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Review

A Review of Small-Scale Vapor Compression Refrigeration Technologies

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Abstract: The study and development of miniature refrigeration and climate conditioning systems based on vapor compression for small-scale applications have received wide interest in recent years due to their advantages compared with other available technologies, both active and passive. This paper identifies different applications and areas of opportunity, including electronic components and personal cooling, where small-scale vapor compression refrigeration systems are anticipated to play a key role in technological development. This paper presents the current state of the art, including applications, component designs, operating conditions, experiments, published results, etc. to describe the current status of small-scale vapor compression refrigeration and illustrate a perspective for the future of this technology.

Keywords: compact systems; miniature refrigeration; small-scale cooling; vapor compression

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1. Introduction

Vapor compression refrigeration (VCR) systems have become a basic need in a wide range of heating, ventilation, air conditioning, and refrigeration (HVAC&R) applications in numerous areas ranging from food and air conditioning to health care, industry, and energy. According to estimates from the International Institute of Refrigeration, there were five billion units in operation worldwide in 2019, and this number is expected to double by 2050. HVAC&R systems are responsible for 20% of global electricity consumption and 7.8% of global greenhouse gas emissions [1]. Research on this topic is therefore critical for improving system efficiency and meeting the climate change mitigation targets established within the implementation of the Kigali Amendment to the Montreal Protocol [2].

Typical VCR applications include domestic/residential, commercial, industrial, and mobile refrigeration and air conditioning, as well as heat pumps, water chillers, and more [3]. In addition to these, small-scale refrigeration is receiving growing attention for low cooling capacity applications, both through active methods, such as vapor compression, as well as passive technologies.

Passive cooling systems do not require an external power source [4], and at a small scale include [5] natural convection, heat pipes, vapor chambers, immersion, phase change materials, as well as thermosyphons [6], and heat sinks [7]. By contrast, active cooling systems do require a power source to perform their function: forced convection, spray cooling, jet impingement, droplet electrowetting, thermoelectric, microchannels, absorption, Stirling, Joule–Thompson, and the focus of this review: vapor compression systems [8]. While passive systems do not consume energy and meet cooling requirements for many applications, they often offer limited performance, demanding the use of active systems for satisfactory cooling. It is therefore critical to identify the right technology (or combination of technologies) for each application.

The growing demand for better heat removal technologies for small-scale applications combined with the scientific and technological progress of miniaturized VCR components, mainly compressors and heat exchangers, has resulted in the development of compact systems [9,10]. Individual components as well as complete systems are already available in the market and used for different cooling applications, such as electronics, chips, lasers, portable air conditioning, personal cooling, body cooling for athletes, medical applications, laboratory equipment, vehicles, farming, and other commercial and industrial applications [11,12]. Due to their high energy efficiency, durability, and adequate performance on a wide range of conditions, VCR systems are considered the most promising option [13] due to the insufficient cooling capacity of conventional passive technologies for many applications [14].

Several studies have been conducted for both individual VCR components and systems to determine their behavior, evaluate their performance, improve the design, and expand their applicability through experiments and modeling. Other studies have directly compared the performance of small-scale passive and active technologies, showcasing the advantages of mini-vapor compression over other technologies. However, the importance of continued research lies in the need for increasing their applicability, since most of the current focus is on electronics and personal cooling at the expense of other potential uses. In addition, there is still a need for further basic research on important topics for small-scale VCR systems including the use of alternative refrigerants, as well as thermal and energetic improvements to the basic cycle.

Considering the importance of small-scale VCR systems, we aim to describe the current state of VCR systems for small-scale applications, focusing on their advantages and disadvantages over alternative active and passive technologies. This is necessary because a large amount of relevant information has become recently available, including novel component designs, different experimental setups for multiple applications, different operating conditions, and more. The aim of this study is to describe the current status of small-scale refrigeration by vapor compression and evaluate perspectives for future development. In this sense, compared to the review presented by Barbosa et al. [10], this document provides an update on the current state of the art of miniature refrigeration, specifically vapor compression. Among the main differences, other active and passive technologies stand out in publicizing the wide range of possible cooling technologies available and justifying the importance of vapor compression over the others. On the other hand, the different options available in terms of designs of the components of the vapor compression system, mainly compressors and heat exchangers, are shown. Finally, we address interesting aspects regarding the challenges, limitations, new applications, and future trends and perspectives in developing this type of system in the coming years.

This review is organized into four sections in addition to this introduction. Section 2 presents existing small-scale refrigeration technologies, both active and passive, their operating principle, particularities, and main applications, describing their similarities and contrasting their differences. Section 3 discusses developments on small-scale VCR systems. A comprehensive review of previous works is presented, starting with studies on complete VCR systems and continuing with investigations and comparisons of the different options for each of the four main refrigerator components. Section 4 discusses trends and the future role of miniaturized refrigeration, identifying opportunity areas where these systems could fit adequately. Finally, concluding remarks are presented in Section 5.

2. Small-Scale Refrigeration Technologies

Small-scale refrigeration refers to systems with lower cooling capacity than those provided by conventional units, and its purpose is providing localized cooling at a certain place, space, system, or body demanding cooling. Compactness and light weight are important because there is a global trend towards the miniaturization of numerous devices in different areas such as mechanics, electronics, computing, and others, and many of these devices demand refrigeration for thermal management and heat dissipation to ensure proper operation and durability. Furthermore, compactness allows its use in applications where portable cooling systems are needed. Applications of small-scale cooling systems are vast and range from automotive to medical, military to aerospace, and personal to electronics cooling [9].

Classifications for small-scale systems vary between authors. Some classify systems according to cooling capacity, while an alternative classification may be based on dimensions. In terms of cooling capacity, several studies define small systems as those with cooling power below 1000 W; however, some others consider even lower thresholds for particular applications, e.g., 500 W for electronics cooling [14]. Regarding the dimensions, Phelan et al. [15] consider that miniature systems are comprised of microscale (size in millimeters) and meso-scale systems (not exceeding 5 cm in any dimension), while Warren et al. [16] consider the meso-scale in the range of tenths of a millimeter to tenths of a meter. An additional classification is presented by Zhang et al. [5], where thermal management methods are divided into two categories: direct or indirect contact of the cooling fluid with the targets.

In this review, we define 1000 W cooling capacity as the threshold for small systems and classify systems as active and passive depending on whether they need input power to perform their function. We start with a brief description of passive technologies used in small-scale refrigeration and continue with a more detailed description of active technologies, with special focus on vapor compression.

2.1. Passive Technologies

As previously mentioned, passive cooling systems do not require power input to perform their function. The following paragraphs describe passive technologies with applicability to small-scale cooling. While application to small-scale systems often leads to miniaturization, it is noted that many of these passive cooling systems also have applicability for larger systems with higher cooling power.

Natural convection [17] is the simplest, easiest, and least expensive passive cooling technology for thermal management; however, sometimes it is not enough to reach the needed rates of heat removal, so other methods are used. Heat pipes [18] are another passive technology consisting of a closed tube containing a refrigerant that can evaporate and condense in different zones of the device as it absorbs and releases heat, thus enhancing heat transfer. Vapor chambers [19] work on the same principle and are therefore also known as planar heat pipes. Thermosyphons [20] operate by circulating a fluid through a loop, from hotter areas to colder areas, driven by gravity and differences in density between hot and cold regions.

Another option is the use of heat sinks [21]. These are heat exchangers machined in various geometries from different materials used to transfer heat from a device to a fluid medium, usually air. Immersion cooling [22] is an alternative technique where a single component or a complete system is immersed in a dielectric liquid used as the coolant. Finally, phase change materials [23] are substances capable of absorbing/releasing large amounts of (latent) heat during their melting or freezing.

Although the cooling demand of small-scale refrigeration is low, the heat dissipation rate of passive technologies is often insufficient, so combinations of passive and active technologies are often used to reach cooling targets. Active technologies are often necessary due to their potential for higher cooling rates.

2.2. Active Technologies

This section is dedicated to active technologies used in small-scale cooling, describing their operational mechanism, main applications, and other technical details. Several technologies are described, ending with a more complete description of mechanical VCR technology. It is again noted that the active systems described next may also have applicability to full-scale systems with respect to dimensions and cooling capacities.

2.2.1. Forced Convection

Forced convection is one of the most common active cooling technologies. In forced convection, fluid (gas or liquid) motion is generated by an external component (a fan or pump), thereby increasing heat transfer rate; the fluid can be in direct contact with the target although sometimes there is an intermediate heat sink to further increase heat transfer [24], as shown in Figure 1. Forced convection is typically used in combination with another cooling method, either passive or active. For example, Behi et al. [25] evaluated a heat pipe air-cooled system, while Afshari [26] tested a thermoelectric refrigerator (to be described later) cooled on both sides by forced convection. Many other papers can be found in the literature dedicated to improved thermal management and heat dissipation in numerous applications such as electronic devices, data centers, personal cooling, photovoltaic collectors, Li-ion batteries, etc. Forced convection to air can reach heat flux ranges between 800 and 16,000 W/m^2, and between 11,000 and 1×10^6 W/m^2 for liquid cooling [27].

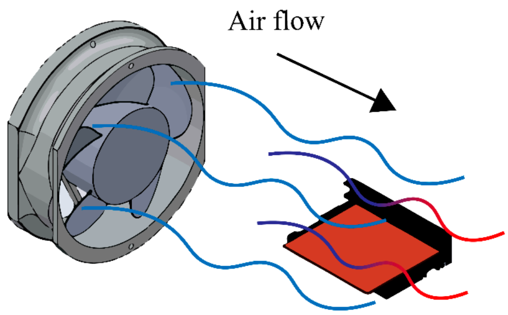

Figure 1. Schematic of forced convection heat transfer over a hot device.

2.2.2. Spray Cooling and Jet Impingement

Spray cooling is another active technology where a high-pressure liquid is atomized directly into the heat source through a nozzle, as can be seen in Figure 2. The droplets, upon coming in direct contact with the hot surface, evaporate and some others form a thin liquid film on it, combining several heat transfer mechanisms to obtain high heat removal rates. Fluids such as water, alcohols, fluorocarbons, refrigerants, and others are used in spray cooling, possibly in combination with additives to improve their physical properties, such as nanofluids [28].

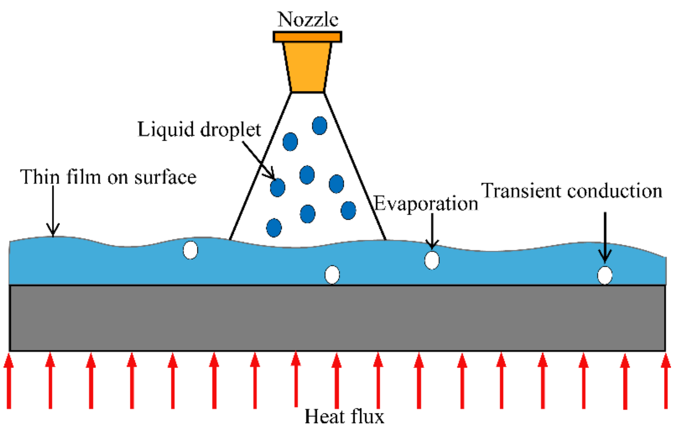

Figure 2. Schematic of spray cooling.

Similarly to spray cooling, jet impingement is also used for high heat flux removal, with the particularity that high-speed liquid jets instead of an atomized mix flows through the nozzle. Impinging jets can be classified according to three device surface scenarios: free, submerged, and confined jets, as shown in Figure 3. Free jet impingement occurs when the jet exiting the nozzle encounters ambient gas before commonly impacting the target surface, as opposed to when the nozzle is submerged in which the jet impacts a layer of the same fluid resting on the surface, and finally, confined jets occur when the jet remains limited by the target surface and nozzle plate. These cooling methods are generally used in diverse applications such as the steel industry, cooling of heat engines, nuclear power processes, cooling of gas turbine components, material processing, and the most representative small-scale application: electronic devices [29].

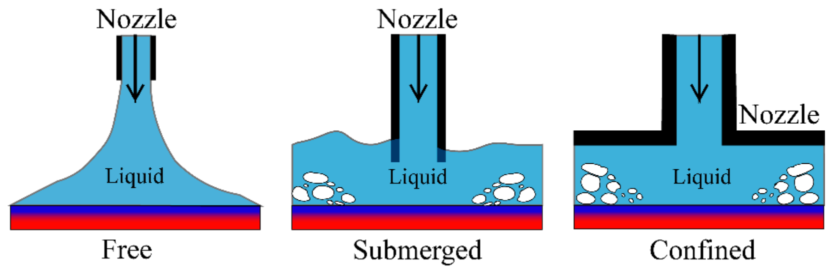

Figure 3. Schematic of jet impingement.

Several publications on spray and jet cooling strategies for high heat flux applications have demonstrated heat fluxes of the order of 10^6 W/m^2. Heat fluxes over 3×10^6 W/m^2 have been achieved through thermal inkjet-assisted spray cooling technique by controlling the timing and location of jet impingement on the hot surface [30]. In another study, the water jet impingement strategy was used to cool three surfaces with different wettability, reaching heat flux values over 3.5×10^6 W/m^2 for specific conditions [31].

An important aspect of spray and jet cooling techniques is that their effectiveness is very sensitive to changes in the position and geometry of the nozzle, the temperature and geometry of the impact surface, the characteristics of the fluid used, and the jet conditions.

2.2.3. Droplet Electrowetting

Droplet electrowetting controls coolant droplet location with a small potential difference in the presence of an electric field. Droplets are moved to hot spots to optimize cooling, as seen in Figure 4. The droplet rests on a solid surface coated with dielectric and hydrophobic material and moves as neighboring electrodes are activated; this configuration is called EWOD (Electro-Wetting on Dielectric), but other configurations are available.

