A Review of Multistage Vapor Absorption Refrigeration System Under Different Heat Sources

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Abstract - This review paper systematically analyzes the state-of-the-art developments, innovations, and applications of multistage vapour absorption refrigeration systems, emphasizing their adaptability to various heat sources. The manuscript navigates through the fundamental principles of vapor absorption refrigeration, highlighting the advantages and drawbacks of single-stage systems. It then delves into the intricacies of multistage systems and their potential to enhance performance and efficiency. Various configurations are explored, offering insights into the key factors influencing system performance.

The core of the review revolves around the compatibility of multistage vapor absorption refrigeration systems with a diverse range of heat sources, including waste heat, solar energy, geothermal sources, and industrial processes.

Furthermore, this review paper addresses the challenges, limitations, and future prospects of multistage vapor absorption refrigeration systems, paving the way for an informed discussion on the advancement of sustainable cooling technologies.

Key Words: Gas energy sources, VARS, VCRS, Absorption cooling system.

1. INTRODUCTION

The demand for efficient and sustainable cooling technologies has become increasingly paramount in the face of escalating global energy consumption and environmental concerns [1,2]. Among the myriad of cooling systems, vapor absorption refrigeration has emerged as a promising alternative, offering advantages in terms of energy efficiency and reduced environmental impact. This review paper endeavors to provide a comprehensive exploration of multistage vapor absorption refrigeration systems, with a particular focus on their performance under diverse heat sources [3,4].

The journey into the world of refrigeration begins with an examination of the foundational principles of vapor absorption, emphasizing the advantages and limitations of single-stage systems[5]. As the discussion unfolds, the spotlight shifts towards the intricacies of multistage vapor absorption refrigeration, unraveling the potential improvements in efficiency and performance that these systems can offer. This exploration encompasses various configurations and working fluids, shedding light on the nuanced factors influencing their operation [6].

A pivotal aspect of this review centers on the adaptability of multistage vapor absorption refrigeration systems to different heat sources. The utilization of waste heat, solar energy, geothermal sources, and industrial processes as primary energy inputs provides a comprehensive view of the versatility of these systems [7]. Real-world case studies drawn from diverse sectors serve to underscore the practical applications and economic viability of multistage vapor absorption refrigeration [8].

In addition to celebrating the achievements and advancements in the field, this review also confronts the challenges and limitations inherent in multistage vapor absorption refrigeration systems. By addressing these hurdles head-on, we pave the way for a nuanced discussion on potential solutions and future avenues for research and development [9].

As we embark on this journey through the multifaceted landscape of multistage vapor absorption refrigeration, this review aims to not only consolidate existing knowledge but also to inspire further inquiry and innovation in the quest for efficient and sustainable cooling technologies. By fostering a deeper understanding of the intricate interplay between system design, heat sources, and environmental impact, we contribute to the collective endeavor to reshape the future of refrigeration towards a more sustainable and energy-efficient paradigm.

2. System Description

2.1 Foundational Principles of Vapor Absorption Refrigeration:

The exploration of multistage vapor absorption refrigeration systems necessitates a thorough understanding of the foundational principles of vapor absorption technology. This section delves into the core principles of single-stage vapor absorption refrigeration, examining its advantages and limitations. Single-stage systems have laid the groundwork for advancements in the field, providing a basis for the subsequent evolution toward more sophisticated multistage configurations.

The single effect Vapour absorption cycle using lithium bromide-water as working fluid is shown in Fig. 1. In this system, the week or diluted solution of LiBr-H_2O mixture in the absorber at state 1 is pumped to the generator via a preheater (PH). In preheater the solution is heated before entering the generator by using the heat rejected from the strong solution leaving the generator at state 10. The solution after getting heat in the generator releases pure refrigerant that flows to the condenser. The remaining strong solution flows down to the absorber through the preheater. This improves COP of the system. On the other hand, the refrigerant vapour passing through the condenser condenses after rejecting heat to the sink. The condensate refrigerant is allowed to pass through the Precooler for sub cooling. The sub cooled condensate refrigerant is throttled through TV1 to reduce it to the evaporator pressure and temperature. Evaporator vaporize due to cooling load, there by producing cooling effect. The refrigerant vapour leaving the evaporator is then passed through the Precooler for cooling the condensate liquid refrigerant coming from the condenser which is at last taken to the absorber where it gets absorbed in the solution coming from the generator. Thus, the cycle gets completed [10].

