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Sustainable Innovations in Vapor Compression Systems: A Review of Heat Recovery and Environmental Performance

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Abstract

Vapor-compression refrigeration systems are widely used in residential, commercial, and industrial sectors, contributing significantly to global energy consumption and greenhouse gas emissions. This review explores sustainable innovations in vapor-compression systems, focusing on waste-heat recovery techniques and their impact on environmental performance. Key advancements include the integration of heat exchangers, ejector systems, and hybrid configurations that enhance energy efficiency while reducing refrigerant load and emissions. Auxiliary heat-exchanger integration, ejector-based refrigeration systems, and hybrid system topologies that efficiently utilize waste heat generated during system operation are among the major technological developments covered. These methods have been demonstrated to maintain or increase cooling capacity while lowering refrigerant charge, improving the coefficient of performance, and reducing compressor power consumption. Furthermore, this review emphasizes the growing use of low-GWP, environmentally friendly refrigerants, as well as sophisticated control schemes and advanced system-optimization methods. Taken as a whole, these developments facilitate the shift toward environmentally friendly, energy-efficient, and sustainable cooling solutions, providing viable approaches to reduce emissions and meet future cooling demands. These methods have also been shown to reduce refrigerant charge and related emissions, increase overall energy efficiency, and improve the coefficient of performance. The review further highlights the increasing use of eco-friendly refrigerants and sophisticated control techniques designed to reduce energy losses and maximize system performance. The study also addresses emerging eco-friendly refrigerants and control strategies. Overall, the adoption of sustainable technologies presents a pathway toward environmentally responsible and energy-efficient cooling solutions.

Keywords: Vapor compression refrigeration, waste heat recovery, sustainable cooling, energy efficiency, eco-friendly refrigerants, environmental performance

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INTRODUCTION

Vapor-compression refrigeration machines are commonly employed in industrial applications such as food storage, processing, manufacturing, and healthcare. A household refrigeration unit, commonly known as a refrigerator, typically has a tightly sealed inner chamber. To achieve cooling within this enclosed space, it transfers heat from the interior to the surrounding environment during operation [1–3]. In a conventional household refrigerator equipped with an air-cooled condenser, the heat absorbed from the refrigerated space is released directly into the ambient air through natural or forced convection [4]. Alternatively, in systems employing a water-cooled condenser, the extracted heat is transferred to potable or cooling water, which carries the thermal energy away from the system. The choice between air-cooled and water-cooled condenser configurations depends on factors such as efficiency requirements, environmental conditions, and the availability of cooling resources [5–7]. Overall, vapor-compression refrigeration systems play a crucial role in modern industrial and domestic environments by ensuring effective temperature control, energy efficiency, and reliable performance across a wide range of applications [8–10].

In a typical household refrigerator equipped with an air-cooled condenser, heat is rejected directly to the ambient air. In a system with a water-cooled condenser, the heat is transferred to potable water. Today, with a few exceptions, a vast majority of household refrigerators operate with tetrafluoroethane (HFC-134a) refrigerant. Refrigeration machines, used for food preservation, heating, and air conditioning in commercial, household, and industrial applications, are designed to extract heat from low-temperature regions and reject it to higher-temperature surroundings [11–13]. Potable water passing through an ice-maker unit and many simple air-cooling configurations are capable of dissipating heat directly into the ambient air. In a rapidly developing nation such as India, most vapor-compression-based cooling, air-conditioning, and low-temperature transport systems continue to operate with hydrofluorocarbon refrigerants because of their favorable thermophysical properties and affordability [14]. One component that can be incorporated into vapor-compression refrigeration systems is a gravity-assisted vertical flash-tank separator. The refrigerant liquid flow originates from a two-phase liquid–vapor mixture in the vapor-injection vertical flash tank, which separates the phases and supplies only liquid refrigerant to the evaporator while providing cold vapor for injection into the compressor. With the use of the flash-tank vapor-injection (FTVI) technique, the thermal stress generated during compression and the electrical power required by the compressor are reduced. After injection, the refrigerant is directed to the next expansion device and subsequently to the evaporator in the following cycle stage. Consequently, under low-temperature operating conditions, the compressor discharge temperature decreases, resulting in an increase in system capacity. Excess heat generated during various industrial and mechanical processes is often released into the surroundings but remains available for recovery and beneficial use. Detailed evaluations of thermal losses in refrigeration and air-conditioning systems indicate that approximately 3–5 kW of waste heat may be discharged to the surroundings for every kilowatt-hour of electrical energy consumed by the system. Recovering this energy can help reduce overall energy costs [15]. However, in many refrigeration and air-conditioning (RAC) system designs, the potential for energy recovery has not been adequately considered.

