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"HALOCARBON REFRIGERANTS IN VAPOUR COMPRESSION REFRIGERATION SYSTEMS: A REVIEW OF REFRIGERANT SELECTION, SUPERHEATING AND SUBCOOLING, EXERGY ANALYSIS, AND MODEL-BASED OPTIMIZATION"

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ABSTRACT

Vapour compression refrigeration is the dominant technology for domestic, commercial, and industrial cooling, and the refrigerant, the operating pressures and temperatures, and the degrees of superheat and sub cooling together determine its coefficient of performance (COP) and its environmental impact. The phase-out of chlorofluorocarbons and the later concern for global warming have led to the search for alternative halocarbon refrigerants, among which R-134a and R-152a are widely studied replacements. This review paper presents an assessment of published work on the performance of vapour compression systems with halocarbon refrigerants, with emphasis on the comparison of R-123, R-124, R-125, R-134a, R-143a, and R-152a, the influence of evaporating temperature, condensing pressure, superheating, and subcooling on COP, second-law and exergy analysis of the cycle and its components, and the use of dynamic models and model-based optimization to reduce energy consumption, particularly in supermarket refrigeration. The reviewed literature indicates that R-152a gives a COP close to or somewhat higher than R-134a in experiments with only small changes to the equipment, that subcooling consistently raises the COP, that irreversibility in the compressor is a principal source of exergy loss, and that optimizing control can reduce operating cost substantially. Research gaps are identified, including limited consistent property data in comparative theoretical studies, the lack of experimental validation of theoretical COP at low evaporating temperatures, and scarce combined treatment of refrigerant choice and operating-condition optimisation. The findings are intended to guide refrigerant selection and the analysis of vapour compression cycles.

Key Words: *Vapour compression refrigeration; R-134a; R-152a; coefficient of performance; sub cooling; superheating; exergy analysis; refrigerant selection; model-based control.*

I. INTRODUCTION

A refrigeration system transfers heat from a low-temperature space to a higher-temperature surrounding, and a work input is needed to do so. In the vapour compression cycle a refrigerant that evaporates and condenses at temperatures and pressures close to ambient is circulated through four main components: the evaporator, in which the low-pressure liquid absorbs heat and evaporates, usually with a small amount of superheat; the compressor, in which the vapour is raised to the condenser pressure; the condenser, in which the superheated vapour is desuperheated, condensed, and often sub cooled; and the expansion device, which reduces the pressure and controls the flow to the evaporator [1], [2]. The two principal advantages of the cycle are that a large amount of heat is absorbed in the latent heat of vaporisation, and that evaporation is isothermal, so that heat can be absorbed without raising the temperature of the refrigerant to that of the cooled space [1]. These features make the cycle suitable for all purposes, from a small domestic refrigerator to a large air-conditioning plant.

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The performance of the cycle is expressed by the COP, the ratio of the refrigerating effect to the compressor work, and it is bounded by the Carnot COP between the evaporating and condensing temperatures. The ratio of the actual COP to the Carnot COP is a second-law efficiency and indicates how much of the thermodynamic potential is used. The COP of an actual cycle falls as the evaporating temperature is lowered or the condensing temperature is raised, because the pressure ratio and the compressor work increase, and it depends on the refrigerant through its thermodynamic properties [1], [2]. Superheating of the vapour at the evaporator outlet protects the compressor from liquid but changes the suction state, and subcooling of the liquid before the expansion device increases the refrigerating effect without any extra compressor work, so that its effect on the COP is generally beneficial [3].
The choice of refrigerant has also been shaped by environmental concerns. The chlorofluorocarbons were phased out because of ozone depletion, hydrochlorofluorocarbons and hydro fluorocarbons were introduced as replacements, and the global warming potential of hydro fluorocarbons such as R-134a is now a concern in turn, so the search for alternatives with zero ozone depletion potential and lower global warming potential continues [4], [5]. In addition, refrigeration is a major consumer of energy: in supermarkets it can account for a large part of the electricity use, and dynamic modelling and control of the system can reduce the energy cost [6]. This paper reviews the literature on these topics and identifies the gaps that remain.