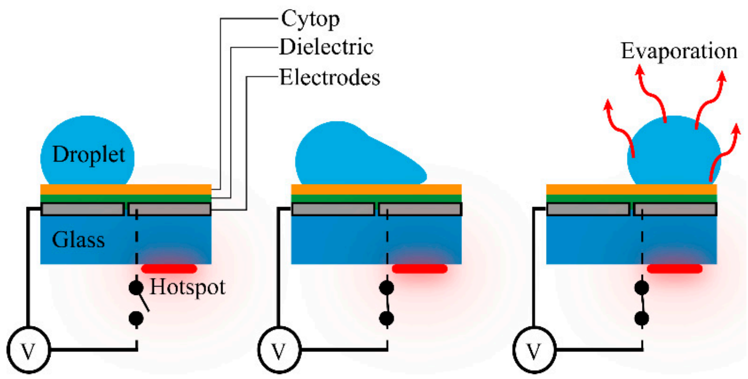

Figure 4. Schematic of electrowetting cooling.

Electrowetting has been used in various applications such as liquid lenses, electronic displays, lab-on-a-chip, as well as biomedical and biochemical systems, among others. A recent application considers the cooling of a hotspot through a hydrophobic and hydrophilic surface by using deionized water droplets. Among the most relevant results, it was found that the temperature of a hotspot on a hydrophilic surface could be reduced by more than 70 °C and maintained by continuous droplet addition under a heat flux of 5.35×10^4 W/m^2 [32]. More studies can be found in a recent review [33].

2.2.4. Thermoelectric Cooling

Thermoelectric cooling is generated based on the Peltier effect, by converting electricity into a temperature difference. A thermoelectric cooler consists of two thin ceramic wafers that enclose a series of N-P-type semiconductor material junctions between them. When a DC current is supplied, one of the ceramic plates cools down, while the other warms up, thus generating a temperature difference between them. Usually, two additional heat sinks are mounted on these ceramic plates to enhance heat transfer, forming a thermoelectric module. Figure 5 shows the components of a thermoelectric cooler.

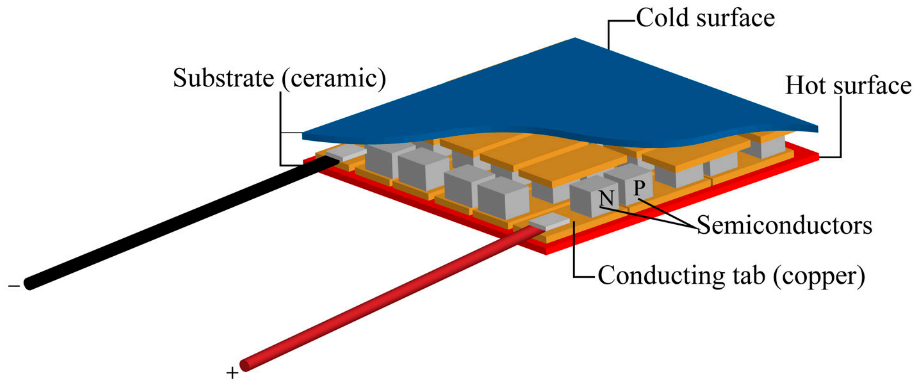

Figure 5. Schematic of thermoelectric cooler.

Thermoelectric devices are used for heating or cooling, power generation, and as sensors. Cooling applications include small refrigerators, electronics cooling, air conditioning, vehicle refrigerators, picnic coolers, motorcycle helmet coolers, and other uses in medical, marine, and aircraft applications [34].

An important issue with thermoelectric cooling is their low coefficient of performance, COP, limiting this technology to applications that need relatively low cooling capacity. Therefore, hybrid systems have been studied and the results show that a high heat flux of the order of 0.5–1 $\times$ 10^7 W/m^2 can be dissipated [35].

2.2.5. Microchannel Heat Sinks

A microchannel heat sink consists of a high-conductivity material block with multiple parallel channels where a refrigerant may flow. Sometimes these channels are machined on the back of the substrates of electronic components in integrated circuits [36]. The heat generated at the source is transferred to the coolant through forced convection, possibly with phase change. Figure 6 shows a schematic of a microchannel cooling system.

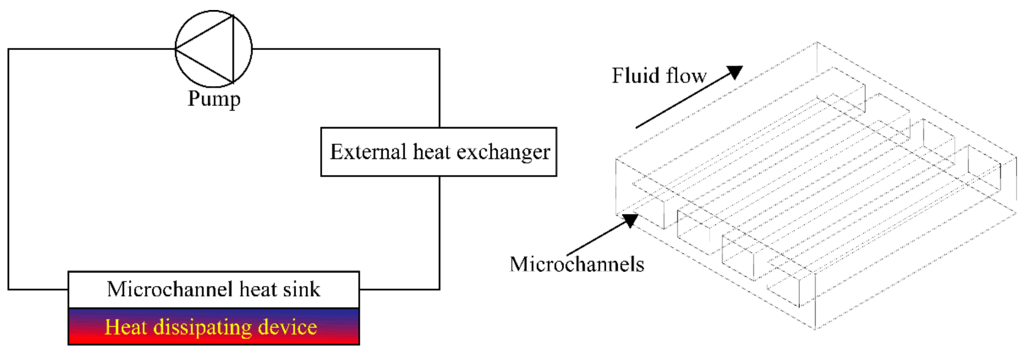

Figure 6. Schematic of a microchannel cooling system.

The application domain of this technology has expanded considerably due to their high heat dissipation fluxes, reaching levels above 10^7 W/m^2 [37]. Cooling applications include electronics, personal, air conditioning, and some industrial, medical, and aircraft applications, among others.

2.2.6. Absorption Cooling

Absorption refrigeration systems have similarity to VCR systems, except for their use of a thermochemical rather than mechanical compressor, in addition to using two working fluids (Figure 7). The refrigerant plays the same role as in vapor compression: cooling in the desired area, while the absorbent captures the refrigerant gas from the evaporator to transfer it to the generator by using a pump. Once in the generator, the working fluids are separated by applying heat from an external source; the refrigerant flows to the condenser while the absorbent returns to the absorber. The most common working fluid pairs used in these systems are ammonia/water and water/lithium-bromide. The main applications of small-scale absorption refrigeration systems include electronics cooling, medical and laboratory applications, food and beverage, climate control, and solar-powered refrigerators and freezers.

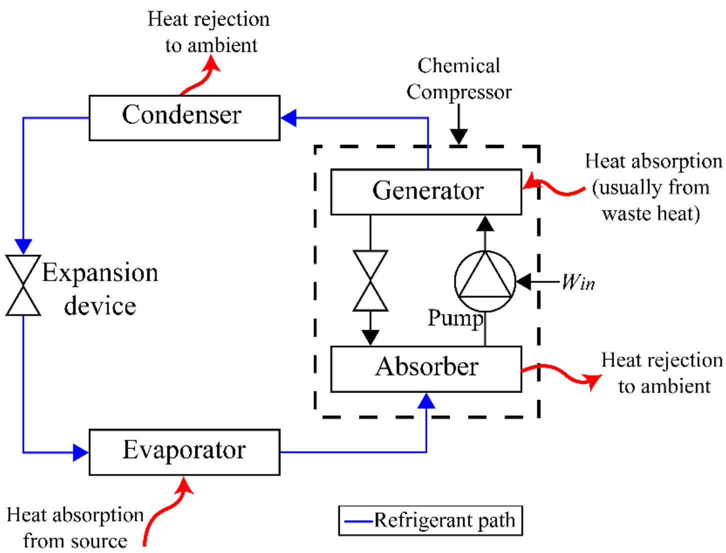

Figure 7. Schematic diagram of an absorption refrigeration system.

Absorption refrigeration systems are more complex and involve the use of more components than VCR. They also require large heat input to the generator, have high gas pressure ratio, provide intermittent instead of continuous cooling, and have limited cooling capacity due to slow compressor operation [15]. Determan and Garimella [38] presented an absorption heat pump for miniaturized or mobile applications with up to 300 W cooling capacity.

2.2.7. Stirling Cooling

A Stirling refrigeration cycle involves two isothermal and two isochoric (constant volume) processes to achieve cooling. Regarding the components that make up the system, it is important to highlight the use of a piston and a displacer unit that are responsible for moving the working fluid in any of the different configurations in which this system can be presented. The system also includes a regenerative heat exchanger. Typical working fluids in Stirling refrigerators are He and H_2, although others (N_2, CO, air, CO_2, etc.) have been reported in the literature [39].

The relative motion of piston and displacer makes cooling possible. When the bulk of the working gas is located between the displacer and the cold end, it expands due to piston motion while absorbing heat at constant temperature. When the bulk of the working gas is located between the displacer and the piston, it compresses at constant temperature, rejecting heat to the environment through the hot heat exchanger. Finally, isochoric processes occur as the piston and the displacer move together while rejecting or absorbing energy to/from the regenerator, as can be seen in Figure 8.

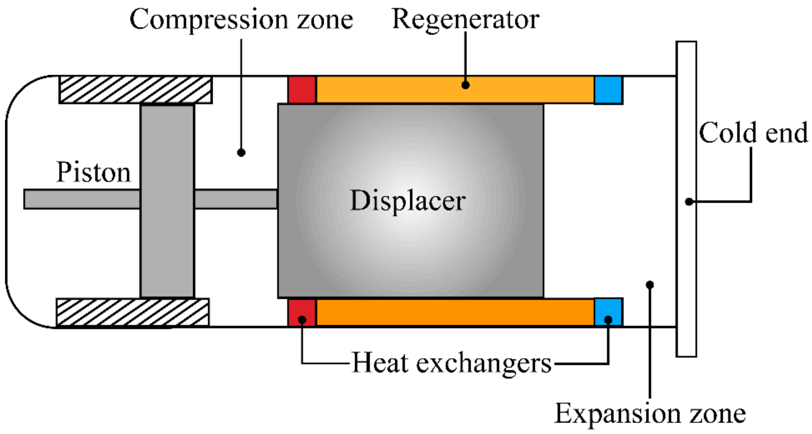

Figure 8. Schematic of Stirling cooling technology.

Stirling coolers are used in a variety of small-scale applications including portable refrigerators, electronic cooling, climate control of small spaces, laboratory equipment cooling, etc. Stirling refrigerators can reach from a few watts to a few hundred watts of cooling. An example of a high-capacity Stirling cryocooler reached a cooling power of 700 W at 77 K [40].

2.2.8. Joule–Thomson (J-T) Cooling

The J-T effect describes the change in temperature of a gas as it is throttled through a narrow orifice, resulting in a pressure drop at constant enthalpy due to nearly adiabatic conditions. For many gases (although not all), temperature decreases during throttling. Based on this principle, cooling systems have been developed where a high-pressure gas from a compressor or a pressurized container cools down as it circulates through a capillary tube or a porous plug. In some configurations and to increase system efficiency, the cooled gas from the J-T valve is rerouted to a counterflow heat exchanger to precool the incoming high-pressure gas, and then the refrigerant is circulated back to the compressor for repressurization, as can be seen in Figure 9. Depending on the refrigerant composition and pressure level, the resulting cold refrigerant can be a pure gas or a mixture of gas and liquid. The choice of the working fluid depends on the temperature and cooling capacity needs of the specific application. Typical working fluids used in these systems are He, H_2, CO_2, air, and N_2.

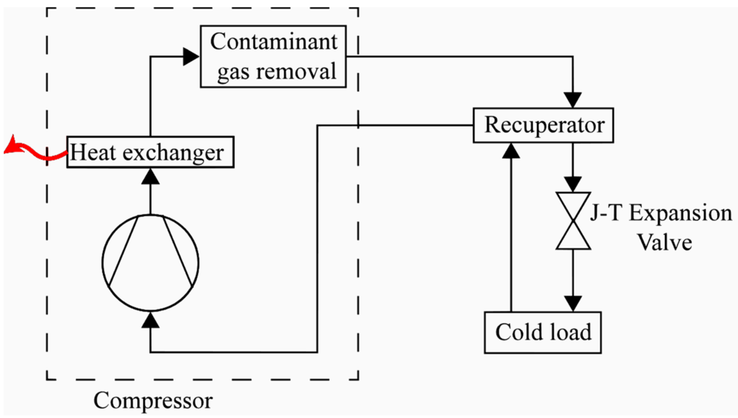

Figure 9. Schematic of a basic closed J-T cycle.

J-T systems often operate at very high pressure (200–500 atm), considerably higher than VCR systems. Therefore, open-cycle configurations using a high-pressure gas cylinder are often used. Cryogenic temperatures can be achieved by using mixed gas refrigerants.

Small-scale applications of J-T coolers include electronics cooling, cooling of biological samples at laboratories, and cryogenic cooling for spacecraft equipment and space probes, among others. An important feature of this technology is the potential for reaching very low temperatures, even though cooling capacity may be small (a few watts). For example, some military J-T coolers have refrigeration capacity in the range of 0.1–0.5 W at 80 K, while some J-T cryocoolers for spacecraft have 2.5 W capacity at 80 K [41].

2.2.9. VCR Systems

VCR refrigerators include four main components: compressor, condenser, evaporator, and expansion device (Figure 10), as well as a refrigerant as working fluid. The refrigerant has a low boiling point and high latent heat, allowing it to absorb and release large amounts of heat while vaporizing or condensing, respectively.

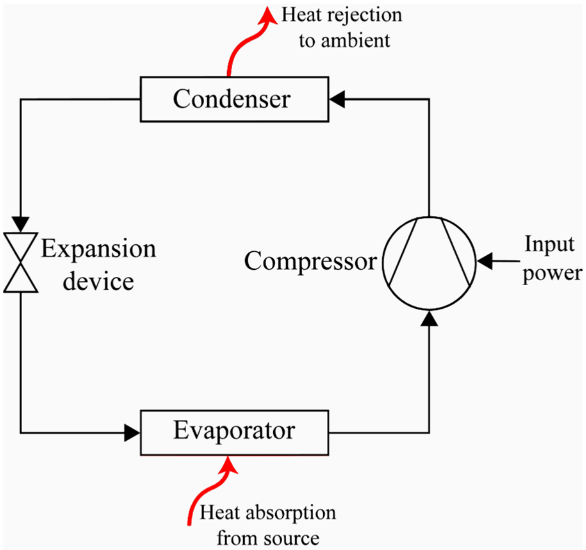

Figure 10. Schematic of a basic VCR cycle.

