

An Overview of Technologies for Small-Scale Vapor Compression Refrigeration

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Abstract - In recent years, there has been a lot of interest in the study and development of small-scale vapor compression-based refrigeration and climate conditioning systems because of their benefits over other active and passive technologies. This study discusses many applications and opportunities where small-scale vapor compression refrigeration systems are expected to play a significant role in technological advancement, such as personal cooling and electronic components. In order to characterize the current state of small-scale vapor compression refrigeration and provide an outlook for its future, this study summarizes the state of the art, including applications, component designs, operating conditions, experiments, published results, etc.

Keywords - miniature refrigeration; small-scale cooling; vapor compression

1. Introduction - In a variety of heating, ventilation, air conditioning, and refrigeration (HVAC&R) applications, including food and air conditioning, healthcare, industry, and energy, vapor compression refrigeration (VCR) systems have become essential. The International Institute of Refrigeration estimates that there were five billion units in use globally in 2019; by 2050, this figure is predicted to quadruple. 20% of the world's electricity consumption and 7.8% of its greenhouse gas emissions are caused by HVAC and R systems. An Examination of Small-Scale Vapor Compression Refrigeration Systems[1]. Heat pumps, water chillers, commercial, industrial, and mobile refrigeration and air conditioning systems are examples of typical VCR applications [2]. Passive cooling systems operate independently of an external power source [3]. On a smaller scale, they encompass [4] natural convection, heat pipes, vapor chambers, immersion methods, phase change materials, thermosyphons [5], and heat sinks [6]. In contrast, active cooling systems necessitate an external power source to function, including techniques such as forced convection, spray cooling, jet impingement, droplet electrowetting, thermoelectric methods, microchannels, absorption cooling, Stirling cycles, Joule–Thompson processes, and the main focus of this review: vapor compression systems [7]. Although passive systems do not use energy and can satisfy cooling needs for various applications, they typically have limited effectiveness, leading to the need for active systems when adequate cooling is required. Thus, it is essential to determine the appropriate technology—or combination of technologies—for each specific application. Compact systems have been developed as a result of the increasing need for improved heat removal methods for small-scale applications as well as the scientific and technological advancements of downsized VCR components, primarily compressors and heat exchangers [8,9]. Electronics, chips, lasers, portable air conditioning, personal cooling, body cooling

for athletes, medical applications, laboratory equipment, vehicles, farming, and other commercial and industrial applications are just a few of the cooling applications for which both individual parts and entire systems are currently on the market [10,11]. VCR systems are thought to be the most promising choice [12] because of their great energy efficiency, durability, and adequate performance under a variety of situations. This is because conventional passive technologies have insufficient cooling capacity for many applications [13].

In addition to this introduction, the review is divided into four sections. In Section 2, current small-scale refrigeration technologies—both passive and active—are presented, along with their principal uses, peculiarities, and working principles. Their similarities and differences are also discussed. The development of small-scale VCR systems is covered in Section 3.

A thorough analysis of earlier research is provided, beginning with studies on entire VCR systems and continuing with analyses and comparisons of the various possibilities for each of the four primary refrigerator components. In Section 4, trends and the potential applications of tiny refrigeration are examined, along with potential locations for these systems. Section 5 concludes with some closing thoughts.

2. Small-Scale Refrigeration Technologies

In order to deliver localized cooling at a specific location, space, system, or body that requires cooling, small-scale refrigeration refers to systems with a lesser cooling capacity than those offered by conventional units. There is a global trend toward the miniaturization of many devices in various fields, including mechanics, electronics, computing, and others. Many of these devices require refrigeration for thermal management and heat dissipation to ensure proper operation and durability, which makes compactness and light weight crucial. Additionally, its small size makes it suitable for usage in situations requiring portable cooling systems. Small-scale cooling systems have a wide range of uses, including automotive, medical, military, aerospace, and electronics cooling [9]. Different writers have different classifications for small-scale systems. Systems can be categorized based on size, or they can be categorized based on cooling capacity. Some studies define small systems in terms of cooling capacity as those with cooling power less than 1000 W, whereas others take into account even lower limits for specific applications, such as 500 W for electronics cooling [13].