II. Problem Identification

The refrigerant and the operating conditions of a vapour compression system must be selected together. A refrigerant that gives a high COP at one evaporating temperature may perform poorly at a lower one, and the effect of condensing pressure, superheating, and subcooling differs between refrigerants. Theoretical comparisons of refrigerants are usually made at a few conditions, with property data taken from different sources, so that results from different studies are not directly comparable and the sensitivity of the conclusions to the assumed conditions is not always clear.

The existing literature is also divided between thermodynamic studies of the cycle, experimental studies of retrofit or drop-in refrigerants, and control-oriented studies of whole refrigeration plants. Few investigations connect a theoretical comparison of several refrigerants at low evaporating temperatures with an experimental unit, and the second-law and exergy results are often reported without a check of the consistency of the property data. A consolidated review is therefore required to summaries what is known about the effects of refrigerant, evaporating and condensing conditions, superheating, and sub cooling on the performance of the cycle, and to identify the gaps for future work.

III. Research Objective

The main objective of this review paper is to examine published work on halocarbon refrigerants in vapour compression refrigeration systems. The specific research objectives are as follows:

- To review the vapour compression cycle: Describe the components of the cycle and the parameters that determine its COP.
- To compare refrigerants: Examine studies of R-134a, R-152a, and other halocarbons as alternatives to chlorofluorocarbons and to each other.
- To examine the effect of operating conditions: Review the influence of evaporating temperature, condensing pressure, superheating, and subcooling on COP.
- To review second-law and exergy analysis: Examine studies that locate and quantify irreversibility in the cycle and its components.
- To review modelling and control: Examine dynamic models and optimising control used to reduce the energy consumption of refrigeration systems.
- To identify research gaps: Identify limitations in existing studies relevant to refrigerant comparison at low evaporating temperatures.

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SJIF Impact Factor : 6.190

IV. LITERATURE REVIEW

The studies reviewed below are grouped by topic. For each study the scope and principal findings are summarised as reported by the authors, and its relevance to the analysis of vapour compression cycles is highlighted. Where a study is described only by its stated scope, no quantitative results are attributed to it.

Refrigerant alternatives. Calm [4] reviewed the history of refrigerants, from the early natural fluids through the chlorofluorocarbons and hydrofluorocarbons to the present concern for global warming, and outlined the considerations that govern the choice of the next generation of refrigerants, namely safety, environmental properties, performance, and cost. Mohanraj et al. [5] reviewed environment-friendly alternatives to halogenated refrigerants and discussed hydrocarbons, ammonia, carbon dioxide, and mixtures as options, with their advantages and limitations. Bolaji [7] tested R-152a and R-32 as replacements for R-134a in a domestic refrigerator designed for R-134a. The average COP with R-152a was 4.7% higher than with R-134a, whereas the average COP with R-32 was 8.5% lower, and the system consumed less energy with R-152a, so the author concluded that R-152a can replace R-134a in a domestic refrigerator. In a separate exergetic study of a domestic refrigerator, Bolaji [8] compared R-12 with R-134a and R-152a; the COP of R-152a was within 1.4% of that of R-12 whereas R-134a gave an 18.2% lower COP, and R-152a had the higher exergetic efficiency and the lower efficiency defect.

Superheating and subcooling. Bolaji [9] investigated experimentally the effect of subcooling on four alternatives to R-12 (R-32, R-152a, R-143a, and R-134a) in a domestic refrigeration system. The sub-cooler improved the performance of all the refrigerants: an increase in the degree of subcooling reduced the pressure ratio and the compressor work and raised the refrigerating capacity and the COP. R-152a and R-134a had the most similar performance to R-12, with R-152a slightly better, whereas R-32 and R-143a were significantly lower. These results agree with the thermodynamic expectation that subcooling raises the refrigerating effect without additional compressor work, and that excessive superheat at the suction raises the compressor discharge temperature and work.