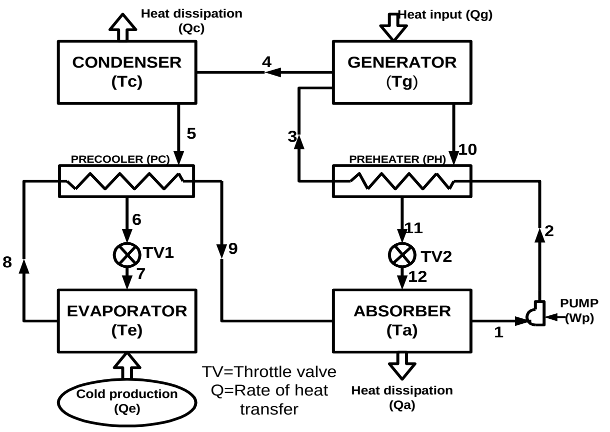

Fig 1 Schematic Diagram of Simple Vapor Absorption Refrigeration System.

Table 1 shows a comparison between both compression and absorption refrigeration systems. A Single effect absorption system so far developed has coefficient of performance between 0.7 to 0.86.

Table 1: Comparison between Compression and Absorption System

Compression system	Absorption system
Work is used to drive the system	Heat energy is used to drive the system
Compressor is used to create pressure difference	Compressor is replaced by absorber, generator and a liquid pump to create pressure difference
High COP	Low COP
Performance is very sensitive to evaporator temperatures	Performance is not very sensitive to evaporator temperatures
System COP reduces considerably at part load	COP does not reduce significantly with load
Liquid at the exit of evaporator may damage the compressor	Presence of liquid at evaporator exit is not a serious problem
Performance is sensitive to evaporator superheat	Evaporator superheat is not a very important thing
Many moving parts exits	Very few moving parts
Regular maintenance required	Less maintenance required
Higher noise and vibration	Less noise and vibration
Small systems are compact and large systems are bulky	Small systems are bulky and large systems are compact
Economic when electricity is available	Economic where low-cost fuels or waste heat is available

Both the VARS and VCRS systems accomplish the removal of heat through the evaporation of refrigerant in the evaporator at low pressure and the rejection of heat through condensation of the refrigerant in the condenser at a higher pressure. Therefore, both systems consist of evaporator, condenser and expansion valve. The main constructional difference is that a compression cycle uses a mechanical compressor to create the pressure level, whereas, in the absorption cycle, the compressor is replaced by absorber/pump/solution heat exchanger/generator assembly, which creates the desired pressure level. This assembly is sometimes called as thermal compressor.

2.2 Unraveling the Intricacies of Multistage Vapor Absorption:

Building upon the fundamentals, our focus transitions to the intricacies of multistage vapor absorption refrigeration systems. This section systematically dissects various configurations in multistage setups. Through a comprehensive analysis, we unveil the potential improvements in efficiency and performance that multistage systems offer, propelling them to the forefront of sustainable cooling technologies. Multistage vapor absorption refrigeration systems introduce a level of complexity that extends beyond their single-stage counterparts. This section initiates a detailed exploration of the diverse configurations employed in multistage setups. These configurations include series arrangements, parallel arrangements, and hybrid configurations that integrate both series and parallel elements. The examination of these configurations illuminates the nuanced engineering choices made to optimize system performance under varying conditions.

The schematic diagram of a double effect vapour absorption system is shown in Fig 2. It consists of two generators. The main generator (G) and the condenser (C3) are at pressure P3 (=Pg = Pc3) while the main condenser (C) and the generator (G2) are at pressure P2 (=Pc = Pg2). Heat is provided to the main generator and heat rejected is from the main condenser. The evaporator and the absorber work at low pressure P1 (=Pe = Pa). In this system, the weak solution at state 1 is pumped from the absorber to the main generator (G) through two heat ex- changers (i.e. PH1 and PH2). The solution in the main generator is heated at relatively high temperature to boil out the refrigerant vapour from the solution. The primary vapour, from G goes to the condenser C3. The heat of condensation in C3 is used to heat the solution in the generator G2. The strong solution leaving the generator G at state 8 flows to the generator G2 through PH2 which is cooled by the weak solution. The vapour released in the generator G2 and the refrigerant-condensate from the condenser C3 flow into the main condenser. Thus the total amount of liquid refrigerant leaving the main condenser will be the sum of refrigerant coming from the generators G and G2. The refrigerant liquid from this condenser flows to the evaporator through a throttle valve. After extracting heat from the medium to be cooled, the refrigerant evaporates and then passes to the absorber, and gets absorbed by the strong solution coming from the generator G2 through a preheater PH1. The resulting weak solution in the absorber is then pumped to the main generator and the cycle completes.