Along its path through the system, the refrigerant experiences four distinct processes. Superheated vapor at low pressure and temperature enters the compressor and leaves as high-pressure and temperature superheated vapor. The refrigerant then flows into the condenser, where it releases heat and cools down to the point of condensation, resulting in high-pressure subcooled liquid at the outlet. The refrigerant next undergoes an isenthalpic depressurization as it flows through the expansion device, reaching the evaporator as a low temperature mixture of liquid and vapor. In the evaporator, the refrigerant absorbs heat from the medium to be cooled, leaving as superheated vapor at low pressure and temperature, concluding the cycle and returning to the initial state.

Advantages of a VCR system vs. alternative technologies include the following. (1) They can provide cooling to systems at temperatures below ambient. This is unlike other technologies (e.g., forced convection cooling) that only work at temperatures above ambient. Moreover, when compared with spray cooling, jet impingement, and flow boiling in microchannels, VCR is the only one capable of cooling the junction temperature below ambient temperature [10]. (2) VCR systems can reach higher COP than other technologies such as thermoelectric cooling [42]. (3) Long periods of large cooling capacity are achieved with low mass flow rates, and (4) heat is transported away from its source [43]. The main applications for small-scale VCR systems are electronics and personal cooling, and they have proven to be a viable option for reaching cooling capacities up to 1000 W [44]. Other commercially available applications of small-scale VCR systems include medical, laboratory, mobile air conditioning, farming, commercial, telecom, and industrial applications.

Table 1 presents a summary of the information previously discussed on active technologies for small-scale cooling applications to highlight the most salient differences between them. As can be seen, for some of the technologies, capacity is defined based on the heat flux density that they can dissipate (W/m^2), while others use cooling capacity (W). It is important to emphasize that having a high heat flux density does not necessarily imply that cooling capacity will be high, and vice versa. It is also evident that some of the technologies share common applications; however, not all offer the same levels of capacity, performance, or efficiency. VCR systems often have an advantage compared to the others, by offering higher efficiencies and covering a broader range of applications.

Table 1. Summary of the main features of small-scale active refrigeration technologies.

Active Technology	Contact with Cooling Fluid		Common FLUIDS	Heat Flux Density [10^6 W/m^2]/Heat Load [W]	Main Application at the Small-Scale Level
	Direct	Indirect			
Forced convection	×	×	Air/Water	<1/	Electronics, data centers, personal cooling, Li-on batteries, etc.
Spray cooling	×		Water/Alcohols/ Refrigerants	>3/	Electronics cooling
Jet Impingement	×		Water/Mineral oils/Refrigerants	>3/	Electronics cooling
Droplet electrowetting	×		Electrolytes/Oils/ Hydrocarbons	0.05/	Electronics cooling
Thermoelectric	-	-	-	5–10/	Small refrigerators, electronics, air conditioning, medical, marine, and other applications
Microchannel		×	Water/Ethylene and Propylene glycol/Refrigerants	>10/	Electronics, air conditioning, personal cooling, medical, industrial, and aerospace applications, etc.
Absorption		×	Ammonia–water Lithium-bromide	/300	Electronics, medical and laboratory applications, food and beverage, climate control, and more
Stirling		×	He/H_2	/700	Portable refrigerators, electronics, climate control, laboratory equipment, etc.
Joule-Thomson		×	He/H_2/N/CO_2/Air	/<100	Electronics cooling, laboratory applications, spacecraft applications in cryogenic levels, etc.
Vapor compression		×	Refrigerants (R134a)	/1000	Electronics, data centers, avionics, telecommunications, personal cooling, air conditioning, medical, military, laboratory applications, and more

It is essential to mention that to have a better comparison between the different technologies in terms of energy efficiency and environmental impact, it is advisable to carry out a life cycle analysis, which provides an exhaustive evaluation from the extraction of raw materials to the final disposal of the system.

Section 3 describes previous VCR system studies to illustrate the current status of this technology.

3. Small-Scale Vapor Compression Refrigeration (VCR) Systems

VCR systems have been proposed for small-scale cooling due to their high efficiency and performance. The main reason triggering their development is the fact that several of the technologies mentioned in the previous section, both active and passive, often have insufficient performance to satisfy the cooling needs of important applications including electronic component and computer system cooling. A challenge to small-scale VCR systems is component miniaturization, since the equipment or systems that demand cooling are compact and require small cooling units. Miniaturization, in turn, enables applicability to mobile or even portable systems, including another major area of current research: personal refrigeration.

There are many publications dedicated to both modeling and experimentation in the field of small-scale VCR systems, where different operating conditions and component designs have been evaluated, mainly for heat exchangers, seeking to obtain higher cooling capacities and COP. Next, various recent research works are described, first considering complete system prototypes and models, and then individual VCR system components.

3.1. Small-Scale Vapor Compression Applications

Designing and/or coupling a miniature refrigeration system for small-scale applications can be a very interesting challenge. According to Barbosa et al. [10], some important aspects include (i) designing an efficient, reliable, and compact compressor, (ii) developing and improving suitable evaporators, (iii) integrating the cooling system in a restricted space, (iv) solving packaging related issues, and (v) maintaining a competitive cost for the entire system. Moreover, an ideal cooling technology should be (i) efficient in converting input power into cooling capacity; (ii) compact (i.e., small and lightweight); (iii) eco-friendly and nontoxic; (iv) capable of large heat flux density (W/m^2); (v) designed with the minimum number of moving parts; (vi) inexpensive; and (vii) scalable to reduced dimensions to meet future needs. In addition to these desired features, the application at hand and the operating conditions are very important aspects that must be considered since they also influence its design. We next describe recent work on VCR systems for small-scale applications.

3.1.1. Electronics Cooling

The growing demand for electronic devices in ever-increasing applications is due to the constant improvement of technology, increasing accessibility and affordability, as well as the need for constant connectivity and immediate access to information. In this sense, the number of transistors that make up these chips had been doubling approximately every 18 months for several years according to Moore's law. However, this trend has slowed down in recent years, and it is even believed that it will end as the transistors reach atomic scale and manufacturing costs continue to increase [45]. In consequence, an increase in power consumption and therefore greater heat flux densities have been observed; in fact, the International Technology Roadmap for Semiconductors, ITRS, predicted that by 2022 the average power consumption for a typical stationary chip would be over 400 W and over 800 W by 2026 [42]. Efficient and powerful refrigerating solutions such as vapor compression cooling have been proposed and evaluated.

With the aim of solving this problem, Wu and Du [14] demonstrated a miniature VCR system measuring 300 × 230 × 70 mm^3 and 3.5 kg in weight with a cooling capacity of 200 W and R134a as a refrigerant. They conducted a series of systematic tests to find the best system characteristics, prioritizing cold plate temperature. Optimum system conditions were 1800 mm capillary tube length, 100 g refrigerant charge, and 2858 rpm compressor speed. With these conditions and 200 W heat load, the cold plate could be maintained at 60 °C for many hours with a COP equal to 8.5. The second law efficiency of the system was measured at 23–31%, mainly due to compressor irreversibility. Figure 11a shows an illustrative representation of this system. A similar work used a variable speed compressor for R134a, a microchannel condenser, a capillary tube, and a microchannel heat sink as an evaporator [46]. The authors focused their attention on the surface temperature of the heat source, achieving a suitable range between 54 and 73 °C when the heating power was 200 W. The authors found that slower compressor speeds reduced power consumption and led to improved coefficient of performance (as high as 9.0). It is finally noted that it is critical to control the refrigerant temperature at the evaporator inlet to avoid droplets that may damage the electronic device if the temperature is below the dew point. Figure 11b shows the experimental equipment built for this research.

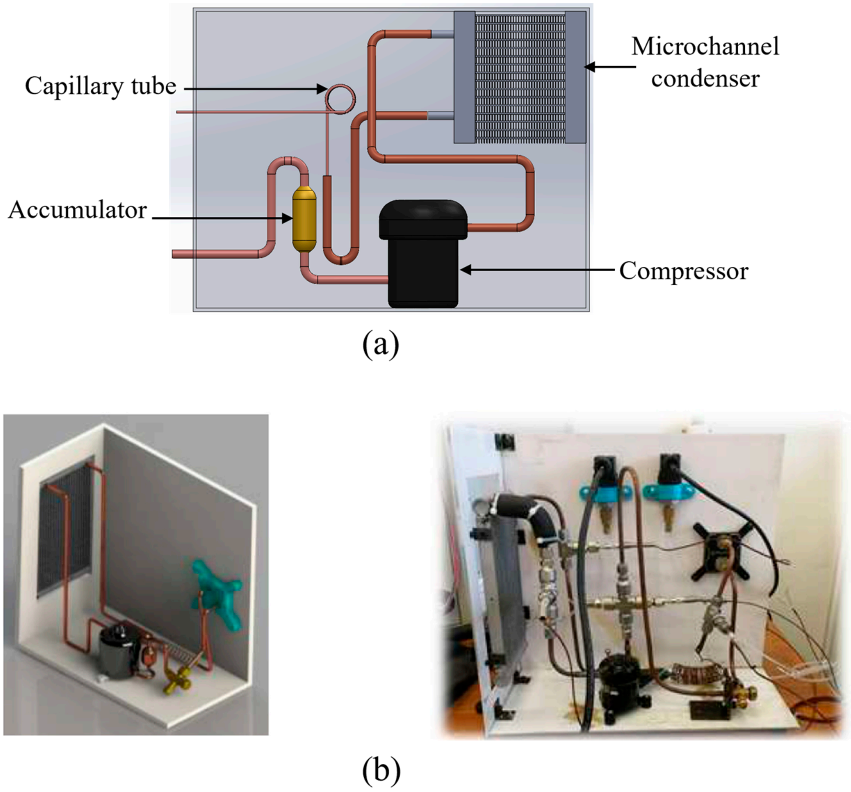

Figure 11. Experimental equipment of (**a**) Wu and Du and (**b**) Poachaiyapoom et al. [46].

Yang et al. [47] tested a miniature cooling system with 2.5 kg weight and 250 × 200 × 120 mm^3 size. The system used a spiral-tube evaporator of their own design. At test conditions of mass flow and ambient and chilled water temperatures, their experiments showed a 63 W cooling capacity with 24.5 W input power (COP = 2.57) and 40 g optimal refrigerant charge.

Seeking a system with even smaller dimensions that could fit into the free space of a personal computer, a miniature refrigeration system was developed with commercially available components and R134a as the working fluid [48]. Cooling capacity and COP were measured between 121–268 W and 2.8–4.7, although these values were expected to be lower according to the design specifications of the compressor. The largest losses originated in the rotary compressor, which was not designed for the test conditions. This experimental setup was also used to validate a MATLAB numerical model [49].

Mongia et al. [50] successfully fitted a miniature refrigeration system into a notebook computer. The system used isobutane as the working fluid and the tests were conducted with a thermal load close to 50 W. The results showed that the system could reach COP greater than 2.25 at evaporating (50 °C) and condensing (90 °C) temperatures higher than typically used. Possamai et al. [51], on the other hand, demonstrated a compact VCR system that is adapted but not integrated into a gaming laptop for supplying cold air to improve its performance. The required cooling capacity was 30 W at 10 °C evaporating temperature and 45 °C condensing temperature. Isobutane was selected as refrigerant from a theoretical comparison that considered operating pressures, discharge temperature, and volumetric flow, among other properties. All system components were designed for this specific application; a linear reciprocating compressor was constructed and tested in a calorimeter, obtaining a cooling capacity of 34.6 W, for a COP = 2.55, and 42% isentropic efficiency, under the specified operating conditions on a basic cycle mode. For the condenser and evaporator, microchannel heat exchangers were designed and constructed. Finally, the capillary tube was dimensioned according to a methodology proposed by Melo et al. [52]. Figure 12 shows the experimental unit.

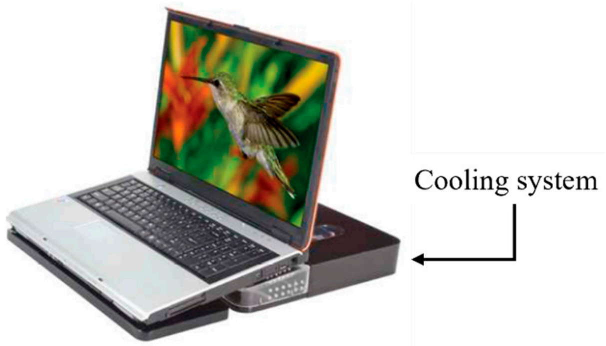

Figure 12. Cooling system developed by Possamai et al. [51].

The telecommunications area is another important application that demands the cooling of electronic components for adequate operation. The need for compact telecom cooling units that may perform as efficient substitutes for thermoelectric coolers and the scarcity of studies in the literature motivated Ribeiro to test a VCR system for this application. The initial work [53] presented a prototype made of a linear oil-free micro compressor, finned tube heat exchangers as condenser and evaporator, and a capillary tube as an expansion device, operating with R134a. The overall dimensions were $528 \times 127 \times 96$ mm^3 and 3.1 kg weight, and it used 59 g of optimized refrigerant mass and a 1.10 m long capillary with 0.518 mm diameter. The cooling capacity and COP evaluation considered both controlled and full piston stroke cases. The controlled stroke produced 72.6 W of cooling capacity, similar to that obtained with the thermoelectric unit. However, the COP was doubled at 1.45. The full stroke test resulted in a larger cooling capacity of 109 W and a lower COP of 1.01.