2.1. The Use of Passive Technology

As stated before, electricity input is not necessary for passive cooling systems to function. The passive technologies that can be used for small-scale cooling are discussed in the paragraphs that follow. It is observed that many of these passive cooling techniques can also be used for bigger systems with more cooling power, even if their application to small-scale systems frequently results in downsizing. The simplest, least complicated, and least expensive passive cooling solution for thermal management is natural convection [14]. Nevertheless, different techniques are frequently employed because natural convection is insufficient to provide the required rates of heat removal.

Using heat sinks is an additional choice [15]. These heat exchangers, which transport heat from a device to a fluid medium—typically air—are machined in a variety of geometries from various materials.

Combinations of passive and active technologies are frequently utilized to achieve cooling targets because, despite the modest cooling demand of small-scale refrigeration, the heat dissipation rate of passive technologies is frequently insufficient. Because active technologies have the potential for higher cooling rates, they are frequently required.

2.2. Technologies in Use

The operational mechanism, primary uses, and other technical specifics of active technologies used in small-scale cooling are covered in this section. After describing a number of technologies, a more thorough explanation of mechanical VCR technology is given. It should be mentioned once more that the active systems that follow may also be applicable to full-scale systems in terms of cooling capacity and dimensions.

2.2.1. Forced Convection

Usually, forced convection is combined with another cooling technique, either passive or active. For instance, a heat pipe air-cooled system was assessed by Behi et al. [16].



Figure 1. Schematic of forced convection heat transfer over a hot plate.

2.2.2. Jet Impingement and Spray Cooling

Another active approach is spray cooling, which uses a nozzle to atomize a high-pressure liquid directly onto the heat source. When the droplets come into direct contact with the heated surface, some of them evaporate while others create a thin liquid coating on it. This process combines many heat transfer processes to achieve high rates of heat removal. Spray cooling uses a variety of fluids, including water, alcohols, fluorocarbons, refrigerants, and others, often in conjunction with additives like nanofluids to enhance their physical characteristics [17].

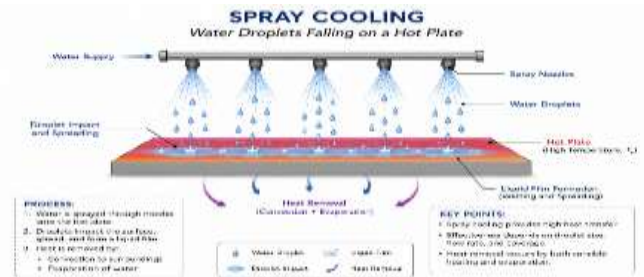


Figure 2. Schematic diagram of spray cooling

2.2.3. Cooling via Thermoelectric

By transforming power into a temperature differential, thermoelectric cooling is produced using the Peltier effect. Two thin ceramic wafers with a number of N-P-type semiconductor material connections between them make up a thermoelectric cooler. One of the ceramic plates cools while the other warms when a DC current is applied, creating a temperature differential between them. To improve heat transfer, two more heat sinks are typically installed on these ceramic plates, creating a thermoelectric module. The parts of a thermoelectric cooler are depicted in Figure 3.



Figure 3. Schematic of thermoelectric cooler.

Thermoelectric devices are utilized as sensors, for power generation, and for heating or cooling. Small refrigerators, air conditioning, electronics cooling, car refrigerators, picnic coolers, motorcycle helmet coolers, and various uses in medical, maritime, and aviation applications are examples of cooling applications. [18]

2.2.4. Cooling via Absorption

With the exception of having two working fluids and a thermochemical compressor rather of a mechanical one, absorption refrigeration systems are similar to VCR systems (Figure 4). The role of the refrigerant is identical to that of vapor compression:

cooling in the intended location, whereas the absorbent uses a pump to move the refrigerant gas from the evaporator to the generator. After entering the generator, heat from an external source is used to separate the working fluids; the absorbent returns to the absorber while the refrigerant flows to the condenser. Ammonia/water and water/lithium-bromide are the most often utilized working fluid couples in these systems.