Fig.3. shows schematic diagram of triple effect vapour absorption system. It consists of three generators and three condensers. The main generator G and the condenser C4 are at

pressure P4 (=Pg = Pc4), the condenser C3 and the generator G3 are at pressure P3 (=Pg3 = Pc3) and the condenser C and the generator G2 are at pressure P2 (=Pg2 = Pc), while the evaporator and the absorber are at low pressure P1 (=Pe = Pa). In this system, the weak solution at state 1 is pumped from the absorber to the main generator (G) through three preheaters (i.e. PH1, PH2 and PH3). The main generator is heated to boil out the refrigerant vapour from the solution. The vapour released from G, enters the condenser (C4) which condenses and releases heat that is utilized by the generator G3. The strong solution leaving the generator G at state 8 flows into the generator G3 through the preheater PH3, where it is cooled by the weak solution. In the generator G3, some more vapour is released that enters the condenser (C3), from which the heat of condensation is utilized by the generator G2. The strong solution, now leaving the generator G3 at state 8c, flows to the generator G2 through PH2 where it is further cooled by the weak solution coming from the preheater PH1. In the generator G2, still more refrigerant is released that enters the main condenser C from which heat is released to the sink. Thus, the total refrigerant entering the main condenser in the triple effect cycle will be the sum of the refrigerants from all the generators. The liquid refrigerant from the condenser (C) flows into the evaporator through a throttle valve, which vaporizes after taking heat from the space to be cooled. It then enters the absorber, and gets absorbed by the strongest solution coming from the generator G3 via the preheater PH1, thus completing the cycle, this is also explained by the authors [11].

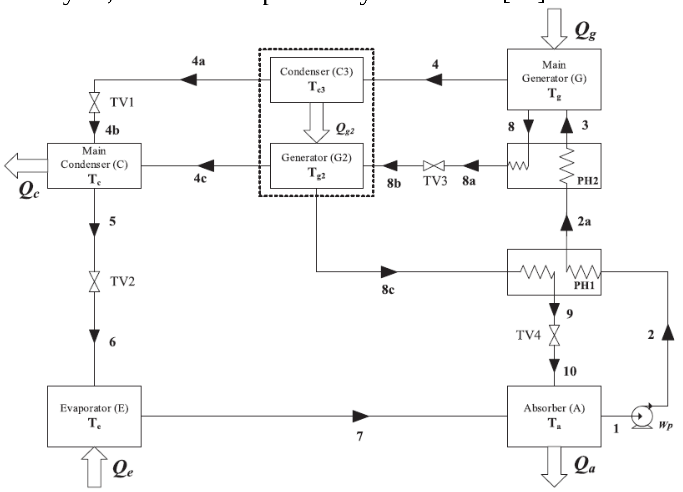

Fig 2 Schematic Diagram of Double Effect Vapour Absorption Refrigeration System.

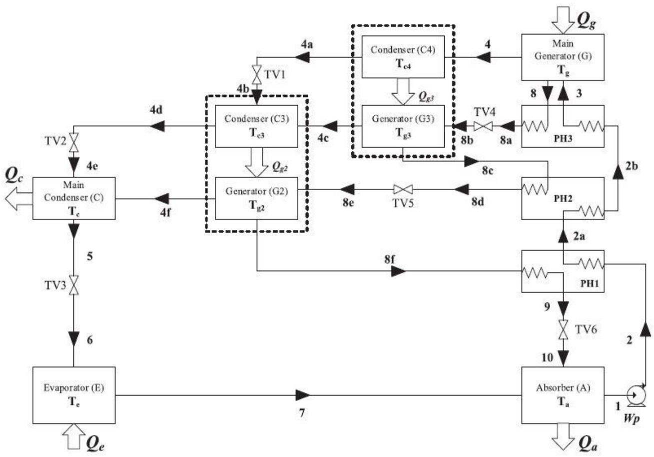

Fig 3 Schematic Diagram of Triple Effect Vapour Absorption Refrigeration System.

2.3. Adaptability to Diverse Heat Sources:

A critical aspect of this review centers on the adaptability of multistage vapor absorption refrigeration systems to a spectrum of heat sources. From waste heat and solar energy to geothermal sources and industrial processes, each heat source is explored for its unique application in enhancing the versatility of these systems. Real-world case studies drawn from diverse sectors serve as compelling evidence, underscoring the practical applications and economic viability of multistage vapor absorption refrigeration under various heat sources [12].