LITERATURE REVIEW

Vapor-Compression Device and Its Components

Various research studies on heat-recovery applications in refrigeration systems have been conducted. These studies also provide an overview of adaptation measures that can be implemented to reduce energy consumption and improve the efficiency of condensation-cooling applications. With a focus on condensation heat-recovery methods, this review provides a comprehensive summary of recent research advancements related to heat-reuse applications in vapor-compression refrigeration systems.

Several adaptation strategies are discussed in detail, including the integration of auxiliary heat exchangers, ejector-based refrigeration systems, and hybrid system designs. These approaches enable the efficient utilization of waste heat generated during system operation, thereby reducing energy consumption, increasing the coefficient of performance, and decreasing compressor power requirements while maintaining or enhancing cooling capacity [16].

The review also highlights how advanced control strategies, intelligent system-optimization techniques, low-global-warming-potential (GWP), and environmentally friendly refrigerants can further improve energy efficiency and minimize environmental impact. The integration of eco-friendly refrigerants, heat-recovery technologies, and optimal control schemes has been shown to significantly reduce refrigerant charge and emissions while improving the overall efficiency of condensation-cooling applications. Overall, this review highlights the potential of sustainable heat-recovery technologies as a practical pathway toward future-ready, environmentally responsible, and energy-efficient refrigeration and cooling systems [17].

A study was conducted on heat recovery from the condenser of a vapor-compression refrigeration system using cooking and water-heating units installed between the condenser and compressor sections. The availability of these units provides an opportunity to recover waste heat from the discharged refrigerant vapor and utilize it for cooking and water-heating purposes. The performance of the system was evaluated under different operating conditions. The potential for heat recovery was assessed by analyzing the operating performance of the cooking and heating units while varying the operating time of the refrigeration system [18].

One study modified a vapor-compression refrigeration cycle using R22 and potential ozone-safe alternative refrigerants (R404A and R507). The research concluded that R22 exhibited the lowest pressure ratio and discharge temperature, followed by R507. The average discharge temperatures of R507 and R404A were 4.2% and 15.3% higher than that of R22, respectively. R507 exhibited a higher cooling capacity than R22, whereas R404A exhibited a lower cooling capacity. The study found that R507 can be effectively used as a retrofit refrigerant in existing air-conditioning systems originally designed for R22 during the HCFC phase-down period [19–21].

A conceptual study was conducted using waste heat from a vapor-compression refrigeration system. The recovered thermal energy can be utilized to operate low-grade refrigeration devices, such as ejectors. Based on the evaluation of several configurations, a combined-cycle system was proposed. This technology effectively recovers waste heat and improves the overall efficiency of vapor-compression refrigeration systems [22–24].

Another study investigated modifications aimed at optimizing the refrigerant injection mass-flow rate. The optimization analysis concluded that an injection rate of 5.9 kg/s resulted in superior performance based on exergy analysis. The optimum mass-flow rate of the injected refrigerant was found to be relatively insensitive to variations in ambient conditions and the temperature of chilled water entering the evaporator [25].