In a second work, Ribeiro [54] proposed a similar experimental apparatus, except that an additional pre-condenser and post-evaporator were added to the system as seen in Figure 13, causing an increase in the dimensions and weight ($660 \times 200 \times 120$ mm^3, and 8 kg). The aim of adding these devices was to partially condense the refrigerant in the pre-condenser and then send it to the post-evaporator, which was a serpentine tube in contact with the compressor, to decrease the shell temperature, permitting its suitable operation in hot climates. Other system components remained unchanged. The tests were carried out with a full piston stroke at 25, 35, and 55 °C ambient temperatures. The results showed an optimized R134a charge of 138 g and 1.15 m capillary length. Moreover, the vapor compression system demonstrated a COP of 1.09—double that of two thermoelectric cooling units used for comparison, although a thermoelectric unit had higher cooling capacity (150 vs. 120 W).

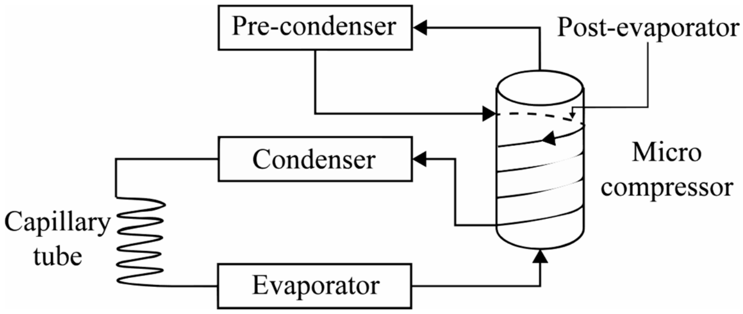

Figure 13. Schematic representation of the refrigeration system.

Another application within the field of electronic component cooling is in avionic systems. Unlike other systems, electronic components in aeronautical applications can operate at temperatures as high as 80–120 °C. However, size and weight minimization is critical, resulting in atypical designs. Mancin et al. [55] used a cold plate as evaporator specifically developed for use inside an avionics package. Their use of a fixed-speed linear compressor allowed for the testing of compression ratios between 1.54 and 3.75, and piston displacements between 25 and 90%, obtaining COP values between 1.04 and 5.8 and cooling capacities between 37 and 374 W.

Zilio et al. [56] developed a hybrid cooling system by coupling a compact loop heat pipe with a mini vapor compression system to overcome the issues related to system layout onboard helicopters and aircraft. The first system was used to cool a hot spot on integrated modular avionics, and the second was used to reject the heat to the cold sink, as can be seen in the illustrative representation of the system in Figure 14. One of the most innovative aspects of this system lies in the use of a thermal connector or plug evaporator, disconnecting the heat load and the available heat sink and locating it in a different aircraft partition. The authors found that ambient temperature strongly affects the performance of the system; however, under different scenarios, they managed to keep the temperature below 120 °C for an ambient temperature of 55 °C.

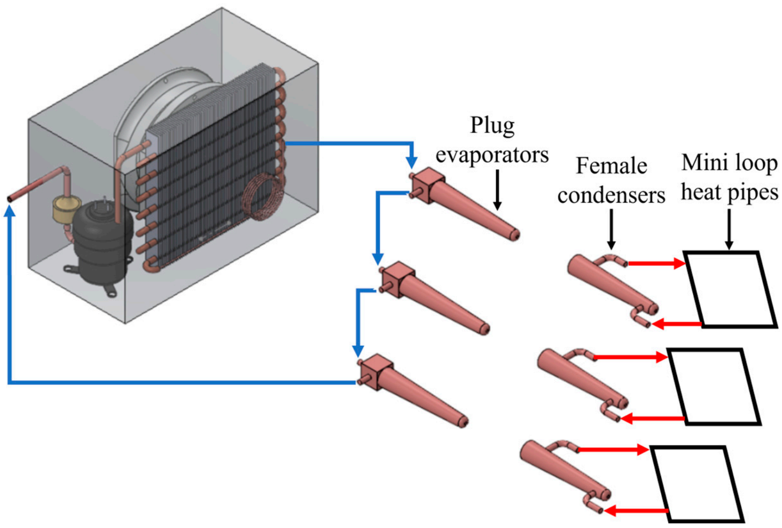

Figure 14. Illustrative representation of the hybrid cooling system.

A very singular meso-scale VCR system design stacked a rotary vane-type compressor, a film-wise condenser, an expansion nozzle, and a microchannel evaporator, similar to the scheme shown in Figure 15 [57]. Additionally, three heat pipes were incorporated with the condenser and the evaporator was designed by the Taguchi method to further increase heat transfer. The overall dimensions of the system were 60 × 60 × 100 mm^3 and the selected refrigerant was R123. A maximum cooling capacity of 80 W was determined experimentally, keeping the temperature of the heat source at 46 °C and reaching COPs up to 2.15. Chen et al. [58] integrated a miniature cooling system comprising vapor compression and thermosyphon loop for electronics cooling in avionics. This device has the particularity that it can change its operating mode depending on the thermal load and ambient temperature. At low heat load and ambient temperature, it works in a thermosyphon loop for energy conservation and switches to vapor compression mode at high heat load and ambient temperature for safety. The system consists of an evaporator made of multi-hole aluminum flat tubes, a forced convection micro-channel condenser, a micro rolling rotor compressor, an electronic expansion valve, a check valve, and two solenoid valves, with a total weight of 2.8 kg. In experimental tests, the dynamic characteristics of the two operating modes and the switching mode were studied, and among the most relevant results, it was found that the thermosyphon loop mode can handle a heat load of 600 W with an efficiency of 35.7, with input work invested in operating the fan, while the vapor compression mode has 1000 W of cooling power with COP of 3.1 considering fan and compressor input work, both at 20 °C ambient temperature.

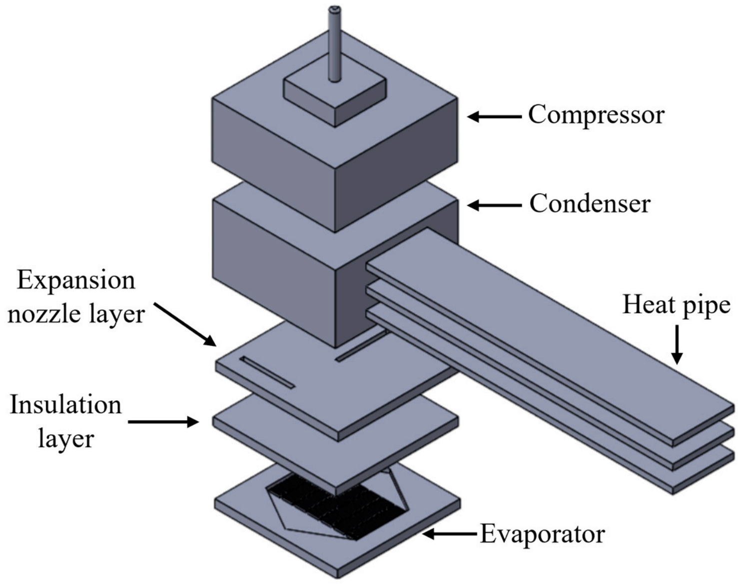

Figure 15. Illustrative representation of the meso-scale VCR system.

As can be seen, the number of applications where a vapor compression refrigeration system is needed for the cooling of electronic components is vast, and more will surely emerge as the technology advances and the demand for efficient systems with high heat removal rates rises, since the COP of these systems is a strong function of the temperature difference between the heat source and the sink and only a relatively weak function of the technological miniaturization of the components.

3.1.2. Personal Cooling

When we talk about personal cooling, it is important to mention that there has been an evolution in the last three decades in the way in which individuals have been seeking to create a comfortable thermal environment: we have been moving from the use of HVAC systems, through "task ambient conditioning (TAC)" strategies, followed by "personalized environmental control systems (PECS)", and more recently, "personal thermal management systems (PTMS)" [59]. In other words, there has been a transition from controlling the climate of an entire space to creating a micro-climate in a localized area, until reaching the point of developing wearable cooling systems that only focus on the comfort of the human body, as can be seen in Figure 16.

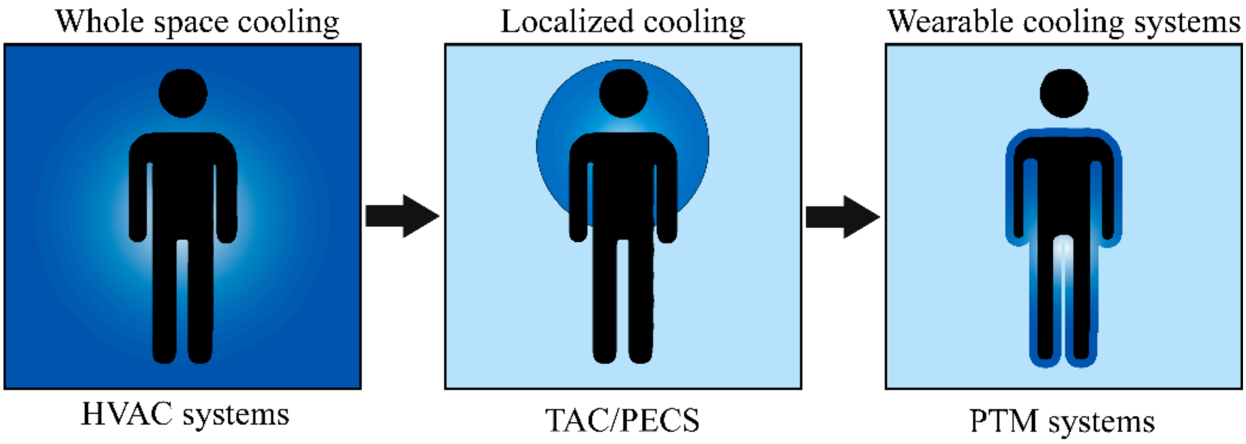

Figure 16. Conditioning area moving closer to the human body.

PTM systems are important because they can help individuals exposed to high-temperature environments, such as firefighters, soldiers, and other hazardous duty and chemical-spill personnel, increase productivity, increase the duration of missions, reduce fatigue, and improve safety by reducing thermal stress [60]. We next outline some research works focused on this topic.

Zhong et al. [61] designed and manufactured a miniature vapor compression refrigeration system for microclimate control applications using a Wankel compressor, a miniature air-cooled multi-channel parallel-type condenser, a spiral-tube-type evaporator, and a capillary tube. The dimensions and weight of the equipment were 260 × 250 × 120 mm^3 and 2.85 kg, reaching 4 kg when a high-performance lithium battery was added. Experimental tests were performed to determine optimal R22 refrigerant charge (100 g) and capillary tube length (1000 mm). Additional tests were conducted to evaluate the effect of compressor speed on system performance. The results show that the miniature refrigeration equipment provided 300 W of cooling with a COP above 2.0 at 40 °C ambient temperature. Wu et al. [62] presented follow-up work evaluating the influence of refrigerant charge and capillary length on system operating conditions (superheating, subcooling, operating pressures, and temperatures). The results show a compression ratio above 3.0, cooling capacity above 300 W, and COP of 2.3.

Ernst and Garimella [60] designed, fabricated, and tested a wearable personal cooling system including an engine-driven compressor and a wearable evaporator. The system was assembled in a backpack-type configuration with a total mass of 5.3 kg and measuring 318 × 273 × 152 mm^3. The authors found that the system can provide 178 W of cooling for 5.7 h in an ambient temperature of 43.3 °C. An even more compact wearable system was proposed by Yuan et al. [63] with 190 × 190 × 100 mm^3 overall dimensions and 2.75 kg in weight. The system includes a liquid cooling vest and therefore demands an additional pump, and yet the system is lighter and more compact. The system reached a cooling capacity of 260 W and a COP of 1.62 under an ambient temperature of 50 °C and a cold-water temperature of 24 °C. The study also analyzed the influence of the expansion valve opening, and the mass of refrigerant charge in the system, finding an optimal mass of 120 g of R134a. The system incorporated a microchannel plate-fin-type evaporator.

The development and study of small-scale VCR systems for personal cooling will continue to grow in the following years for at least two reasons: (1) extreme weather is becoming more prevalent in many areas of the world due to climate change, and (2) technological development and progress in new manufacturing techniques will allow the creation of increasingly compact vapor compression refrigeration systems, leading to improved portability and wearability.

3.2. Modifications to the Basic Vapor Compression Cycle

As previously discussed, the basic vapor compression cycle is made of four components: compressor, condenser, expansion valve, and evaporator. However, different and more complex cycle configurations involving the use of additional elements are often proposed to improve system performance. These modifications to the basic cycle can be as simple as the installation of an intercooler or as complex as the use of ejectors or cascade systems, and although it is more common to find them in large-scale systems, they are also being considered for small-scale systems.

Alzoubi and Zhang [64] developed a compact experimental VCR prototype that included an intercooler or recuperator, since relatively few systems have incorporated internal heat exchangers with linear compressors. They also developed models for all system components as well as an overall system model. The recuperator model used a moving boundary characterization to predict the degrees of subcooling and superheating of the refrigerant under different operating conditions. Chiriac and Chiriac [65] developed a model of a small-scale refrigeration system using ejector vapor compression. Their objective was comparing the thermal performance of this technology with the traditional mechanical VCR system to reduce the size of an electronics cooling system by replacing the compressor with a small ejector. It was found that the ejector can be more compact than a traditional compressor. However, an electric boiler was necessary to obtain the high-pressure flow, increasing system dimensions. In addition, it was found that the ejector system COP was 20 times lower than for the mechanical vapor compression, considerably increasing inlet power demand.

The study of cascaded VCR systems has received relatively little attention. One of the main objectives sought with this type of system is reaching lower evaporation temperatures than single-stage systems. In this sense, Coggins [66], based on previous work by Wadell [67], developed a two-stage cascade refrigeration system using R508B and R404A for cooling of high-performance microprocessors; however, the system was relatively large at 60,000 cm^3. It was found that the cooling capacity of the system was 40 W, sufficient to maintain the chip at −61 °C.

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.