2.3.1. Geothermal heat source

The slow decay of radioactive particles in the earth's core, a process that happens in all rocks, produces geothermal energy. Geothermal energy is heat within the earth. The word geothermal comes from the Greek words geo (earth) and therme (heat). Geothermal energy is a renewable energy source because heat is continuously produced inside the earth. People use geothermal heat for bathing, to heat buildings, and to generate electricity. Scientists have discovered that the temperature of the earth's inner core is about 10,800 degrees Fahrenheit (°F), which is as hot as the surface of the sun. Temperatures in the mantle range from about 392°F at the upper boundary with the earth's crust to approximately 7,230°F at the mantle-core boundary. The earth's crust is broken into pieces called tectonic plates. Magma comes close to the earth's surface near the edges of these plates, which is where many volcanoes occur. The lava that erupts from volcanoes is partly magma. Rocks and water absorb heat from magma deep underground. The rocks and water found deeper underground have the highest temperatures [13].

2.3.2. Solar heat

The sun has produced energy for billions of years and is the ultimate source for all of the energy sources and fuels that we use today. People have used the sun's rays (solar radiation) for thousands of years for warmth and to dry meat, fruit, and grains. Over time, people developed technologies to collect solar energy for heat and to convert it into electricity [14].

2.3.3. Biomass heat

Biomass is renewable organic material that comes from plants and animals. Biomass was the largest source of total annual U.S. energy consumption until the mid-1800s [15].
Biomass continues to be an important fuel in many countries, especially for cooking and heating in developing countries. The use of biomass fuels for transportation and for electricity generation is increasing in many developed countries as a means of avoiding carbon dioxide emissions from fossil fuel use [16]. In 2020, biomass provided nearly 5 quadrillion British thermal units (Btu) and about 5% of total primary energy use in the United States. Biomass contains stored chemical energy from the sun. Plants produce biomass through photosynthesis. Biomass can be burned directly for heat or converted to renewable liquid and gaseous fuels through various processes.

Biomass sources for energy include:
• Wood and wood processing wastes—firewood, wood pellets, and wood chips, lumber and furniture mill sawdust and waste, and black liquor from pulp and paper mills
• Agricultural crops and waste materials—corn, soybeans, sugar cane, switch grass, woody plants, and algae, and crop and food processing residues
• Biogenic materials in municipal solid waste-paper, cotton, and wool products, and food, yard, and wood wastes

2.3.4. Waste heat

It is the heat that produced by a machine or other processes that produces energy, as a by-product of doing work. All such processes give off some waste heat as a fundamental result of laws of thermodynamics. Waste heat has lower utility than the original energy source. Sources of waste heat includes all manner of human activities, natural systems, and all organisms for example an IC engine generates high temperature exhaust gases etc [17].

2.3.5. LPG and CNG

In unveiling the potential of LPG (Liquefied Petroleum Gas) and CNG (Compressed Natural Gas) as energy sources for vapor absorption refrigeration systems, it is imperative to explore the distinctive attributes that set these fuels apart. LPG, a versatile hydrocarbon mixture primarily composed of propane and butane, exhibits a unique liquid state at moderate pressures, allowing for efficient storage and transportation. On the other hand, CNG, primarily composed of methane, is stored in a gaseous state under high pressure, providing a distinct set of characteristics [18] .

The calorific value of LPG and CNG, a key indicator of their energy content, contributes significantly to their appeal as alternative energy sources. LPG, with its higher energy density in the liquid state, facilitates prolonged energy supply, making it suitable for applications demanding extended operational periods. Conversely, CNG, although stored in a gaseous form, offers a cleaner combustion process and is known for its lower carbon content, aligning with contemporary environmental considerations.

Beyond their energy content, the combustion characteristics of LPG and CNG play a pivotal role in the efficiency of vapor absorption refrigeration systems. LPG, known for its consistent combustion properties, ensures stable heat release during the absorption cycle. In contrast, the combustion of CNG, being more homogenous and complete, presents an advantage in terms of reduced emissions and a potentially higher efficiency yield.

Furthermore, the infrastructure for handling LPG and CNG varies, influencing their applicability in diverse settings. LPG, being easily transportable in liquid form, lends itself to centralized storage and distribution systems. CNG, with its gaseous nature, often requires specialized compression and dispensing facilities, influencing considerations of system design and implementation [19].

