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STATE OF THE ART OF MINIATURE COMPRESSORS

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ABSTRACT

Thermal management is becoming more challenging due to the increasing compactness and computational power of processors. While various cooling technologies like thermoelectric cooling, heat pipes, and liquid cooling methods exist, vapour-compression technologies demonstrate the highest power density. However, this technology is not yet sufficiently developed for small-scale systems that generate large amount of heat, such as micro- and power-electronics. In this review, we present technology trends of the development of efficient small-scale compressors used in vapour-compression systems. They are compared in terms of mechanical and isentropic efficiencies, and *COP*. Challenges associated with miniature compressors in vapour-compression systems will be presented and discussed to provide guidelines for future research and development.

Keywords: compressor, vapour compression, heat transfer, cooling, refrigeration, miniaturization, energy efficiency

1. INTRODUCTION

Thermal management in electronic devices has reached a new challenge and has thus entered a new phase. The number of passive components in electronic chips has increased exponentially, while the size and cost have decreased according to Moore's prediction (1965). However, the trend towards compact device designs has led to an intensified generation of heat per unit of space occupancy. This increased heat generation requires new cooling measures to keep operating system and local temperatures below the prescribed material and performance limits. According to the review by Benam et al. (2021) on cooling technologies for electronics with high heat fluxes, researchers propose phase-change heat transfer mechanisms, notably flow boiling. Such cooling achieves high heat transfer coefficients during flow boiling and higher heat dissipation for a given mass flow rate of the coolant.

Criteria for size classifications of compact cooling system is unclear and has not been standardized yet. Good definition was provided by Warren et al. (1999) who referred to mesoscale as characteristic length scale that ranges from tenths of a milimetre to tenths of a metre. In this review, we applied this mesoscale size criteria to miniature compressors which are designed for applications where space and weight are limited but efficient cooling is essential. Miniature systems covered in this work are the most impactful literature related to miniature compressors used in active cooling of high heat flux devices.

Agositini et al. (2007) carried out a comparative analysis of various technologies for microchip cooling, revealing notable findings. Specifically, they observed that the highest heat fluxes achieved in two-phase flow boiling in microchannels were 275 $W \cdot cm^{-2}$ with subcooled boiling, and 250 $W \cdot cm^{-2}$ with saturated boiling of water. In contrast, heat fluxes attained with refrigerants typically reach lower values, with the highest heat fluxes reported to be 94 $W \cdot cm^{-2}$, except in a single case where a heat flux of 200 $W \cdot cm^{-2}$ was achieved through utilization of the low-pressure refrigerant R245fa.

Compressor is the most challenging component of the vapour compression system in terms of its miniaturization. Barbosa et al. (2012) pointed out in their review pointed out that most studies that have dealt with applications in electronics cooling used commercially available small compressors but were not concerned about actual system miniaturization. Compressors are typically engineered to operate at high pressure ratios, resulting in relatively poorer performance when encountering lower pressure ratios often necessary for electronics cooling applications.

Compressors are generally divided into two types: positive-displacement compressors and dynamic compressors.

Most representative positive-displacement compressors in refrigeration industry are reciprocating, screw, scroll, and rotary-vane compressors, and centrifugal for the dynamic compressors. Further classification between various compressors can be based on the methodology employed in their construction. We differentiate between open-drive, semi-hermetic, and hermetic compressors. The latter are usually used in miniature vapour compression systems due to clear advantages, e.g., sealed system, compact design, reduced vibrations and noise, ease of installation, reliability, durability, and energy efficiency.

2. MAIN SECTION

The main part of the paper showcases different types of compressors used in research of miniature cooling vapour compression devices. The subsections are divided into linear, rotary-vane, screw, centrifugal, and multi-stage compressors. In the final subsection we examined miniature compressors utilized for other applications, such as cryogenic cooling.

2.1. Linear compressor

Unlike traditional reciprocating (piston) compressors that use a crank mechanism to achieve linear motion to compress the refrigerant gas, linear compressor's reciprocating motion is achieved by using linear motor, like it is shown in Figure 1. In comparison to rotary-vane compressors, linear compressors have many advantages, including high efficiency, simple control, and oil-free operation (Liang et al., 2014). This gives a significant advantage regarding heat transfer performance of the condenser and the evaporator in a refrigeration system.

