerce of CFCs as a means to protect the ozone layer [3]. Substitution of hydrofluorocarbons (HFCs) for CFCs and HCFCs has efficiently alleviated the problem in the years since [4]. Nevertheless, after the Kigali deal in 2016, controversy arose regarding high global warming potential (GWP of the HFCs). The utilization of eco-friendly refrigerants such as hydrocarbons (HCs), hydrofluoro olefin (HFO), R744 (carbon dioxide), and environmentally safe nanorefrigerants can reduce ozone depletion potential (ODP) and GWP. In addition to GWP

Abbreviations: HC, Hydrocarbon; HFC, Hydrofluorocarbon; CO_2, R744; HFO, Hydrofluoro olefin; CFC, Chlorofluorocarbon; HCFC, Hydrochlorofluorocarbons; GWP, Global Warming Potential; ODP, Ozone Depletion Potential; TEWI, Total Equivalent Warming Impact; LCCP, Life Cycle Climate Performance; SAC, Split Air Conditioner; PAG, Polyalkylene Glycol; RAC, Residential Air Conditioner; HTC, Heat Transfer Coefficient

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and ODP, two other measures of refrigerants have risen to prominence: total equivalent warming impact (TEWI) and life-cycle climate performance (LCCP). Direct LCCP is chiefly related to refrigerant leakage. Indirect LCCP encompasses emissions from system manufacturing, transportation, and operations [5]. Other environmental factors are equally important; these include toxicity and flammability, along with physical factors such as vapor pressure, solubility, stability, and lubricity; all these should be taken into account in the process of refrigerant selection [6].

Due to the relatively small harmful impact that refrigerants such as HCs have on the environment, this type of refrigerant has been popular since the 1990s. After legal regulations were instituted for CFCs and HCFCs, perfluorocarbons and HFCs were introduced. However, due to these substances' high GWP, they were criticized in the Kyoto Protocol in 1997. HFO refrigerants have recently been implemented. Nanoparticles have provided the opportunity to improve the performance of conventional refrigerants and lubricants.

In the past decade, some review papers have been published on environmentally friendly refrigerants, but none of them have provided a comprehensive view of this subject. Mohanraj et al. [7] reviewed the literature on environmentally friendly alternatives to halogenated refrigerants. Although that review focused on halogenated refrigerants, not all refrigerants are restricted to this type. Furthermore, since 2008, there has been significant progress in the development of environmentally friendly refrigerants such as HFOs. Bolaji and Huan [8] provided a literature review of natural refrigerants such as HCs; these substances have low GWP and no ODP, but their applications are limited due to their high flammability. Bhatkar et al. [9] studied some of the recent research on alternative refrigerants in vapor-compression refrigeration cycles to see which were the most environmentally sustainable. Sarbu [10] presented a literature review on the substitution of non-ecological refrigeration with vapor-compression-based refrigeration, air conditioners, and heat pumps. This article is more comprehensive than others, but its focus was not on eco-friendly refrigerants. Harby [11] undertook a review of both pure HCs and mixtures to find solutions for the high ODP and GWP of halogenated refrigerants. The solutions go beyond the bounds of mere natural HCs. Azmi et al. [12] and Saidur et al. [13] appraised the effects that nanorefrigerants and nanolubricants had on the performance and energy efficiency of refrigeration cycles. Abas et al. [14] conducted a major review of the history of both natural and synthetic refrigerants in an effort to focus more attention on ODP and GWP. They proposed a parametric quantitative model to environmentally and thermodynamically optimize the decision-making regarding refrigerant selection based on the Paris Agreement, the F-gas law, and the Montreal and Kyoto Protocols. Reviewing the abovementioned studies reveals that none of them considered all of these topics: environmentally friendly refrigerants, nanorefrigerants, and compatible lubricants. Therefore, it is necessary to provide comprehensive information regarding the application of zero-ODP, low-GWP refrigerants, as well as their compatible lubricants.

This paper reviews the development of environmentally friendly refrigerants and their applications in various fields since 2005. To the best of our knowledge, there has been no comprehensive literature review of eco-friendly refrigerants and nanorefrigerants. Hence, this study is an attempt to present a comprehensive database on the progress of environmentally safe and energy-efficient refrigerants. The present work classifies the articles on refrigerants into five groups: HCs, R744, HFCs, HFOs, and nanorefrigerants.