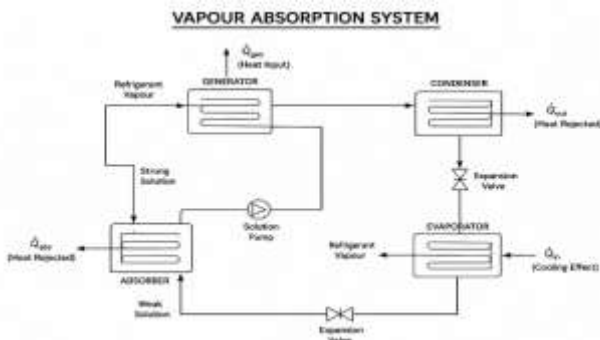


Figure 4. Schematic diagram of an absorption refrigeration system

Compared to VCR, absorption refrigeration systems are more intricate and require more parts. Additionally, they feature a high gas pressure ratio, a considerable heat input requirement for the generator, intermittent cooling rather than continuous cooling, and a limited cooling capacity because of slow compressor operation. [19]

2.2.5. VCR Systems

The compressor, condenser, evaporator, and expansion device are the four primary parts of a VCR refrigerator (Figure 5), along with a refrigerant that serves as the working fluid. Because of its low boiling point and high latent heat, the refrigerant can absorb and release significant amounts of heat during vaporization and condensation, respectively.

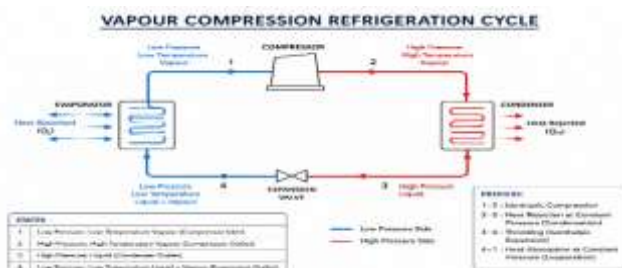


Figure 5. Schematic of a basic VCR cycle

The refrigerant goes through four different processes as it moves through the system. Superheated vapor at low temperature and pressure enters the compressor and exits as superheated vapor at high temperature and pressure. After entering the condenser, the refrigerant releases heat and cools to the point of condensation, producing high-pressure subcooled liquid at the exit. After passing through the expansion device, the refrigerant experiences an isenthalpic depressurization before arriving at the evaporator as a low-temperature mixture of liquid and vapor. The cycle is completed

and the refrigerant returns to its initial state in the evaporator after absorbing heat from the medium to be cooled and leaves as superheated vapor at low pressure and temperature.

Systems at lower temperatures can be cooled by them. This contrasts with other methods that only function at temperatures higher than ambient, such as forced convection cooling. Furthermore, VCR is the only method that can lower the junction temperature below ambient temperature when compared to spray cooling, jet impingement, and flow boiling in microchannels. Compared to other methods like thermoelectric cooling, VCR systems can achieve better COP [20]. Low mass flow rates allow for extended periods of high cooling capacity, and heat is moved away from its source [21].