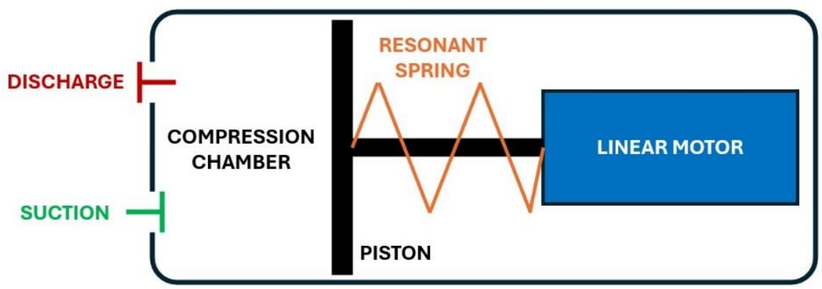

Figure 1: Schematical representation of linear compressor

A review paper by Liang (2017) presents various designs and modelling of linear compressors for use in domestic refrigeration and the cooling of electornics with miniature vapour-compression systems. Main challenge they mention is high cost due to the use of expensive permanent magnets, and special manufacturing processes.

Unger and Novotny (2002) presented a high-performance compact oil-free linear compressor for cooling multiple CPUs in server computer applications, developed by Sunpower in collaboration with Sun Microsystems. Compressor used refrigerant R134a and could provide 1250 W of cooling capacity with *COP* of 3.6 at evaporation and condensation temperatures of 20 °C and 55 °C, respectively. Additionally, they presented an even smaller compressor for cooling a single processor. Such compressor in size of Ø 38 mm × 150 mm could fit onto the mother board of a desktop computer and could provide cooling capacity in the range of 150–200 W. The study, however, did not include solutions and optimisations of the entire vapour-compression cooling system.

The development backlog in the field of linear compressors has been slowly closing over the last decade. Wang and Tai (2010) presented a prototype of miniature linear compressor, also based on the Sunpower's design. Researchers concluded a comparison of theoretical and experimental results between characteristics of magnetic foce, piston displacement and volumetric flow. Characteristics were similar but between them is an apparent difference according to too much leakage and friction. Maximum piston displacement was 7.2 mm in theoretical model, and 6.5 mm in experiment. Optimum frequency is 16 Hz in theoretical calculation, and 12 Hz in the experiment.

Bradshaw et al. (2011, 2012) presented a comprehensive model of a miniature linear compressor for electronics cooling that predicted the dynamic behaviour of the piston. The model incorporated all major sub-models associated with piston motion: valve flow model, leakage model, vibration model, and heat transfer model. Chosen working fluid was refrigerant R134a. The model was experimentally validated with custom-designed and built prototype compressor due to no commercially available ones. Model predicted piston stroke of 5.8–6.6 mm and was within 1.3 % of mean absolute error. Due to slight variation of the piston stroke, which depends on the operating conditions, it affected volumetric efficiency. This varied from 0.1 to 0.65 and was within 24 % of mean absolute error. Overall isentropic efficiency of 0.015–0.058 was significantly lower than any of typical commercially available compressor. Researchers claimed it can be significantly improved, as the prototype's purpose was only to validate the model. Bradshaw et al. (2013) continued with their work with the sensitivity analysis of compressor model. Researchers explored key parameters governing compressor performance: leakage gap, eccentricity, and piston geometry. Authors showed that leakage gap and frictional parameters should be minimized in order to achieve optimum performance.

Recently a numerical model of the vapour injection linear compressor for any refrigerant was developed and validated by Li et al. (2024). They proved that cooling capacity is lower at lower working frequencies, but it increases more greatly with increased supply voltage. Based on the cooling characteristic they obtained, a control strategy was proposed to meet desired cooling performance. Driving frequency and supply voltage were being adjusted oppositely to maintain a constant cooling ratio or cooling capacity. Researchers also found that structural parameters like larger vapor injection area and smaller distance to the top death center increase overall cooling performance.