2. HC refrigerants

HCs include natural refrigerants such as R290, R600a, R1150, R1270, R170, and various blends of these products. These natural refrigerants have many practical applications and many advantages over other types:

- zero ODP and low GWP;
- high-quality thermodynamic properties;
- good compatibility with components; and
- low charges, allowing for small heat exchangers and pipes.

The natural refrigerants R432a, R433a, R600a, and R290 showed potential for use in a broad range of refrigeration cycles as a substitute for R22 and R134a [3]. Chinnaraj et al. [15] pointed out that R290, when used in window air conditioners, had more beneficial effects in terms of both coefficient of performance (COP) and energy efficiency than did R22, especially when the system was fitted with an electronic expansion valve instead of a capillary tube. R290 has zero ODP, low GWP, and one-third of the TEWI of R12. Halimic et al. [16] concluded that the utilization of R290 instead of R12 could have brought about a similar COP and an even higher cooling capacity when used in a vapor-compression refrigeration system. There is evidence that R600a, an environmentally friendly refrigerant, has promising COP, mass, and volumetric refrigerating capacity, as well as a much lower TEWI in heat pumps than either R22 and R134a [17,18]. The main concerns about HCs are related to their flammability. The ignition frequency and severity of split air conditioners are significantly lower than those of domestic refrigerators, so HCs are much safer than domestic refrigerators in such split air conditioners [19].

Since the emergence of transcritical air conditioners in the late 1980s, considerable attention has been paid to the two-phase ejector as an expansion device for enhancing energy efficiency. A number of researchers have presented analyses of vapor-ejector refrigeration systems with environmentally friendly refrigerants [20,21]. Based on these observations, R1270 had better performance in a transcritical ejector refrigeration cycle than did R744, R32, R143a, R125, and R115. HCs have also shown a satisfying chemical compatibility with most of the lubricants that are currently used in refrigeration cycles, but eco-friendly HCs require specific lubricants. Mineral oils have been introduced as lubricants for use with HC refrigerants [22], but it is better to use lubricants that have higher viscosity and less solubility than mineral oils, such as polyalphaolefin and polyalkylene glycol (PAG). Fig. 1 illustrates the compatibility of various lubricants with HC

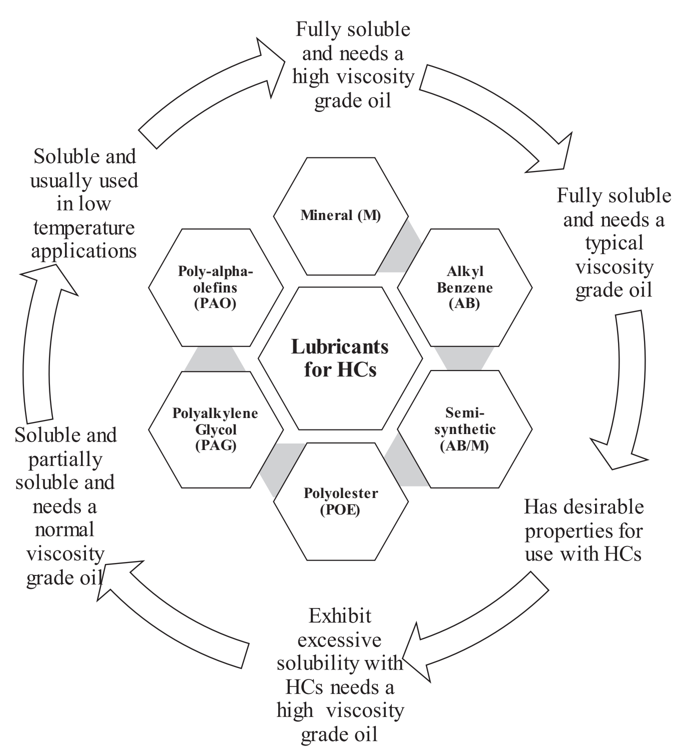

Fig. 1. Compatibility of various lubricants with HC refrigerants.