3. Vapor Compression Refrigeration (VCR) Systems on a Small Scale

Because of their excellent performance and efficiency, VCR systems have been suggested for small-scale cooling. The primary factor driving their development is the fact that many of the passive and active technologies discussed in the preceding section frequently perform insufficiently to meet the cooling requirements of significant applications, such as computer system and electronic component cooling. Component miniaturization is a problem for small-scale VCR systems because the systems or equipment that require cooling are small and need tiny cooling units. Applicability to mobile or even portable systems, covering another significant area of current study, is made possible by miniaturization: Individual refrigeration

3.1. Applications of Small-Scale Vapor Compression

It might be a fascinating challenge to design and/or couple a micro refrigeration system for small-scale applications. Barbosa et al. [10] state that some crucial elements are (i) creating a compact, dependable, and efficient compressor; (ii) creating and enhancing appropriate evaporators; (iii) integrating the cooling system in a limited area; (iv) resolving packaging-related problems; and (v) keeping the system's overall cost competitive.

3.1.1. Cooling of Electronics

The desire for constant connectivity and instant access to information, as well as the ongoing advancements in technology, affordability, and accessibility, are all contributing factors to the growing demand for electronic devices in ever-expanding applications. According to Moore's law, the number of transistors that comprise these chips has been doubling roughly every 18 months for a number of years. But in recent years, this tendency has slowed down, and it is even thought to be coming to a stop as transistors get closer to the atomic scale and production costs keep rising. [22] A comparable study included a microchannel heat sink as an evaporator, a capillary tube, a microchannel condenser, and a variable speed compressor for R134a [23].

Aviation systems are another area where electronic component cooling is used. Electronic components in aeronautical applications can function at temperatures as high as 80–120 °C, in contrast to other systems. However, minimizing weight and size is crucial, leading to unusual designs. A cool plate that was created especially for use inside an avionics package was employed as an evaporator by Mancin et al. [24]. They were able to evaluate compression ratios between 1.54 and 3.75, piston displacements between 25 and 90%, COP values between 1.04 and 5.8, and cooling capacities between 37 and 374 W by using a fixed-speed linear compressor.

3.2. The Basic Vapor Compression Cycle Modifications

The compressor, condenser, expansion valve, and evaporator are the four parts of the fundamental vapor compression cycle, as was previously mentioned. To enhance system performance, however, other and more intricate cycle topologies including the inclusion of extra components are frequently suggested. Although they are more frequently found in large-scale systems, these changes to the basic cycle can be as straightforward as installing an intercooler or as complicated as using ejectors or cascade systems. They are also being investigated for small-scale systems.

Using ejector vapor compression, Chiriac and Chiriac [25] created a model of a small-scale refrigeration system. In order to reduce the size of electronics cooling system by substituting a small ejector for the compressor, their goal was to compare the thermal performance of this technology with the conventional mechanical VCR system. The ejector was discovered to be more compact than a conventional compressor. Nevertheless, in order to achieve the high-pressure flow, an electric boiler was required, which increased the size of the system. Furthermore, it was discovered that the ejector system's COP was 20 times lower than that of the mechanical vapor compression, significantly raising the inlet power need.

3.3. Modeling

Modeling is a useful tool for system design and optimization, especially considering that the proliferation of experimental prototypes has provided considerable opportunity for validation. Models predict component and system behavior ahead of manufacture, thereby providing guidance for improving existing designs, even if model results do not closely match experimental results. Types of models include mathematical, physical, numerical, dynamical, empirical, black box, etc.

3.4. Components

The four primary parts of a vapor compression cooling system—the compressor, condenser, evaporator, and expansion device—cause the refrigerant to go through a series of thermodynamic states that comprise the refrigeration cycle, regardless of the system's size. Because these four elements are crucial and essential, further research is required to innovate and remodel these systems, which will increase performance. There are several publications that concentrate on particular components, assess various designs, suggest changes, etc., and small-scale vapor compression systems are not an exception.

3.4.1. Compressors

The compressor, which is regarded as the central component of the refrigeration system, pressurizes the refrigerant that exits the evaporator as a vapor at low pressure and temperature, transforming it into a thermodynamic state of superheated vapor at high pressure and temperature. Although there are many types of compressors, rotary, reciprocating, and linear compressors are the most widely used in small-scale systems, according to reports in the literature. Additionally assessed are acoustic, diaphragm, centrifugal, and scroll compressors.