Heydari [68] presented a steady-state model of the performance of a CPU cooling system employing a mathematical multi-zone formulation for the condenser and evaporator, along with a physics-based efficiency model for the free piston linear compressor, and an empirical correlation for modeling the flow rate through the capillary tube. The model enables the evaluation of the effect of design parameters such as evaporating and condensing temperatures on system components and overall efficiency. The results showed an increase in system efficiency and a decreasing condenser heat load as evaporating temperature increases under a fixed junction temperature (the operating temperature of the semiconductor) and evaporator load. On the other hand, the rise in condenser temperature leads to a reduction in system COP when evaporating temperature, junction temperature, and evaporator load remain constant. The model also allows evaluation of different refrigerants. The authors selected R134a based on thermodynamic, physical, chemical, and safety and environmental aspects, leading to a COP equal to 3. Other refrigerants (ammonia, R22, R290, R718, R404A, R504A) were also evaluated. Other authors focused their modeling work on improving the overall thermal performance of miniaturized vapor compression systems by finding optimum component designs [69]. Through a COOLPACK [70] simulation for a system with 100 W of cooling capacity, 10 °C evaporating temperature, 55 °C condensing temperature, and a scroll-type compressor with 90% isentropic efficiency, the authors optimized evaporator and condenser dimensions, leading to a COP as high as 4.5.

Considering the relative scarcity of dynamic and control models applied to meso-scale VCR systems, Sung et al. [71] presented an empirical model and robust control system of a prototype developed in a previous study [57], with the purpose of maintaining the heat source temperature constant as the cooling load changes. This was accomplished with a black-box model developed to predict dynamic behavior under varying cooling load. After some tests, the 2nd order empirical Box–Jenkins (BJ) model was selected as it successfully reproduced the transient behavior of the system for the given cooling load. The model has two inputs: compressor speed and cooling load, and one output: the temperature of the heat source. In addition, the authors developed a robust control system based on the black-box model to ensure acceptable performance for variable or unknown cooling loads, to develop a future multi-input multi-output (MIMO) control system. The results show that the robust controller can adjust the temperature of the heat source to the desired value within 70 s, with oscillations between 1.25–2.5 °C.

A methodology for designing a meso-scale VCR system using a novel model capable of assessing the effects of downscaling vapor compression systems uses thermodynamic and empirical correlations and considers the impact of component interactions on system performance [72]. The system comprises a roll-bond-plate-type evaporator, an air-cooled louvered fin-and-plate multi-layered condenser, a fixed orifice as expansion device, and a reciprocating compressor. A 3D heat conduction model calculates heat leakage from the condenser to the evaporator, 2D heat conduction models calculate temperature distribution and heat transfer rates at the cold and hot ends, and the fluid flow was modeled as 1D considering both the momentum and the energy conservation equations on heat exchanger design. Moreover, semi-empirical sub-models for variable speed compressors and fixed-orifice expansion devices were incorporated into the cycle simulation model, which was then used to assess the effect of component characteristics (expansion orifice size, compressor stroke and speed) on system COP. The results indicate that a 5×5 cm^2 heat source at 40 °C with the surroundings at 25 °C can be optimally cooled with a system with 110 W cooling capacity and a COP of 1.6.

An innovative personal cooling system was designed comprising a miniature vapor compression system made of a rotary compressor, a microchannel heat exchanger as an evaporator, a thermal expansion valve, and a condenser made of helical refrigerant tubes immersed into a container filled with phase change material thermal storage [73]. Originally, the system worked with refrigerant R134a; however, the need to evaluate alternative low GWP refrigerants led to the development of a dynamic model using hierarchical structures consisting of component models connected with appropriate interfaces in Modelica [74]. Discretized models were used for the microchannel evaporator and PCM condenser dynamics. The model was validated with experimental data and used for evaluating system performance with R32, R1234yf, R1234ze(E), and R290. Even though R32 showed the highest COP with an increase of 8% vs. R134a, it was concluded that R1234yf could be a drop-in replacement for R134a because it resulted in very similar system behavior.

A good synergy between modeling and optimization techniques can assist in system redesign, leading to improved performance. For example, a recent study presented the theoretical modeling and optimization of a miniature VCR system [75]. The model was based on physical principles and empirical correlations while the optimization used heuristic multi-objective algorithms, such as the nondominated storing genetic algorithm II (NSGA-II), and multi-objective particle swarm optimization (OMOPSO). Before conducting the optimization, the authors compared their model with experimental results from other publications, resulting in a maximum error of 10%. The evaluation considered various scenarios, some seeking to maximize COP or cooling capacity, and others seeking to minimize refrigerant mass flow or compressor energy consumption. The results showed a cooling capacity of 500 W and a COP of around 7. Marchi et al. [76] conducted a multi-objective optimization of a portable vapor compression cooler focused on maximizing performance and minimizing weight. A steady state system simulation model was developed and validated against experimental data showing deviations within ±10%. The model was developed on EES software [77] and includes sub-models for the compressor and heat exchangers, while the refrigerant charge and capillary tube sub-models were replaced by prescribed values for evaporator superheating and condenser subcooling. The optimization was conducted to evaluate a change from the baseline reciprocating compressor to a mini-rotary compressor, which demanded a resize of the heat exchangers. The optimization was conducted to determine optimum heat exchanger areas and cabinet wall insulation thickness leading to minimum energy consumption for a fixed weight, or minimum weight for a fixed energy consumption. The resulting system configuration consumes 13% less energy than the baseline cooler if the weight remains unchanged, or a system with the same energy performance can have a 15% lower weight.

Modeling has also been applied to the optimization of micro-scale vapor compression systems [78]. A numerical model was conducted on EES [79] using fundamental thermodynamic equations to define inlet and outlet states of each component, and calculate cooling power and cycle COP, neglecting pressure drop, heat losses, and superheating and subcooling values near the saturation curve. As a conclusion, the authors emphasize how challenging the size reduction is for this type of system, maintaining a competitive performance as this depends on different variables: a correct compressor configuration (relationship between displacement and revolutions), the heat exchangers design, and the choice of the refrigerant fluid, being these the three main focused aspects of their work. The analysis also considered refrigerant selection attending current socio-environmental needs. Many refrigerants of current interest were compared, including R450A, R513A, R152a, R448A, R449A, R452A, and R600a, with the latter being the best choice based on the favorable characteristics found as high COP and low compression ratio.

Another application where small-scale VCR systems have been modeled is in food preservation, specifically fish refrigeration on fishing boats. Through a model developed in CoolPack [80], Nasution et al. [81] evaluated the performance of a refrigeration system operating with R134a and R600a for −10 °C evaporation temperature and condensation temperatures between 32 and 44 °C. The results showed that the system has better performance when operating with R600a, reaching COP values between 3 and 5, and a cooling capacity from 450 to 610 W.

As a summary of this section, Figure 17 shows the typical modeling approaches for small-scale VCR systems. Although not all studies share the same input and output variables, those listed are the most common. As can be seen, some propose the cooling capacity as input, while others obtain it as output, depending on the particular needs and objectives of each case. On the other hand, the compressor efficiency can refer to isentropic or volumetric, and finally the values of temperature, pressure, and enthalpy as outputs refer to each thermodynamic state that comprises the refrigeration cycle.

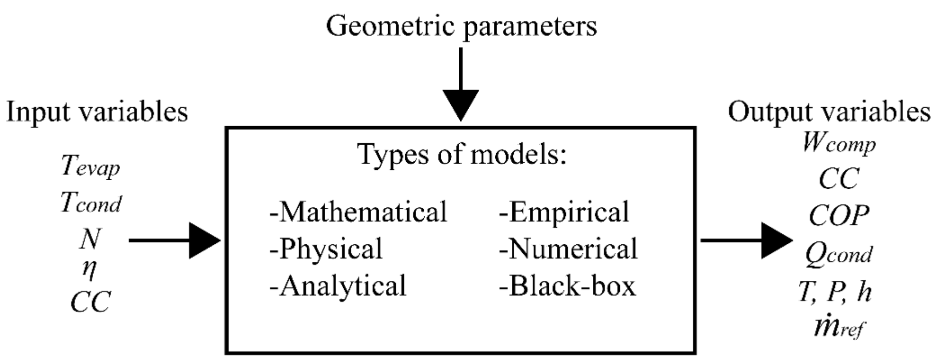

Figure 17. Common modeling strategies used for small-scale VCR systems.

3.4. Components

A vapor compression cooling system, whether on a small or large scale, consists of four main components (compressor, condenser, evaporator, and expansion device) that cause the refrigerant to experience a sequence of thermodynamic states that make up the refrigeration cycle. These four components are important and necessary, which is why continued research is key for innovating and redesigning these systems, leading to improved performance. Small-scale vapor compression systems are not the exception and there are several publications focusing on specific components, evaluating different designs, proposing modifications, etc. For example, diverse types of compressors and heat exchangers for both the condenser and the evaporator have been evaluated, as well as different expansion devices made of diverse materials and varied dimensions and characteristics.

An important aspect is that even though some miniature vapor compression refrigeration systems and individual components for such systems may be commercially available, their manufacture and distribution is still limited, making it difficult or even impossible to purchase them. Therefore, the authors of previously cited publications typically manufacture their own experimental components due to lack of availability.

We next consider each of the components of small-scale vapor compression refrigeration systems separately to describe the different types of components that are being evaluated and define their characteristics, performance, and identified areas of opportunity.

3.4.1. Compressors

The compressor is considered the heart of the refrigeration system; its function is to pressurize the refrigerant that leaves the evaporator as a vapor at low temperature and pressure, taking it to a thermodynamic state of superheated vapor at high temperature and pressure. There are different types of compressors; however, the most common in small-scale systems, based on what has been reported in the literature, are rotary, reciprocating, and linear. Scroll, centrifugal, diaphragm, and acoustic compressors have also been evaluated.

The compressor deserves the most attention when it comes to miniaturization, mainly because its moving parts make it the component with the greatest irreversibility. In addition, there is a strong correlation between reduction in size, operating speed, and volumetric efficiency. This correlation, as well as the coupling between the drive mechanism and the compression system demand considerable attention [51].

Technological progress and improved manufacturing methods have resulted in very sophisticated compressors that a few decades ago could not even be imagined. Undoubtedly, this scientific and technological progress used in the development of these new compact compressors is impressive. This opens a wide field of research to characterize the operation and performance of these devices and find new applications for them. Some recent works where compressors for small-scale systems have been studied are described next.

Zhong et al. [61] developed a small-scale rotary variable speed Wankel-type compressor by using micro-electro-mechanical system technology. It consists of a triangular motor rotating within an epitrochoidal chamber without a gas outlet valve. It was manufactured using iron and aluminum alloy, weighing less than 400 g, measuring 5 cm diameter and 7 cm height, and designed to provide 300 W of cooling capacity. At this working condition, the speed of the compressor was 1650 rpm with a shaft power consumption of 95 W. The system ran with R22, and mineral oil lubricant. More information on this compressor was provided in a subsequent work [62], where a second Wankel compressor of 700 g was manufactured but not tested. In another work [82], a Wankel compressor with a flat design was used for a microscale vapor compression cycle that can theoretically provide 45 W of cooling power at 1000 rpm at a temperature 40 K above ambient, and a COP of 4.6 while using R134a. Device specifications include 367 mm^3 displacement, 25 mm $\times$ 30 mm footprint, and 6.25 mm thickness. The inherent advantage of the Wankel rotary compressor is its flat shape facilitating packaging in tight spaces. Figure 18a shows a similar scheme of this flat-shaped Wankel compressor.

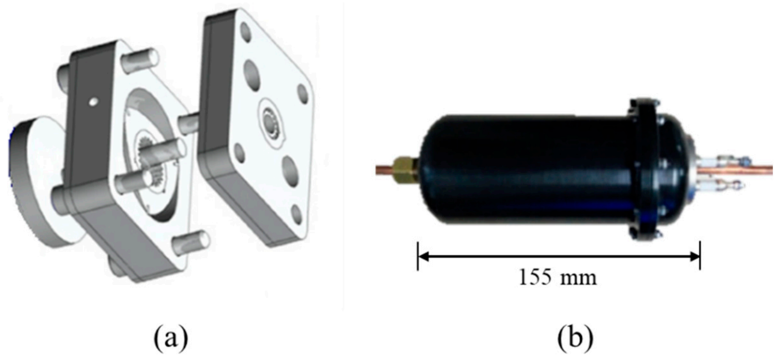

Figure 18. Prototypes of Wankel compressors: (**a**) flat-shaped design and (**b**) lightweight design.

Zhi et al. [83] recently presented the development and performance evaluation of a lightweight miniature Wankel compressor for aerospace applications (see Figure 18b). The main objective was demonstrating a compact and portable device, investigating its sealing, housing, and materials. Two approaches were adopted for lightweighting: (1) optimize and redesign the structure; and (2) use lightweight materials instead of steel. The final product was a 340.2 g compressor with 65 mm diameter and 85 mm length made of aluminum 7075 alloy that reached 1.49 kg and 155 mm in length once the coupling of a DC brushless motor was included. For the performance tests, a vapor compression cycle was constructed using R134a to evaluate the optimal operating conditions by varying the refrigerant charge, compressor speed, and condenser cooling water temperature. Under a 100 W heat load, the optimum refrigerant charge is 220 g with 40 W minimum power consumption and a COP of 2.5. When evaluating the rotational speed, a maximum COP of 2.8 was obtained for 4800 rpm, while the increase in rotational speed led to a decrease in COP due to an increase in compressor power consumption. Finally, the increase in inlet temperature of cooling water led to a decrease in COP.

Sathe et al. [84] also tested a miniature rolling-piston rotatory compressor (Figure 19) using a hot-gas bypass load stand and refrigerant R134a. The main characteristics of this commercial compressor were 78 mm height, 58 mm diameter, 1.4 cc displacement, and 600 g weight. The tests were conducted by varying the suction pressures, pressure ratios, and rotational speeds, producing the following results: 73–90% volumetric and 44–70% isentropic efficiencies, as well as 2.1–7.4 COP, and a theoretically calculated cooling capacity of 489 W. This compressor was then used by Wu and Du, who considered it the most compact in the market at that time [14], although other studies have demonstrated even more compact compressors, such as a reciprocating compressor that fits within a notebook computer [50].