Liang et al. (2014) tested a prototype moving magnet linear compressor in a refrigeration system using R134a refrigerant. Motor efficiency ranged from 75 % to 68 %, and the isentropic efficiency varied between 32 % and 44 %. *COP* of the system ranged between 1.3 and 3.2 for evaporating temperature between 6 °C and 21 °C, and condensation temperature of 54 °C, reaching 384 W cooling capacity at the highest *COP*. This performance data indicated a possible use of the system for electronics cooling.

Another oil-free dual piston compressor was tested by Sun et al. (2021) in a refrigeration system with refrigerant R134a. Results were compared with conventional compressor operated by crank mechanism. *COP* of the linear compressor varied from 5.34 to 2.9 for evaporating temperatures between 5 °C and 10 °C, and condensation temperatures in range of 35 and 54.4 °C. Results were compared with conventional compressor operated by crank mechanism, which showed that linear compressor's *COP* is higher than conventional for around 80 %. Maximum motor efficiency, volumetric efficiency, and isentropic efficiency of the linear compressor were 87.9 %, 79.1 %, and 63.7 %, respectively.

2.2. Rotary-vane compressor

Rotary compressors in general belong to the category of positive displacement machines and include screw, spiral, vane, and piston rotary compressors. This subsection focuses on rotary-vane compressors, whose main advantage over reciprocating piston compressors is their better overall efficiency. In rotary-vane compressors, there are no so-called dead volume and losses associated with the re-expansion of the coolant during its suction into the cylinder. In addition, rotor with vanes rotates continuously while the piston in the reciprocating compressor moves from the upper to the lower position, stopping momentarily in the extreme positions. Their compression cycle is shown in Figure 2. Rotary-vane compressors are lighter in weight, experience less vibrations, typically also have lower heat losses, and fewer sealing problems. Their main disadvantage compared to other types of compressors is achieving and maintaining high pressure differences.

Heppner et al. (2007) designed a rotary compressor based thermally insulated micro-cooler. It was a hybrid micro-scale system consisting of microfabricated components including microchannels, in plane microelectromechanical (MEMS) valves, and MEMS temperature, pressure, and flow sensors integrated with mesoscale. The design of the Wankel rotary compressor utilizes a 367 mm^3 displacement. Compressor's size is 25 mm × 30 mm × 6.25 mm. System's performance was analysed with thermal resistance model, which included thermal resistance across the evaporator insulation, thermal insulation of the compressor, and device layer thermal resistance. System operated using R134a and achieved 45 W of cooling power with *COP* of 4.6 at evaporation and condensation temperatures of -15 °C and 37 °C, respecitvely.

Sathe et al. (2008) experimentally evaluated comercially available miniature rotary compressor for applications in electronics cooling. Aspen compressor A4–24–1101 of size Ø 56 mm × 78 mm working with refrigerant R134a, achieved volumetric efficiencies in range of 73–90 % and isentropic efficiencies in range of 44–70 % for pressure ratios between 2 and 3.5. For this range of pressure ratios, the estimated cooling capacity and the *COP* varied from 163–489 W and 2.1–7.4, respectively. Compressor was compared with two other miniature compressors: Engel rotary compressor and Hitachi reciprocating compressor model XL0623D1. The comparison indicated that Aspen compressor performs better in terms of the efficiencies and cycle *COP*. With its small size and low weight, the compressor has the potential for use in miniature vapour-compression systems for electronics cooling. Compressor was furthermore used in miniature vapour compression refrigeration system for electronics cooling in investigation by Poachaiyapoom et al. (2019). Results showed *COP* in range 3–9, and exergetic efficiency of 60 to 83 %. Evaporating temperature and superheat were in range from 3 to 22 °C and 4 to 33 °C, respectively, for cooling capacities of 100 to 200 W.