Because of its moving parts, which make it the component with the highest irreversibility, the compressor merits the greatest attention when it comes to downsizing. Furthermore, there is a strong relationship between volumetric efficiency, operating speed, and size reduction. Considerable attention must be paid to this connection as well as the coupling between the compression system and the drive mechanism [26].

Due to their advantages over traditional crank-drive reciprocating compressors, the use of linear compressors for refrigeration has been extensively researched in both small-scale and traditional applications, such as home refrigeration [27]. In order to enhance the design and, consequently, the performance of these compressors, detailed numerical models have been created and validated [28,29]. Additionally, experimental tests have been conducted [30] in which a constant-speed, oil-free linear compressor was utilized for electronics cooling in aeronautical applications, where the mass flow and cooling capacity were controlled by adjusting the piston stroke. Ribeiro introduced the same micro compressor [31].

The performance of small-scale refrigeration systems using various compressor types can be compared in the literature [88]. Two commercially available portable coolers with mini-rotary and reciprocating compressors were thermodynamically evaluated by these authors. In conclusion, it is evident that despite the difficulties associated with compressor miniaturization, a wide range of systems are currently available for small-scale applications; the choice will rely on the operating conditions or even the weight and dimension requirements for each application.

3.4.2. Condensers

The condenser transfers heat between the surrounding environment and the refrigerant at the compressor discharge (at high temperature and pressure). At its output, the refrigerant reaches a saturated or subcooled liquid state as it condenses while transferring heat to the surroundings, roughly at constant temperature and pressure. Although there are various designs for this device in large-scale refrigeration equipment, condensers are usually microchannel heat exchangers in the majority of small-scale systems.

In contrast to louvered fins [32], several designs have been suggested, such as the insertion of metal foams on the air side to improve heat transfer [33]. The working fluids, pressure drop, and optimization of these devices for single-phase and two-phase flow were the subjects of several articles [34]. Due to their ability to achieve extremely high heat transfer rates, microchannel heat exchangers have been studied and used in a wide range of applications, including the military,

bioengineering, medical, nuclear, and solar cells [35], as well as the cooling of computer components and information technologies, high power semiconductor devices, laser diode arrays, fuel cells, and the subject of this review: miniature VCR systems [36].

It is clear from the information provided that a variety of heat exchanger types can be used as condensers; however, microchannel condensers are the most popular for small-scale applications because of the three benefits mentioned above: (1) high heat transfer rates; (2) compactness; and (3) reduction in refrigerant mass. It is anticipated that as technology advances and becomes more widely used, research on these elements will continue.

34.3. Devices for Expansion

An essential part of the cooling process is the expansion device. It creates a low pressure and temperature two-phase flow by throttling the refrigerant into a low pressure by an isenthalpic expansion process after receiving it at the condenser outlet as a saturated or subcooled liquid at high pressure.

The most popular expansion devices used for these systems are needle valves [37,38] and capillary tubes, although micro-orifice [39] and miniature electronic expansion valves [40] have also been used. In the case of capillary tubes, more attention has been paid to determining their length under a previously selected fixed diameter. Some works simply evaluate different lengths and choose the one that shows the best results [13],

3.4.4. Evaporators

The evaporator is the cold-heat exchanger where the refrigerant removes the heating load. At the expansion device outlet, the refrigerant is in a liquid-vapor mixture, which evaporates at low temperature and pressure as it flows through the evaporator, promoting heat transfer between the area to be cooled and the refrigerant fluid. In small-scale refrigerators, this is undoubtedly the device for which more designs have been proposed and evaluated, as described next.

It's noteworthy that they employed two evaporators connected in series; this concept was then utilized to assess two evaporators arranged in parallel and series [41]. The findings show that the series system achieved a higher COP. Yuan et al. [40] created a single microchannel plate-fin evaporator to reduce the size and weight of the cooling system.