Figure 19. Miniature rolling-piston rotary compressor [84].

A small-scale off-the-shelf portable air compressor was used and considerably modified to function as a refrigerant compressor for a portable cooling system [60]. System power was supplied by a 2-stroke compression ignition engine, eliminating the need for an electric grid connection. Several tests were conducted and cooling rates up to 300 W were demonstrated, indicating the air compressor's potential for practical applicability.

The use of linear compressors for refrigeration has been widely studied both in traditional applications such as domestic refrigeration, as well as in small-scale refrigeration due to the advantages over the conventional crank-drive reciprocating compressors [85]. Detailed numerical models have been developed and validated to improve the design and therefore the performance of these compressors [86,87], as well as experimental tests [55], where a constant-speed, oil-free linear compressor was used for electronics cooling in aeronautical applications, in which the mass flow and cooling capacity were controlled by varying the piston stroke. This same micro compressor was presented by Ribeiro [54]. It is a hermetic linear compressor with cylindrical form and 60 mm in diameter and 160 mm in length that weighs 1.3 kg. The most relevant aspect is its orientation independence, i.e., it can be mounted vertically or horizontally because it does not require any type of lubricant, increasing the practicality of its assembly in reduced areas. Figure 20 shows a schematic of a linear compressor and the one used by Ribeiro [54].

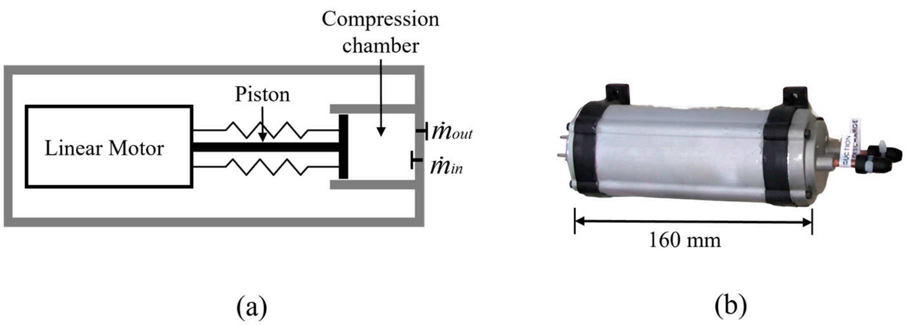

Figure 20. (**a**) Schematic of a linear compressor and (**b**) miniature linear compressor used by Ribeiro [54].

It is possible to find works in the literature comparing the performance of small-scale refrigeration systems operating with different types of compressors [88]. These authors conducted a thermodynamic evaluation of two commercially available portable coolers operating with reciprocating and mini-rotatory compressors. The portable cooler was a 38-liter cabinet originally equipped with a fixed speed reciprocating compressor operating with 42 g of R134a at 60 Hz, while the proposed replacement is a mini-rotary-type compressor with two compression stages evaluated at 40 and 58 Hz. In a brief comparison, the mini-rotary compressor showed better attributes, such as large evaporating temperature range, longer stroke, more compactness, lower mass, and more. It was observed that the system with the original compressor yields higher second law efficiency (by 20%) vs. the rotary compressor. However, the rotary compressor produced a higher cooling capacity, leading to a shorter cooldown time. Based on their results, the authors assert that the performance of the portable cooler using the rotary compressor can be greatly improved with an adequate heat exchanger design.

In summary, it can be seen that despite the challenges of compressor miniaturization, there is currently a wide variety of available systems for small-scale applications, where the selection will depend on the operating conditions or even the requirements of weight and dimensions for each application.

3.4.2. Condensers

The condenser transfers heat between the refrigerant at the compressor discharge (at high temperature and pressure) and the surrounding environment. The refrigerant condenses as it transfers heat to the environment, and this process occurs approximately at constant temperature and pressure, reaching a saturated or subcooled liquid state at its outlet. In large-scale refrigeration equipment, there are different designs for this device; however, in most small-scale systems, condensers are typically microchannel heat exchangers.

Several works have reported the use of microchannel heat exchangers, describing manufacturing methods, thermo-hydraulic performance, applicability [89], and numerical simulations [90]. Entropy generation analyses have also been conducted [13]. In addition, different designs have been proposed, including the addition of metal foams on the air side to enhance heat transfer [91] compared to louvered fins [92]. Other publications focused on the working fluids used, pressure drop, and optimization of these devices for both single-phase and two-phase flow [37]. Microchannel heat exchangers can achieve very high heat transfer rates, and therefore their study and use have extended to various applications such as the military, bio-engineering, medical, nuclear, and solar cells [93], as well as the cooling of computer components and information technologies, high power semiconductor devices, laser diode arrays, fuel cells, and the topic of this review: miniature VCR systems [94].

Another advantage of microchannel heat exchangers in small-scale refrigeration systems, either as condensers, evaporators, or both, is the reduction in refrigerant mass in the system, maintaining high heat transfer rates, as mentioned in the previous paragraph. We next describe relevant research involving the use of microchannels as condensers in small-scale refrigerators.

A brazed aluminum multichannel parallel-type condenser with two-refrigerant passes [61] showed major improvements in heat transfer coefficient and heat exchange vs. a finned tube condenser. The finned tube condenser weighed 1.7 kg and dissipated 300 W of heat vs. 400 W for the multichannel condenser weighing less than 0.4 kg. The comparison showed that the parallel-type condenser was even more suitable for the miniature refrigeration system subject of study. More detailed information about this device such as dimensions and weight ($130 \times 140 \times 16$ mm^3 and 0.26 kg) were then presented by Wu et al. [62]. Similarly, an aluminum microchannel condenser was used in the system proposed by Wu and Du [14]. This model was even more compact, at $100 \times 100 \times 16$ mm^3. There are other works where microchannel heat exchangers have also been used as condensers; however, they provide little detail on the characteristics of the devices, such as an aluminum microchannel multi-louvered fin heat exchanger (0.260 m wide, 0.238 m height, 0.0211 m deep) presented by Ernst and Garimella [60] or the one used by Mongia et al. [50] with a thermal resistance of approximately 0.5 °C/W. Figure 21 shows different designs of microchannel condensers.

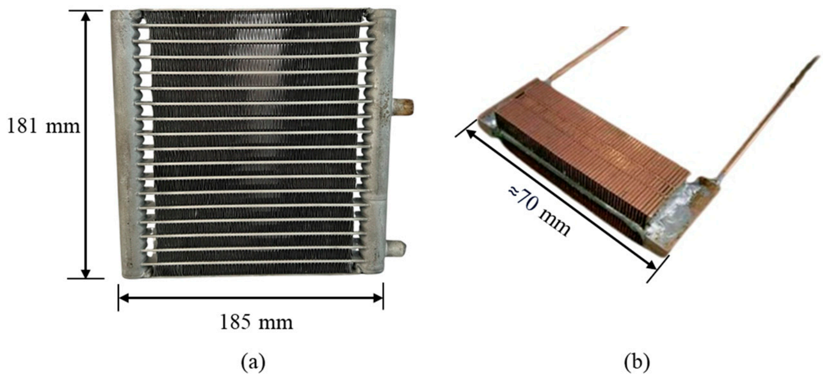

Figure 21. Microchannel condensers: (**a**) design 1 and (**b**) design 2.

Other types of condensers have been evaluated. Mancin et al. [55] considered a tube in tube-type condenser. Ribeiro [54] used a finned tube heat exchanger made of copper with aluminum louvered fins as condenser and pre-condenser, with the particularity that both were mounted together into a single device, as can be seen in Figure 22. Similarly, Yang et al. [47] used the same type of condenser. However, little geometric information is given.

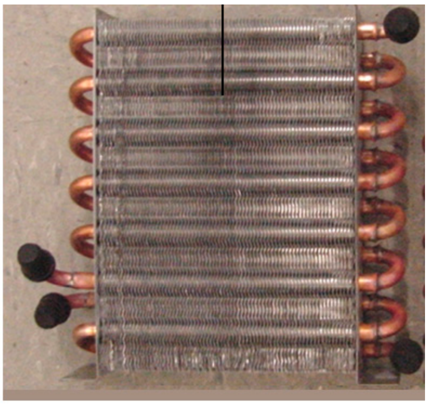

Figure 22. Finned-tube condenser used by Ribeiro [54].

Based on the available information, it can be appreciated that several types of heat exchangers can be used as condensers; however, microchannel condensers receive the most attention for small-scale applications due to the previously listed advantages: (1) high heat transfer rates, (2) compactness, and (3) reduction in refrigerant mass. It is expected that research on these components will continue due to technological progress leading to extended applicability of the technology.

3.4.3. Expansion Devices

The expansion device plays a very important role in the cooling process. It receives the refrigerant at the condenser outlet as a saturated or subcooled liquid at high pressure and throttles it into a low pressure in an isenthalpic expansion process, producing a low-pressure and temperature two-phase flow.

There are different types of expansion devices available according to system needs or conditions. A poor selection of the expansion device could cause problems such as insufficient flow of refrigerant to the evaporator, causing liquid to reach the compressor, or excessive overheating at the evaporator outlet, which is reflected in deficient system performance. This is why different expansion devices and their effect on performance of small-scale vapor compression refrigeration systems have been studied, including, for example, a study of the effect of expansion valve opening vs. COP [95].

The most popular expansion devices used for these systems are needle valves [48,60] and capillary tubes, although micro-orifice [96] and miniature electronic expansion valves [63] 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 [14], while others look for the best match between this variable and some other operating condition, such as refrigerant charge, in terms of system performance [61,62]. Finally, others describe an approach to size this component [46,51,52,97], or even apply various methods to the calculation of single-phase and two-phase region to obtain the overall capillary length, as considered by He et al. [98]. The main advantage of capillary tubes over other expansion devices is their simplicity and low cost [68].

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.

Zhong et al. tested three evaporator types (spiral-tube, tube-strip, and tube-in-tube) to select the better option in terms of heat transfer performance for the miniature system they were investigating [61]. Cooling power and weight were 300 W and 0.16 kg, 260 W and 0.12 kg, and 200 W and 0.22 kg, respectively. A schematic of the spiral-tube evaporator shown in Figure 23, it was assembled into the miniature refrigeration system because it was made of copper and therefore was easier to weld. It is worth mentioning that this device fits in the palm of a hand.

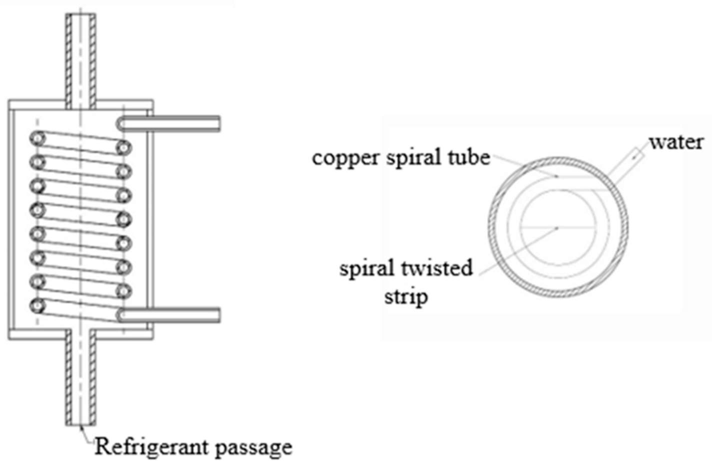

Figure 23. Illustrative representation of the miniature spiral-tube type evaporator.

The use of microchannel heat exchangers as evaporators has also been quite common, again due to their high rates of heat transfer. In some works, the effect of design characteristics has been studied. Chiriac and Chiriac [99] analytically compared six microchannel designs used as evaporators in a small-scale refrigeration system for electronics cooling with different overall size and hydraulic diameter. The authors found that the cooling power decreases with the increase in hydraulic diameter, due to the decrease in overall heat transfer. In a more recent study [46], the authors indicated that microchannel heat sink application to miniature refrigeration systems for electronics cooling has received little attention in the literature, along with determination of the heat source surface temperature. They tested a miniature vapor compression system in which the evaporator was a microchannel heat sink with 106 channels with rectangular cross-section shown in Figure 24a. Channel dimensions were 150 μm wide, 450 μm high, and 20 mm long, with 150 μm fin thickness. The microchannel heat sink was made of nickel-plated copper to prevent corrosion by the refrigerant.

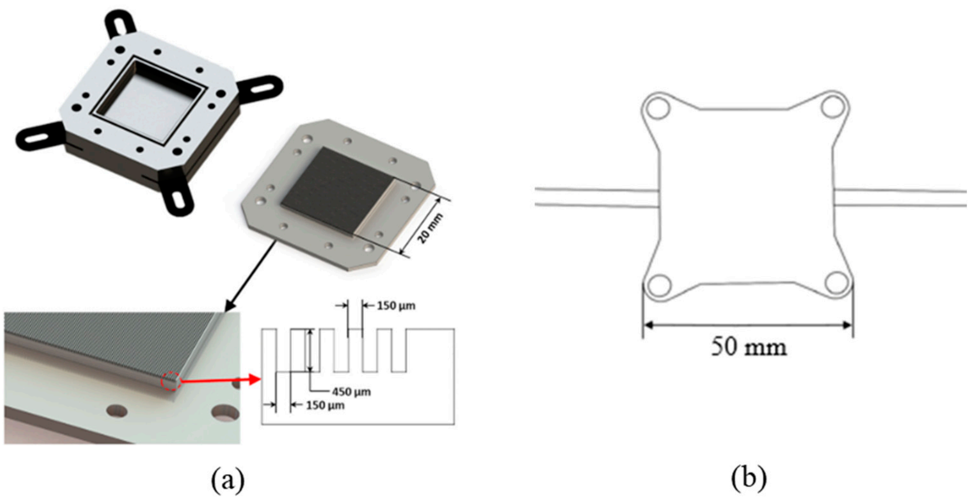

Figure 24. Miniature microchannel evaporators used by (**a**) Poachaiyapoom et al. [46] and (**b**) Mongia et al.