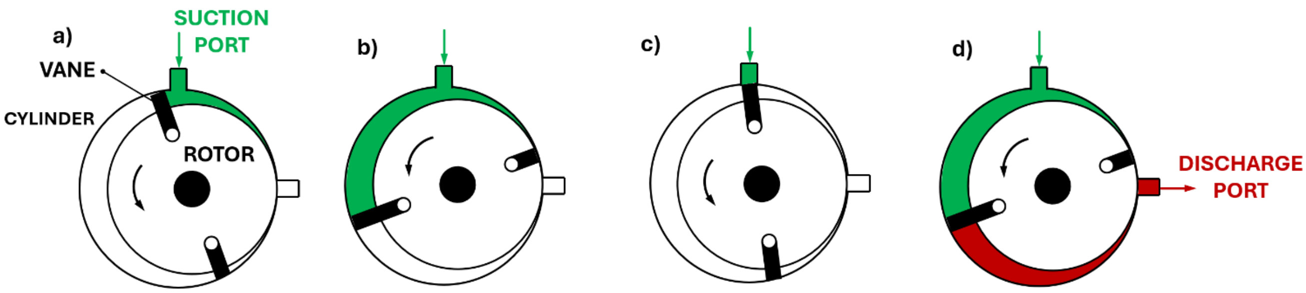

Figure 2: Four stages of the compression cycle for rotary-vane compressor: a) Start of the suction phase, b) Suction phase, c) Suction phase ends, d) Start of discharge phase with a new suction phase

Influence of microgravity on performance of the compressor was tested by Ma et al. (2016) on previously miniature Aspen A4–24–1101 compressor with refrigerant R134a in two different positions – upright and inverted. *COP* at low speed of the compressor was 1.2 times higher in inverted positions compared to upright position, however exergy efficiency of the upright position was still higher for approximately 42 %. Most importantly, vapour compression system could normally operate in inverted mode for period of time. Rotor and stator were still in dynamic equilibrium state, but oil couldn’t lubricate moving parts. Compressor ran fine until there’s was no more oil that was left on the internal components in the initial state. Compressor is therefore considered gravity independent, and results showed potential applications in spaces of micro or zero gravity.

Influence of tilt angle was tested by Chen et al. (2017) also on miniature Aspen rolling-piston rotary compressor with refrigerant R134a. It was found out that when the tilt angle exceeded a certain angle, the compressor couldn’t run and stopped for self-protection. The oil level on the bottom of the compressor became so low that it couldn’t lubricate the corresponding moving parts, which lead the compressor to the state of oil starvation. Due to inclination rotor and stator fell out of dynamic balance, outer wall of the rotor therefore encountered the inner wall of the stator increasing friction, torque, and current. Maximum tilt angle of the compressor at low-speed operation was 60 °, but when compressor’s speed reached 4000 rpm, maximum tilt angle was 20 °.

2.3. Screw compressor

Screw compressors embody a mechanism featuring two interlock screws, known as rotors. Through rotational motion they draw the refrigerant through the inlet port to inter-lobe volume. When inter-lobe volume reaches full capacity, suction ceases and refrigerant is propelled to small space, causing compression, like it is shown on Figure 3. Due to intricate meshing of the rotors, screw compressors necessitate enough lubcrication.

Dmitriev et al. (2015) presented miniature conical rotary-screw compressor developed by VERT Rotors that guarantees minimal vibration levels. Measuring 87.6 mm × 67 mm, the compressor features a 40 mm long screw. Employed within a Carnot-like refrigeration cycle with krypton used as refrigerant, the compression ratio stands at 1:12, with an evaporation temperature of -153 °C. With a power consumption of 16 W and a cooling capacity of 20 W, the compressor can attain a *COP* higher than 1. Researchers Dmitriev and Arbon (2017) continued their work with comparioson of energy-efficiency of 2 kW water-injected conical compressor in comparison with scroll compressor of similar capacity. At 8 bar pressure load, the conical screw compressor used 13 % more energy but produced 42 % more mass flow.