Zhou and Li [42] developed a simple, organized, and cost-effective tiny VCR system for the cooling of electronic components in the car industry using a basic porous media evaporator.

Higher values of these parameters typically result in poorer system performance. Some design considerations must be made in order to prevent these consequences. These include, but are not limited to, the appropriate choice of compressor type and capacity, the use of variable speed compressors, the appropriate sizing of heat exchangers, the implementation of a moisture removal strategy, advanced control strategies like the use of thermostatic expansion valves, and the appropriate selection of refrigerant.

4. Obstacles, Views, and Prospects for Small-Scale Refrigeration

A new phase in the development of vapor compression

refrigeration systems is represented by the downsizing of individual parts and entire systems. Miniaturization is primarily used to create wearable, portable, lighter, and more compact systems with great performance and efficiency. However, there are numerous design, development, and manufacturing obstacles that make scaling down these systems difficult. If not mass produced, component manufacturing may result in higher prices due to the need for complex procedures, highly precise technologies, and skilled workers.

Furthermore, new packing and assembly methods must be created. The fact that many of the parts employed in the systems described in Section 3 were produced or altered by the researchers themselves indicates the need for additional development.

The cooling of electronic components and personal cooling currently occupy the majority of research interest, despite the fact that small systems were first designed for military applications. These areas are also the focus of this paper. However, it is crucial to emphasize that these are not the only applications; there are several uses for small VCR technology, and there are still a lot of uncharted territory. Therefore, it is thought that this is a fruitful ground for future research, including the various applications that have developed over time, including those in fields like agriculture, medicine, and health that offer significant social advantages.

In general, efficient thermal management and heat dispersion are common requirements in many industrial fields. Here are a few instances:

- Food and pharmaceutical industries: these systems can be crucial to guaranteeing the safety and quality of food and pharmaceutical products, particularly those that need to be transported and stored at regulated temperatures.
- Automotive and aerospace industry: Due to weight and space constraints, micro solutions might be useful in the cooling of electronic systems on board cars and airplanes as well as in the thermal management of vital components.
- Medical sector: These systems may be required to guarantee the correct functioning and precision of portable or small-sized medical devices, such as portable diagnostic devices, medical imaging systems, or refrigeration equipment for biological samples. The following are some potential implementation restrictions for these systems: This is the industrial perspective for building micro-VCR systems in the upcoming years. Lastly, this research and information dissemination stage will greatly contribute to the development of new developers of these systems as well as the expansion and industrial positioning of current ones.

5. Concluding Thoughts

This review's goal was to provide an overview of the state-of-the-art in miniature vapor compression refrigeration, highlighting recent experimental and modeling research projects for both whole systems and individual parts while taking into account the various applications that have been suggested thus far. Additionally, an attempt was made to provide a summary of passive and active small-scale cooling solutions, highlighting the benefits of vapor compression over the others. The following is a list of the key findings from this review:

• The quantity of research articles on micro vapor compression refrigeration, which are mostly focused on cooling electronic components and personal cooling, has decreased during the last ten years. Alternative applications, however, are already being offered for sale in a number of industries, including food preservation, pharmaceutical, medical, and automotive. As a result, more investigation is required to confirm their viability for both current and potential uses, enabling broad commercialization.

• It may be inferred that a major obstacle to the extensive research and development of these systems has been the difficulties related to component downsizing. Due to limited commercial availability, many of the components utilized in the articles listed in this review were custom-built by researchers, which slowed technological advancement. However, given the current availability of both individual components and pre-assembled prototypes of miniature VCR systems in the market, it is expected that research will see a resurgence in the upcoming years.

• Finally, it is noted that miniature vapor compression refrigeration has not yet reached maturity because there are still a lot of unexplored areas, such as the assessment of low GWP refrigerants, the search for energy savings, advancements in energy efficiency, artificial intelligence, additive manufacturing, and integration with renewable energies. Some of these issues have been addressed for traditional refrigerators, but they now need to be further developed for use in smaller systems.

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