Continuing with the use of microchannels as evaporators, Mongia et al. [50] presented an even smaller microchannel cold plate evaporator made of copper (similar to the scheme shown Figure 24b). It is interesting to note that they used two evaporators connected in series, an idea that was later adopted for evaluation of a series and parallel arrangement of two evaporators [98]. The results indicate that better COP was obtained for the series system.

A singular microchannel plate-fin evaporator was developed by Yuan et al. [63] to minimize the size and weight of the cooling system. The evaporator was made of dozens of layers of stainless-steel plates and the microchannels on the plates are formed by photochemical etching process. The etched stainless-steel sheets are then laminated together and welded by vacuum diffusion bonding process. Figure 25 represents a similar scheme to the prototype of this device.

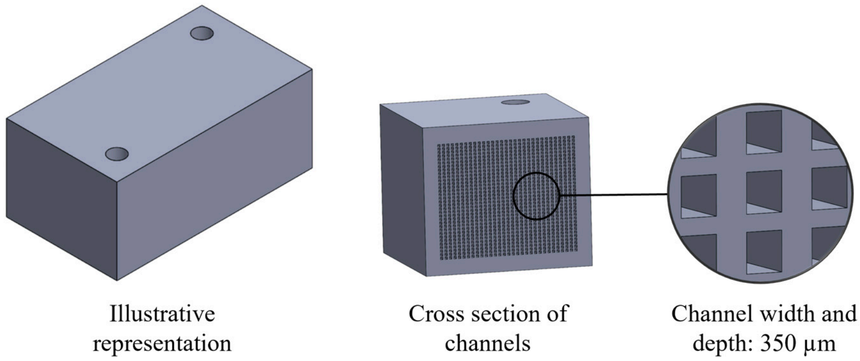

Figure 25. Illustrative representation of the microchannel plate-fin evaporator.

Another type of evaporator widely used at the small-scale level are the cold plates, as shown in Figure 26, similar to the one presented by Wu and Du [14]. This is a small cold plate mounted on top of a heat spreader that simulates the power generation of a chip through two 100 W electrical heaters tightly fitted into the heat spreader. Thus, the heat load of the cold plate can be varied by adjusting the cartridge heaters. The dimensions of the cold plate were 75 mm length, 9 mm height, and 75 mm width.

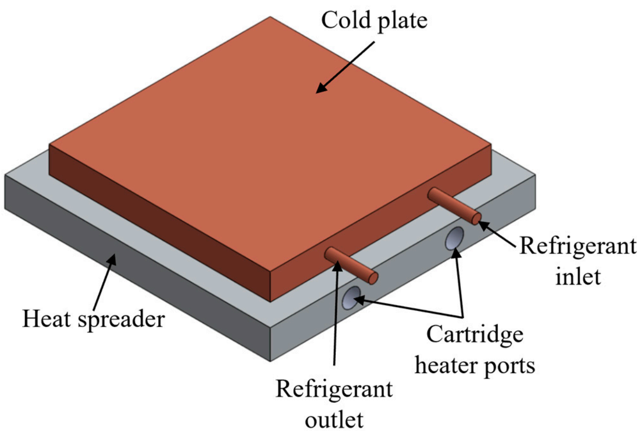

Figure 26. Illustrative representation of a small cold plate mounted on a heat spreader.

A cold plate (similar to Figure 27) for aeronautical electronic thermal management was designed by Mancin et al. [55]. It was a copper plate 400 mm long, 20 mm wide, and 10 mm thick with three guides milled on the top side to weld a tube for refrigerant flow with a total length of 1.2 m; on the bottom side, two more guides were machined to hold a resistance wire, which simulated the heat load.

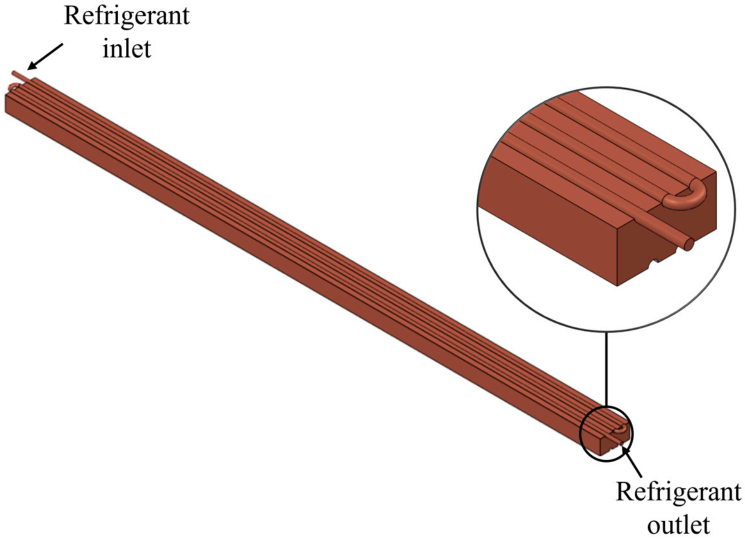

Figure 27. Illustrative representation of the cold plate.

To develop a more economical system, a simple porous media evaporator was used in a simple structured and economical miniature VCR system presented by Zhou and Li [100] for the cooling of electronic components within the automotive sector. The above is based on the scoop that microchannel heat exchangers continue to be very expensive. The developed system can achieve a heat dissipation of 100 W and ensure a chip temperature lower than/close to the ambient temperature, with a total energy efficiency ratio (EER) of 2.25.

As previously mentioned, the evaporator is the component with the greatest number of proposed designs, and type selection depends on the application. A great advance can be observed in the manufacture of microchannel type evaporators and cold plates, although other designs such as finned tube [53] and roll-bond [76], among others, have also been proposed.

Finally, an unconventional type of evaporator was designed and manufactured by [60]. This evaporator was incorporated into a garment in contact with the human torso. It consisted of tubing attached to a thin aluminum foil layer, stitched, and assembled into a neoprene wetsuit. The total length of tubing in the garment was 9.8 m and a surface area of 0.495 m^2 for a total mass of 0.85 kg. The system demonstrated a cooling effect of 178 W for more than 5 h.

Table 2 shows a summary of the most relevant information for the research cited in this section. As can be seen, R134a is still used broadly in these systems. Further research is therefore necessary to identify suitable low GWP substitute refrigerants. Cooling capacity can take values between a few tens and 1000 W depending on the needs of each application, and wide ranges of operating temperatures and COPs are also observed. It is finally observed that several system components receive broad application in these systems, including rotary and linear compressors, microchannels as heat exchangers, and capillary tubes as expansion devices.

Table 2. Summary of the small-scale VCR systems described in Section 3.

Authors	Type Prototype (P) or Model (M)	Application	Refrigerant	T_{evap} [°C]	T_{cond} [°C]	Thermal Load/Cooling Capacity [W]	COP	Dimensions [cm^3]	Compressor	Condenser	Evaporator	Expansion Device
Liang et al. [42]	P	CPU cooling	R134a	20	50	400	3.2	-	Linear	-	-	-
Schmidt & Notohard-jono [44]	P	High-performance computer	R134a	15 to 35	-	650 to 1050	2 to 3	26.7 × 26.7 × 71.1	Rotary	Air-cooled tube-fin	Copper coil internally enhanced heat sink	Thermostatic expansion valve
Wu & Du [14]	P	Electronics cooling	R134a	20	45	100/200	7.4	30 × 23 × 7	Rolling-piston rotary	Air-cooled Al microchannel	Cold plate	Capillary tube
Poachaiyapoom et al. [46]	P	Electronics cooling	R134a	23	-	100/150/200	9.069	-	Rotary	Microchannel	Nickel-plated copper microchannel	Capillary tube
Yang et al. [47]	P	CPU cooling	-	-	-	63	2.57	25 × 20 × 12	-	Air-cooled tube-fin	Spiral tube	Capillary tube
Trutassanawin et al. [48]	P	Electronics cooling	R134a	21	60	121 to 268	2.8 to 4.7	-	Rotary	Air-cooled microchannel	Microchannel	Manual needle valve
Trutassanawin & Groll [49]	P/M	Electronics cooling	R134a	10 to 20	40 to 60	200	<3.7	-	Rotary	Air-cooled microchannel	Cold plate microchannel	Manual needle valve/capillary tube
Mongia et al. [50]	P	Notebook computer	R600a	50	90	50	2.25	-	Reciprocating	Air-cooled microchannel	Copper microchannel cold plate	Capillary tube
Possamai et al. [51]	P	Gaming laptop	R600a	10	45	30	2.55	-	Linear	Air-cooled microchannel	Air-cooled microchannel	Capillary tube
Ribeiro [53]	P	Electronics cooling (telecom stations and command panels)	R134a	16.7/12.4	52.3/58.4	72.68/109.03	1.45/1.01	52.8 × 12.7 × 9.6	Linear	Finned-tube heat exchanger	Finned-tube heat exchanger	Capillary tube
Ribeiro [54]	P	Electronics cooling (telecom stations and command panels)	R134a	18.8	59.3	120	1.09	66 × 20 × 12	Linear	Finned-tube heat exchanger	Finned-tube heat exchanger	Capillary tube
Mancin et al. [55]	P	Electronics cooling in avionics	R134a	5/15/25	30/40/50/60	37 to 374	1.04 to 5.8	-	Linear	Water-cooled tube-in-tube	Copper cold plate	Needle micro metering valve
Zilio et al. [56]	P	Electronics cooling in helicopters	R134a	12 to 20	48 to 62	40	-	-	Rotary	Air-cooled finned coil	Conical bayonet-type	Thermostatic expansion valve

Table 2. *Cont.*

Authors	Type Prototype (P) or Model (M)	Application	Refrigerant	T_{evap} [°C]	T_{cond} [°C]	Thermal Load/Cooling Capacity [W]	COP	Dimensions [cm^3]	Compressor	Condenser	Evaporator	Expansion Device
Sung et al. [57,71]	P, M	-	R123	27.39	60	80	2.15	6 × 6 × 10	Rotary vane-type	Film-wise	Microchannel	Passive-type nozzle
Chen et al. [58]	P	Electronics cooling in avionics	R134a	50	72.7	1000	3.1	-	Rotary	Air-cooled microchannel	Multi-hole Al flat tubes	Electronic expansion valve
Zhong et al. [61]	P	Personal cooling	R22	-	-	300	>2	26 × 25 × 12	Wankel rotary	Air-cooled brazed Al microchannel	Spiral tube	Capillary tube
Wu et al. [62]	P	Personal cooling	R22	7	40	300	2.3	26 × 25 × 12	Wankel rotary	Air-cooled brazed Al microchannel	Spiral tube	Capillary tube
Ernst & Garimella [60]	P	Personal cooling	R134a	22.2 to 26.1	44.2 to 51.5	120 to 280	5	31.8 × 27.3 × 15.2	Reciprocating	Al Microchannel louver-fin	Coiled tube-in-shell heat exchanger	Thermostatic expansion valve
Yuan et al. [63]	P	Personal cooling	R134a	-	-	260	1.62	19 × 19 × 10	Rotary	Air-cooled microchannel	Microchannel plate-fin	Electronic expansion valve
Alzoubi & Zhang [64]	P/M	Electronics cooling	R134a	-	-	50 to 90	<4.5	-	Linear	Air-cooled	Microchannel (evaporator and recuperator)	Expansion valve
Chiriac & Chiriac [65]	M	High-power electronics	R134a	10	55	100	0.14	-	Ejector	Air-cooled microchannel	Microchannel	-
Coggings [66]	P	High-performance desktop computer	R404A/R508b	−72.3	-	40	-	60,000	Reciprocating (two-stage cascade)	Air-cooled	Microchannel	Capillary tube
Wadell [67]	P	High-performance desktop computer	R134a/R508b	−62.2	-	100	-	241,200	Reciprocating (two-stage cascade)	Air-cooled	Microchannel	Capillary tube
Heydari [68]	M	High-performance computers	R134a	20	60	170	3	-	Linear	Compact air-cooled	Cold plate	Capillary tube
Chiriac & Chiriac [69]	M	High-power electronics	R134a	10	55	100	4.24	755	Scroll	Air-cooled microchannel	Microchannel	Capillary tube

Table 2. *Cont.*

Authors	Type Prototype (P) or Model (M)	Application	Refrigerant	T_{evap} [°C]	T_{cond} [°C]	Thermal Load/Cooling Capacity [W]	COP	Dimensions [cm^3]	Compressor	Condenser	Evaporator	Expansion Device
Yee & Hermes [72]	M	Electronics cooling	R134a	30 to 33	63 to 65	110	1.6	-	Reciprocating	Air-cooled louvered fin-and-plate multi-layered	Roll-bond plate-type	Fixed orifice
Dhumane et al. [73]	M	Personal cooling	R134a and substitutes	variable	variable	150	-	-	Rotary	PCM-condenser	Serpentine microchannel	Thermostatic expansion valve
Moctezuma-Hernandez et al. [75]	M	-	R134a	10	35	517	6.9	-	Rotary	Air-cooled microchannel	Cold plate	Capillary tube
Marchi & Hermes [88] Marchi et al. [76]	P/M	Portable cooler	R134a	−15 to −7	24.8 to 52.8	30.2 to 75.1	<2	38 liters	Reciprocating/rotary	Air-cooled tube-fin	Roll-bond	Capillary tube
Goenaga et al. [78]	M	Compact refrigerators	R600a	−5 to 10	25 to 30	100	2.3 to 4.14	4 × 4 × 2	-	Finned tube	Finned tube	-
Nasution et al. [81]	M	Fish-storage box	R134a/R600a	−10	34 to 44	450 to 610	3 to 5	-	-	-	-	-
Heppner et al. [82]	M	Electronics cooling	R134a	−15.15	36.85	45	4.6	-	Wankel rotary	Finned serpentine	Insulated serpentine	Expansion valve
Zhi et al. [83]	P	Aerospace applications	R134a	variable	variable	100	<3.2	-	Wankel rotary	Plate heat exchanger	Microchannel heat sink	Capillary tube
Sathe et al. [84]	P	Electronics cooling	R134a	0 to 15	21 to 62	163 to 489	2.1 to 7.4	-	Rolling-piston rotary	-	-	Expansion valve
Chang et al. [95]	P	Electronics cooling	R134a	-	52	<150	<4.25	35 × 16 × 12	Rotary	Air-cooled finned tube	Microchannel	Expansion valve
He et al. [98]	P	Electronics cooling	R134a	8	48	<160	<3.22	-	-	-	Microchannel heat sink	Capillary tube
Zhou and Li [100]	P	Vehicle electronics	R134a	variable	variable	100	2.5 EER	380 × 350 × 58	Rotary	Finned tube	Porous media	Capillary

As can be seen in Table 2, most of the experimental systems work with R134a. This refrigerant needs to be replaced by an alternative with a lower GWP value, for example, one of those proposed as direct substitutes in larger capacity systems such as R1234yf, R1234ze, R513A, R516A, or even some hydrocarbons. However, for each particular design, different conditions will allow for better, very similar, or even worse performance after the substitution. Therefore, an experimental exploration with alternative refrigerants would be necessary for each system, indicating whether drop-in replacement is viable or needs redesign.