2.4. Confronting Challenges and Limitations:

Despite their promise, multistage vapor absorption refrigeration systems face challenges and limitations. This section critically addresses these hurdles, ranging from the complexities of system design to the impact of operating conditions on overall performance. By confronting these challenges head-on, we lay the foundation for a nuanced discussion on potential solutions and innovative approaches to overcome limitations, thus paving the way for further research and development.

2.4.1. System Design Complexities:

Multistage configurations inherently introduce complexities in system design. The interplay of multiple stages, diverse working fluids, and intricate heat exchange mechanisms requires meticulous engineering. This sub-section dissects the challenges associated with optimizing the design of multistage vapor absorption refrigeration systems. From the selection of appropriate working fluids to the configuration of heat exchangers and absorbers, each element demands careful consideration to achieve optimal performance.

2.4.2. Thermodynamic and Operational Challenges:
The intricacies of multistage systems extend to the thermodynamic and operational realm. Factors such as irreversibility, exergy losses, and the potential for internal heat exchange issues pose significant challenges. This portion scrutinizes the impact of these challenges on the overall efficiency and effectiveness of multistage setups. Additionally, the section explores the influence of varying operating conditions, such as temperature and pressure differentials, on the system's ability to maintain stable and efficient operation.

2.4.3. Size and Scale Considerations:
A notable limitation faced by multistage vapor absorption refrigeration systems lies in the often too large size of the cooling unit. This sub-section investigates the size and scale challenges associated with multistage configurations, exploring how these factors hinder commercial viability. By examining the spatial constraints and the impact on practical implementation, the paper provides a critical perspective on the obstacles faced in deploying multistage systems on a larger scale.

2.4.4. Low Coefficient of Performance (COP):
Another significant obstacle confronting multistage vapor absorption refrigeration systems is the challenge of achieving a sufficiently high Coefficient of Performance (COP). This section analyzes the factors contributing to the often lower COP in multistage systems compared to their single-stage counterparts. By identifying the bottlenecks in performance, researchers can develop targeted strategies to elevate the COP, making multistage systems more competitive with conventional refrigeration technologies.

2.5. Future aspects of development and Innovation:

Many of the studies do not provide specific details about the limitations or challenges faced during their experiments or analyses.
• Some studies lack comparisons between different types of absorption systems, making it difficult to determine which configurations are more efficient under specific conditions.
• Limited information is provided on the practical implementation of the findings in real-world applications, such as HVAC systems or industrial refrigeration.
• The economic aspects of absorption refrigeration systems are discussed in some studies, but a more comprehensive economic analysis, including payback periods and return on investment, is often missing.
• There is a lack of consideration for the scalability and adaptability of the proposed solutions to various cooling and heating demands.
• The studies do not explore the integration of renewable energy sources, such as solar or waste heat recovery, into absorption refrigeration systems, which could contribute to sustainability.
In conclusion, this comprehensive review serves as a roadmap for researchers, engineers, and policymakers, guiding them through the evolving landscape of multistage vapor absorption refrigeration. Through a synthesis of existing knowledge and a forward-looking perspective, it offers a valuable resource for those committed to advancing the frontiers of efficient and sustainable cooling technologies.

3. CONCLUSIONS

In conclusion, this comprehensive review has undertaken a systematic journey through the evolving landscape of multistage vapor absorption refrigeration systems (VARS), illuminating key developments, innovations, and applications that propel this technology into the forefront of sustainable cooling solutions. By navigating through fundamental principles, scrutinizing single-stage systems, and delving into the intricacies of multistage configurations, this manuscript has provided a thorough understanding of the nuanced factors influencing system performance.

The emphasis on the adaptability of multistage VARS to diverse heat sources underscores its potential to revolutionize the field of refrigeration. From harnessing waste heat to leveraging solar energy, geothermal sources, and industrial processes, multistage VARS emerges as a versatile and eco-friendly solution, capable of maximizing efficiency across various applications.

However, the exploration does not shy away from addressing the challenges and limitations inherent in multistage VARS. System design complexities, operational challenges, and size considerations have been critically examined, providing a transparent view of the obstacles that currently impede widespread commercial success. By confronting these challenges head-on, we lay the foundation for an informed discussion on potential solutions and innovative approaches.

As we conclude, this review paper serves not only as a consolidation of existing knowledge but as a catalyst for further inquiry and innovation. It provides a roadmap for researchers, engineers, and policymakers, guiding them toward the development of more efficient, adaptable, and environmentally conscious multistage vapor absorption refrigeration systems. By fostering a deeper understanding of the challenges, limitations, and future prospects, this review contributes to the collective effort to reshape the future of refrigeration in a more sustainable and energy-efficient direction.

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