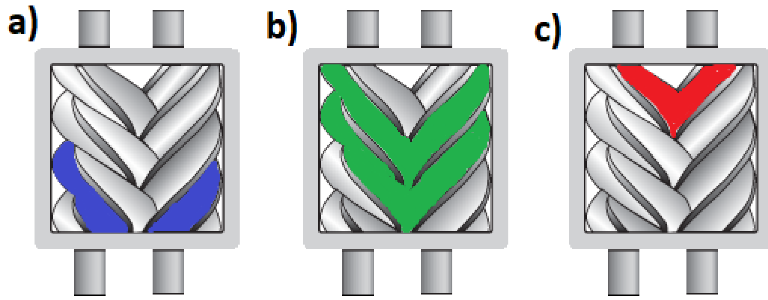

Figure 3: Stages of screw compressor: a) Suction, b) Compression, c) Discharge

2.4. Centrifugal compressor

A centrifugal compressor is a dynamic type of compressor. Unlike positive displacement compressors, which trap and compress gas within a fixed volume, centrifugal compressors use centrifugal force to increase the velocity of the refrigerant gas using a rotating impeller and subsequently convert that kinetic energy into potential energy/static pressure, creating pressure difference between the inlet and outlet of the compressor.

Barsi et al. (2018) designed a compressor and turbine for micro-gas turbine. Researchers used multidisciplinary design optimisation (MDO), which is widely employed to enhance turbomachinery components efficiency. Work is technically not related to cooling of electronics, but design and research results could contribute to the field of miniature Brayton cooling systems. Results showed an increase of compressor's isentropic efficiency from 0.8 to 0.84. The increase of isentropic efficiency was shown on turbine as well, from 0.87 to 0.93. This brought state of the art overall efficiency from a starting value of 30 % up to an optimized value of about 36 %. Apart from higher efficiencies, researchers found that Von Misses stress fields went below the allowable limits and therefore increased life span of the turbomachine.

Similar loss development analysis of a micro-scale centrifugal compressor was conducted by Tiainen et al. (2018). Analysis mostly focused on overall performance deterioration, and the differentiation of the losses originating from different causes. Researchers above all highlighted a fact that decreasing Reynolds number has a negative effect on centrifugal compressor total-to-total efficiency. Results of the analysis showed that at low Reynolds number blade and endwall boundary layer thickness increased from 30 % to 36 %, and from 45 % to 62 %, respectively. This causes an increase of blockage from 5 % to 9 % due to increased radial velocity. In order to improve the performance of the centrifugal compressors operating at low Reynolds number, researchers claim that boundary layers near the impeller hub, and especially in the diffuser, should be suppressed. This however can be problematic in micro-scale gas turbines due to big size and weight of control devices for boundary layer acceleration or suction. Future work therefore should not only focus on increasing overall total-to-total efficiency of compressor but also development of an innovative means of boundary layer control without the need for external control devices.

Giuffre et al. (2022) studied the effect of size and working fluid on the design of high-speed single-stage centrifugal compressors by means of a reduce-order model, which was validated with experimental data. They found that compressor stages operating with fluids made of heavy and complex molecules exhibit lower total-to-total efficiency. Fluid molecular complexity itself has a minor influence on the stage operation range, however, has a great effect on axial thrust acting on the bearings. More complex-molecule fluids, e.g. R1233zd result in lower axial thrust. Simple-molecule fluids, e.g. argon or hydrogen are therefore quite suitable for the use of oil-free gas bearings. Compressors small in size usually result worse than their bigger counterparts regarding the total-to-total efficiency. This is a result of manufacturing constraints that lead to higher relative tip clearance and higher relative surface roughness. However, the size has quite negligible influence on the shape and the position of optimal efficiency.

2.5. Multi-stage compressor

Liu et al. (2019) evaluated volumetric and isentropic efficiency of a miniature multi-stage swash plate compressor with integrated inter-stage cooler and air as working fluid. Results showed that for every 10 K increase in suction temperature, the volumetric efficiency of first, second, third and fourth stage reduced by an average of 1.43 %, 1.86 %, 2.32 % and 2.56 %, respectively. Isentropic efficiencies are also reduced by about 1 %. It is also shown that with higher pressure, the valve is more sensitive to suction temperature. After temperature exceeded 120 °C, 70 °C, and 50 °C for second, third, and fourth stage of the cylinder, the value fluttered severely and the air mass per cycle through suction valves reduced sharply.