Another interesting aspect that can be observed in the table is the different condensation and evaporation temperatures reached by the various systems, demonstrating broad flexibility in the operation of this technology. However, an important detail to consider, which not all authors highlight in their research, is the environmental conditions to which the system was exposed, mainly temperature and humidity. As reported in the literature, these two factors directly influence the operating characteristics of the equipment, as well as its performance. In general, high levels of these parameters lead to lower system performance. To avoid these repercussions, some design considerations must be taken into account, such as proper selection of compressor type and capacity, implementation of variable speed compressors, proper sizing of heat exchangers, implementation of a moisture removal strategy, advanced control strategies such as the use of thermostatic expansion valves, and proper refrigerant selection, among others.

4. Challenges, Perspectives, and Future Directions on Small-Scale Refrigeration

The miniaturization of components and complete systems represents a new era in the development of vapor compression refrigeration systems. The main purpose of miniaturization is producing smaller, lighter, wearable, or portable systems that retain high efficiency and performance. However, scaling down these systems is not easy; there are many design, development, and manufacturing challenges. Component manufacture demands sophisticated technologies with a high degree of precision as well as elaborate processes and qualified personnel, potentially increasing costs if not mass produced. In addition, new assembly and packaging techniques need to be developed. Need for further development is evident from the fact that many of the components used in the systems mentioned in Section 3 were manufactured or redesigned by the researchers themselves.

From the authors' point of view, the challenges just listed are the main reason why the study of miniature systems remains limited, and a reduction in the number of research papers published over the last decade has even been observed. However, research is expected to increase in the coming years, since it is now possible to find both individual components and full prototypes of miniature VCR systems on the market, due to recent technological progress and multiple emerging applications, as can be seen in Figure 28.

Although miniature systems were initially developed for military purposes, the cooling of electronic components and personal cooling now receive most of the research attention, and these areas are also the focus of this review. It is, however, important to highlight that these are not the only areas of applicability: miniature VCR technology has many applications, and many more areas remain to be explored. It is therefore considered that this is fertile ground for future research, covering the new applications that have emerged over the years, including applications that promise great social benefits such as in medicine, health, and agriculture.

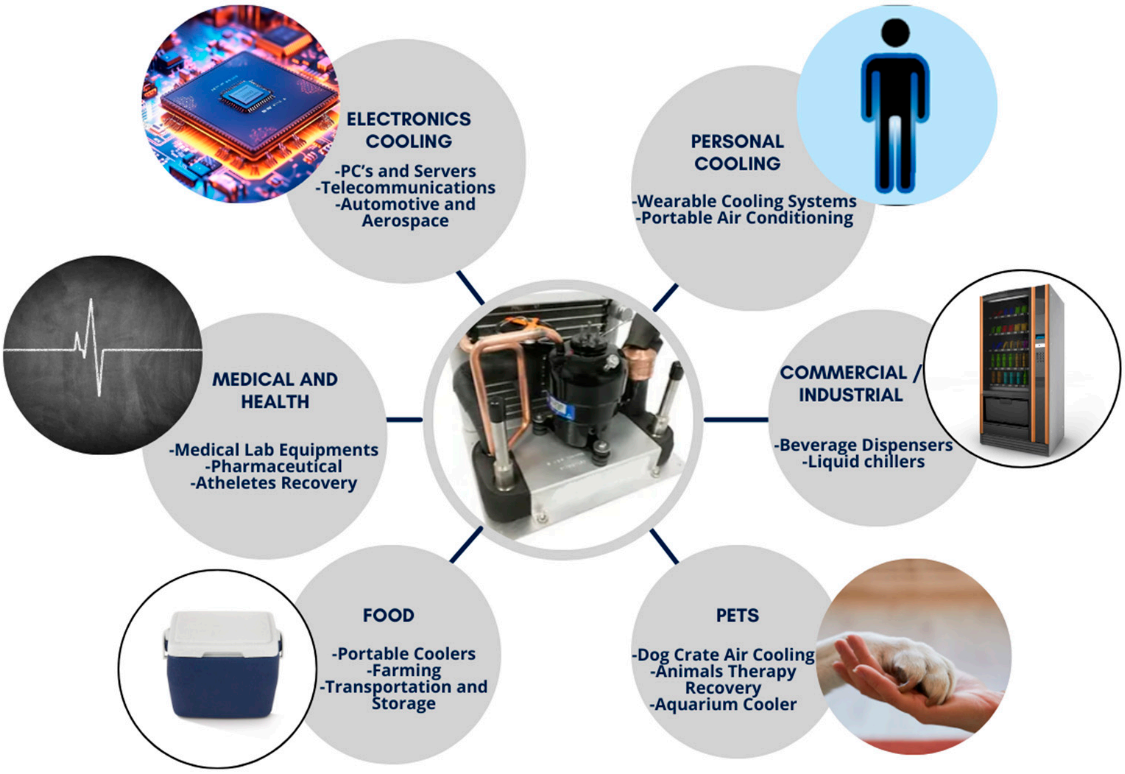

Figure 28. Areas of application of miniature VCR systems.

The industrial application of miniature refrigeration is an attractive field. Broadly speaking, a common requirement across various industrial domains is effective thermal management and heat dissipation. Some examples include the following:

- Electronics and information technology: the manufacture of electronic devices such as computers, servers, microprocessors, and similar components demands precise temperature control for maintaining performance and reliability, as mentioned in Section 3.
- Pharmaceutical and food industry: these systems can be essential to ensure the quality and safety of pharmaceutical and food products, especially those that require storage and transport at controlled temperatures.
- Automotive and aerospace sector: in the cooling of electronic systems on board vehicles and aircraft, as well as in the thermal management of critical components, miniature systems can be beneficial due to space and weight limitations.
- Medical sector: in portable or small-sized medical devices, such as portable diagnostic devices, medical imaging systems, or cooling equipment for biological samples, these systems may be necessary to ensure proper operation and accuracy of the devices.

Some constraints that could arise in the implementation of these systems are as follows:

- Commercial constraints: while major suppliers of these systems maintain an internationally accessible online market, the absence of brick-and-mortar stores and the need to accommodate delivery times pose a limitation directly affecting the affordability of the products.
- Technical constraints: given the limited availability of these systems, technicians providing services may have limited experience installing, operating, and maintaining such technology.
- Regulations and standards: in industries such as pharmaceutical and food, refrigeration systems must comply with strict regulations and standards to ensure product safety and quality. Ensuring compliance with these regulations can be a major constraint in the design and implementation of miniature refrigeration systems.

- Technological constraints: from a technological standpoint, numerous areas of opportunity exist for further enhancements in these systems, as outlined below in the context of future trends.

In conclusion, when considering the implementation of miniature VCR systems in industrial environments, it is important to carefully evaluate these specific needs and constraints to ensure project success.

Regarding the economic and social impact of adopting this technology in developing countries, it would be expected that, in being more efficient than other technologies, an economic impact related to energy savings would arise. In addition, the ability to operate with more environmentally friendly refrigerants makes these systems more sustainable, which has a social impact, as well as some applications related to the healthcare sector, food preservation, agricultural activities, and the cold chain, among others. Finally, the generation of jobs during the manufacturing, installation, and maintenance of these systems will significantly impact both sectors.

Finally, it is evident that the use of this technology for small-scale applications has not reached its maturity, since there are still many areas to be explored, so further research and development in this sector is well warranted. A clear example of this has to do with the two guidelines currently charting the path of vapor compression refrigeration. On the one hand, energy savings and improvement of the energy efficiency of these systems are sought. Some strategies to achieve this are related to potential modifications to the basic vapor compression cycle, advanced compressor designs such as variable-speed ones, improved heat exchangers with innovative heat transfer enhancement techniques, and optimized control algorithms. On the other hand, it is the evaluation of alternative refrigerants with low global warming potential (GWP) required by international agreements to replace traditional refrigerants such as R134a, which is currently one of the most common in these systems, seeking to obtain environmental benefits such as the development and availability of more sustainable miniature VCR systems that help mitigate greenhouse gas emissions. However, one of the main challenges, namely, the availability and affordability of this type of refrigerants, must be addressed due to political issues regarding each country's roadmap in the Kigali amendment.

In addition to these two routes that must be attended to, there are also other research directions and emerging trends, such as those mentioned below, which in turn could improve the scalability of small-scale VCR technology to serve a broader range of applications beyond electronics and personal cooling. The first is the integration of these systems with renewable energies as an energy source. This may include solar-powered systems or systems that use renewable energy storage for their operation, taking up the studies presented by Lei et al. [101] and Jabbar et al. [102] in this matter. On the other hand, the use of additive manufacturing (3D printing) and microfabrication to facilitate the production of complex geometries and customized components for miniature vapor compression systems is another trend. These manufacturing advances enable rapid prototyping, customization, and cost-effective production of compact refrigeration systems. Additionally, the use of artificial intelligence to achieve smart and autonomous miniature VCR systems is another area of opportunity where we could venture. Integrating smart sensors, actuators, and control algorithms enables the development of autonomous and adaptive systems that could optimize performance, adapt to changing operating conditions, and provide predictive maintenance capabilities, leading to improved energy efficiency and reliability.

Overall, the research directions and emerging trends in miniature vapor compression refrigeration systems are very similar to those being followed for larger-scale systems such as domestic, commercial, and industrial refrigeration and are driven by the need for improved energy efficiency, miniaturization, environmental sustainability, enhanced functionality, and expanded application areas. Finally, this research and knowledge dissemination stage will significantly contribute to the emergence of new developers of these systems and the growth and industrial positioning of existing ones, gaining more significant popularity and expanding their market. This is the industrial perspective for developing miniature VCR systems in the coming years.

5. Concluding Remarks

The purpose of this review was to describe the current state of the art of miniature vapor compression refrigeration, showing experimental and modeling research work carried out in recent years both for complete systems as well as for individual components, considering the different applications proposed until now. An attempt was also made to give an overview of active and passive technologies available for small-scale cooling, evidencing the advantages of vapor compression over the others. The main conclusions obtained from this review are listed as follows:

- Miniature vapor compression refrigeration appears to be the best option for many small-scale cooling applications due to advantages such as working over a wide range of operating temperatures, ability to cool down junction temperature below ambient, potential for high COP values, operation for long periods at large cooling capacity with low mass flow rates, and transport of heat away from its source. In addition, vapor compression is well suited for portable applications compared to alternative technologies that involve greater number of components and complexity.
- In the past decade, there has been a reduction in the number of research papers published on miniature vapor compression refrigeration research primarily directed toward cooling electronic components and personal cooling. However, alternative applications are currently being commercially offered in sectors such as medical, pharmaceutical, automotive, and food preservation, among others. Consequently, further research is necessary to validate their feasibility for both existing and prospective applications, facilitating widespread commercialization.
- It can be concluded that the challenges associated with component miniaturization have been a critical factor hindering widespread study and development of these systems. Many of the components used in the publications cited in this review were custom-built by researchers due to limited commercial availability, thus slowing technical progress. It is, however, anticipated that research will experience a resurgence in the coming years, given the current availability of both individual components and pre-assembled prototypes of miniature VCR systems in the market.
- The industrial sector has a strong need for effective thermal management and heat dissipation, while commercial, technical, technological, and normative aspects limit the applicability of small-scale refrigeration.
- It is finally observed that miniature vapor compression refrigeration has not reached maturity since there are still many areas to be explored, including, among others, evaluation of low GWP refrigerants, search for energy savings, improvements in energy efficiency, additive manufacturing, artificial intelligence, and integration with renewable energies. Some of these topics have been addressed for conventional refrigerators and now demand further development for application to miniature systems.

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Nomenclature

h	Enthalpy
$\dot{m}$	Mass flow rate
N	Compressor rotation speed
P	Pressure
Q	Heat rejected/absorbed
T	Temperature
W	Input power
η	Efficiency
Abbreviations	
BJ	Box–Jenkins
CC	Cooling Capacity
cc	Cubic Centimeters
COP	Coefficient of Performance
CPU	Central Processing Unit
DC	Direct Current
EES	Engineering Equation Solver
EER Energy	Efficiency Ratio
EWOD	Electro-Wetting on Dielectric
GWP	Global Warming Potential
HVAC&R	Heating, Ventilation, Air Conditioning, and Refrigeration
ITRS	International Technology Roadmap for Semiconductors
MIMO	Multi-Input Multi-Output
NSGA-II	Nondominated Storing Genetic Algorithm II
OMOPSO	Multi-Objective Particle Swarm Optimization
PCM	Phase Change Material
PECS	Personalized Environmental Control Systems
PTMS	Personal Thermal Management Systems
rpm	Revolutions Per Minute
TAC	Task Ambient Conditioning
VCR	Vapor Compression Refrigeration
Subscripts	
comp	compressor
cond	condenser
evap	evaporator
ref	refrigerant

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