A study employed a desuperheater heat exchanger to recover waste heat from refrigeration systems. High-capacity refrigeration applications can generate substantial amounts of low-grade waste heat. To recover this thermal energy, a heat exchanger is installed between the compressor and condenser. The feasibility of the system was evaluated under various operating conditions, considering the effects of heat recovery on overall system performance and efficiency. Experimental parametric results for several environmentally friendly refrigerants were reported. The study found that heat recovery could improve the overall coefficient of performance (COP) of the system without adversely affecting its cooling capacity. Furthermore, an increase in cooling capacity enhanced the availability of low-grade waste heat for recovery [26].

Another study utilized solar energy as the heat source for a vapor-absorption refrigeration system. Experimental results demonstrated the feasibility of a solar-powered refrigeration system. Solar water-heating systems can provide the thermal energy required to produce cooling. During summer months, when solar radiation is abundant and domestic hot-water demand is low, solar thermal energy can be effectively utilized for refrigeration purposes [27].

Another study investigated the use of waste heat from a gas engine or turbine to power an absorption refrigeration system. Utilizing waste heat from a gas engine significantly improved the performance of the integrated cooling system.

According to one study, steam turbines used in sugar mills discharge substantial amounts of thermal energy. This waste heat can be utilized to drive a vapor-absorption refrigeration system for cooling applications. The study demonstrated the economic feasibility of using waste heat to operate a lithium bromide–water absorption refrigeration system. The objective was to develop a conceptual lithium bromide absorption cooling system utilizing residual heat from the steam-turbine exhaust of a sugar mill.

RESULT AND DISCUSSION

After reviewing the literature on vapor-compression refrigeration systems, significant insights into their components and structure were gained. The major components of a vapor-compression refrigeration system are the compressor, condenser, expansion valve, and evaporator. According to the literature, the compressor, which is the primary component of the system, increases the refrigerant's temperature and pressure, with rotary and reciprocating compressors being the most common types. Research indicates that system efficiency can be significantly improved through compressor optimization.

The condenser's ability to reject heat is critical, and the literature reveals that materials such as copper and aluminum are widely used because of their high thermal conductivity. System stability and refrigerant flow are influenced by expansion valves, which are predominantly thermostatic or electronic. Evaporators are heat-absorbing components that are available in various designs depending on the application, with shell-and-tube and panel-type configurations being among the most common.

Research also emphasizes the widespread use of copper and aluminum to improve thermal conductivity and heat-transfer efficiency. The condenser plays a critical role in dissipating heat from the refrigerant to the surrounding environment. System stability and refrigerant-flow management are greatly affected by expansion valves; thermostatic and electronic expansion valves are the most commonly used types because of their accuracy and versatility. Evaporators are heat-absorbing components available in a variety of designs, such as shell-and-tube and panel-type configurations, depending on application requirements.

Interest in renewable and environmentally friendly refrigerants continues to grow, and recent developments in vapor-compression technology highlight improvements in energy efficiency and reductions in environmental impact. Recent innovations have focused on increasing energy efficiency while reducing environmental impact, and research on renewable refrigerants has become increasingly common.

CONCLUSION

A literature review of vapor-compression refrigeration systems and their components revealed important developments in system configuration, performance, and operational efficiency. Vapor-compression systems, which are widely used in refrigeration and air-conditioning applications, operate by compressing refrigerants to facilitate heat transfer. The performance of a system primarily depends on its key components, including the compressor, condenser, evaporator, and expansion valve. Several studies have identified the need to improve these components to enhance energy efficiency, reduce environmental impact, and improve system reliability.

Moreover, recent innovations in refrigerants and compressor technologies, including variable-speed compressors and microchannel heat exchangers, have contributed to improved overall system performance. However, challenges such as refrigerant leakage and the growing demand for environmentally friendly refrigerants continue to drive ongoing research. As engineering technology advances, further studies and optimization of these components will contribute to the development of more efficient, reliable, and environmentally sustainable vapor-compression refrigeration systems.

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