There hasn't been much work on multi-stage compressor for such small scale we refer to in this article, however, depending on the last reference, multi-stage compressors could satisfy the demand of compactness and lightness to use them in micro vapour compression systems for electronics cooling. Further research in this area should focus on assembling an experimental track of vapour compression system with multi-stage compressor test compressor and system's parameters with different refrigerants.

2.6. Other applications

Miniature compressors are also used in cryogenics. Cao et al. (2022) experimentally and numerically investigated a cooling performance of Hampson-type Joule-Thomson cooler driven by linear compressor. The cooler had a cooling power of 198 W at -128 °C. Gong et al. (2015) used mini oil-lubricated rotary compressor in their Joule-Thomson cooler. The lowest temperature they reached was -133 °C. Sobol et al. (2015) used miniature piezoelectric compressor in their cryocooler design. Achieved maximum operation frequency was 200 Hz, which provided 0.02 $g \cdot s^{-1}$ flow rate of mixed refrigerants.

Khalid et al. (2022) presented modular C-core moving magnet linear oscillating actuator, which could be used as a miniature compressor in miniature vapour-compression systems. Compared to conventional topologies of linear compressor, the novel one should generate more electromagnetic force at lower current values. Due to reduced permanent magnet volume, the overall volume is minimized by 10 % compared to conventional design. This also means lower production cost of the proposed compressor.

3. CONCLUSIONS

This review emphasises the central role that miniature compressors play in various applications, particularly in the cooling of miniature electronic devices. Several articles highlight the loss of system efficiency, primarily attributed to compressor inefficiencies. As a result, forthcoming research endavours should give precedence to designing and developing a more efficient compressor, serving as a focal point for enhancing system's exergetic efficiency.

Miniature compressor research and development therefore lags behind other components in vapour compression systems due to its greater complexity and multidisciplinarity. However, future research should prioritize several key areas: expanding cooling envelopes of miniature compressors while maintaining compactness and cost-effectiveness, integration of machine learning with adaptive control strategies tailored to specific applications, and exploration of novel materials and innovative design methodologies during manufacture of such compressors.

The most promising type of compressor for miniaturization is linear compressor due to its clear advantages regarding high-efficiency and simple control, however their high cost of manufacturing due to use of rare earth materials should be minimized as much as possible. Rotary-vane compressors already follow desired path of miniaturization, future research however should focus on substitution of R134a refrigerant. Refrigerants with tendency of reaching desired condensation and evaporation temperatures at lower pressures and pressure ratios should be prioritized due to clear disadvantages rotary-vane compressors have in this case. Miniaturization of compressors should not be neglected with other types of rotary compressors (scroll, screw, and centrifugal compressors), which could work better with higher pressure ratios.

The widespread adoption of R134a as a refrigerant is likely due to the extensive availability of two-phase flow correlations and compressor data for this particular working fluid. Nevertheless, there is a growing imperative to prioritize environmentally friendly refrigerants with reduced global warming and ozone depletion potentials. The most promising alternatives, given their favorable environmental impact are hydrocarbons (HC) as part of natural refrigerants, hydrofluoroolefins (HFO), and hydrochlorofluoroolefins (HCFO). It is important to consider refrigerants with lower working pressures, which are mostly used in electronics cooling. In HC group best alternative would be R600a (isobuatne), however, R2900 (propane), R1270 (propylene), and R717 (ammonia) could be used for cooling electronics on bigger scale, e.g. server racks. In HFO and HCFO group probable alternatives would be 1234ze(E), and R1233zd(E), especially with integration of centrifugal compressors into vapour compression systems. It is also crucial to note that materials selected for the system should exibit excellent corrosion resistance and compatibility with environmentally friendly refrigerants. Systems should also keep refrigerant charge as minimal as possible due to higher flammability of refrigerants (HC group) and in some cases even higher toxicity, e.g. ammonia.

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