Second-law and exergy analysis. Arora and Kaushik [10] carried out a theoretical analysis of a vapour compression system with R-502, R-404A, and R-507A, in which the exergy destruction in each component was calculated and the effect of evaporator and condenser temperatures on COP and exergetic efficiency was studied. Yataganbaba et al. [11] performed an exergy analysis of R-1234yf and R-1234ze as replacements for R-134a in a two-evaporator system and located the main sources of irreversibility. Both studies show that the compressor and the condenser are the main sources of exergy destruction, and that the exergy loss in the compressor increases with the pressure ratio. The exergy method of Kotas [12] provides the basis for this approach: for an adiabatic compressor the exergy destroyed per unit mass equals the product of the ambient temperature and the entropy generated, and the compressor's exergetic efficiency is the ratio of the minimum to the actual work.

Modelling and optimising control. Willatzen et al. [13] formulated a general dynamic simulation model for evaporators and condensers using a moving-boundary description of two-phase flow with heat exchange. Larsen [14] studied model-based control of refrigeration systems and divided the optimising control into a top layer that optimises set-points and a lower layer for dynamic optimisation of the subsystems. Larsen et al. [15] demonstrated a model-based method on a realistic supermarket model with a full-year simulation and historical electricity prices, and they reported cost savings of the order of 30% compared with a standard thermostat-based control. Rasmussen and Larsen [16] proposed a nonlinear controller for superheat and capacity based on a low-order evaporator model, and they verified its stability theoretically and by experiments over a wide range of operating points. Hovgaard et al. [6] noted that refrigeration can account for a large part of the electricity use of a supermarket and used the thermal capacity of the refrigerated goods to shift the load in an optimisation of the power consumption. These studies concern whole plants and control, but they show that the set-points that the thermodynamic analysis identifies, such as the condensing pressure and the degrees of superheat and subcooling, can be implemented in practice by optimising control.

Table 4.1: Summary of selected studies

Study	Focus	Principal finding reported
Bolaji [7]	R-152a and R-32 versus R-134a, domestic refrigerator	R-152a COP 4.7% higher than R-134a
Bolaji [8]	Exergetic performance, R-12, R-134a, R-152a	R-152a closest to R-12 in COP; best exergetic efficiency
Bolaji [9]	Subcooling with four R-12 alternatives	Subcooling raises COP and capacity
Arora and Kaushik [10]	Exergy analysis of R-502, R-404A, R-507A	Exergy destruction by component
Yataganbaba et al. [11]	R-1234yf and R-1234ze versus R-134a	Irreversibility located by component
Larsen et al. [15]	Model-based control, supermarket model	About 30% cost saving
Rasmussen and Larsen [16]	Superheat and capacity control	Stability proven and tested

Summary and research gaps. Several themes emerge. First, R-152a gives a COP close to or somewhat higher than R-134a in experiments with small changes to the equipment [7], [8], [9]. Second, subcooling increases the COP and the capacity for all the refrigerants tested [9]. Third, the compressor and the condenser are the main sources of exergy destruction [10], [11]. Fourth, dynamic modelling and optimising control reduce the energy cost of whole plants [14]–[16], [6]. The reviewed studies also have limitations: most experiments are at the evaporating temperatures of domestic refrigerators, so that the performance of R-134a, R-152a, and the other halocarbons at evaporating temperatures of −30 °C and below is less documented; theoretical comparisons often use property data from different sources and do not report a consistency check against the second-law limit; and few studies compare a theoretical COP with that of a small experimental unit. These gaps motivate a theoretical comparison of several halocarbons at low evaporating temperatures, supported by a check against the Carnot limit and by a comparison with an experimental COP.

V. Conclusion

This review examined published work on halocarbon refrigerants in vapour compression refrigeration systems. The literature indicates that the COP of the cycle depends on the refrigerant, the evaporating and condensing conditions, and the degrees of superheat and subcooling, that R-152a is a promising replacement for R-134a with a COP that is close to or somewhat higher, that subcooling consistently improves performance, and that the compressor is a principal source of irreversibility. Dynamic modelling and optimising control can lower the operating cost of refrigeration plants. Future research should compare the refrigerants over a wide range of evaporating temperatures with property data from a single consistent source, check every result against the Carnot limit, compare the theoretical COP with that of an experimental unit, and combine refrigerant selection with the optimisation of operating conditions and control. Addressing these gaps will support the selection of efficient and environmentally acceptable refrigerants for vapour compression systems.

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