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Review

Key Technologies and Application of Electric Scroll Compressors: A Review

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Abstract: The electric scroll compressor is driven by a built-in electric motor that rotates the scroll disk. It is known for its simple structure, adjustability, and high efficiency, making it highly promising for various applications. This paper reviews the current application and research status of electric scroll compressors. It covers topics such as the optimal design of scroll compressor profiles, scroll disk leakage sealing, and computer simulation optimization design methods. Additionally, the progress and development trends of vapor-injection scroll compressors (SCVIs) are discussed. This paper also presents the latest research progress on the application of the new refrigerant CO_2 in electric scroll compressors, along with its latest applications that align with sustainable development requirements. Finally, this paper concludes with recommendations for the application of electric scroll compressors and suggests future directions for research.

Keywords: electric scroll compressor; scroll profile; leakage sealing; vapor injection; CO_2 scroll compressor

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1. Introduction

Driven by the goal of sustainable development, many countries and corporations have focused on researching and developing electric vehicles (EVs). EVs are favored by consumers for their advantages such as environmental friendliness, economy, quietness, and low operating costs. Within EVs, heat pump air conditioning (HPAC) systems are crucial for regulating cockpit temperature to ensure a comfortable driving environment for occupants [1,2]. The HPAC system is the main power-consuming auxiliary equipment in automobiles, and the electric scroll compressor accounts for about 65% of the total power consumption of the air conditioning system. Improvements in the compressor performance will raise the efficiency of the system and reduce the consumption of electricity [3,4]. Therefore, analyzing the factors influencing the electric scroll compressor's operation is essential for optimizing its design and enhancing efficiency. The motor and compressor of the electric scroll compressor feature an integrated structure design, offering benefits such as smooth operation, lightweight construction, and infinite speed regulation. This technology finds extensive applications in refrigeration, air conditioning, and gas conveying, promising a wide range of potential uses and significant economic advantages [5,6].

This paper reviews various techniques for profile optimization correction, secondary compression, leakage sealing, and the computer simulation optimization of electric scroll compressors. It also discusses the impact of SCVIs on improving the operational performance of scroll compressors and provides an overview of the latest research progress on the application of CO_2 as a new environmentally friendly refrigerant in electric scroll compressors.

Finally, this paper presents the future development trends and application prospects of electric scroll compressors, including intelligent control, new materials and processes, and new refrigerants. In the future, these compressors will continue to leverage their advantages and play a significant role in various fields, becoming an important force in promoting sustainable development and energy structure transformation.

2. Developments Related to Electric Scroll Compressors

In 1905, French engineer Leon Creux applied for a patent of the scroll-type machine, which is the earliest research on the technical aspects of scroll machinery in history [7]. With the rapid development of scroll machinery, scroll compressors are now widely used in air-conditioning systems, transport systems, and power engineering.

2.1. Working Principle of Scroll Compressor

Scroll compressors with the same parameters of the orbiting and fixed scroll profiles are mounted together with the base circle centers at a distance of r and in phase with each other by 180°. This forms several pairs of closed crescent-shaped working chambers between the orbiting and fixed scrolls, whose planar projection is shown in Figure 1. Inside the compressor, the fixed scroll is fixed on the frame, while the orbiting scroll is driven by the motor around the fixed scroll for circumferential orbital motion of radius R_{or}, to achieve the periodic change in the volume of the closed working chamber [8].

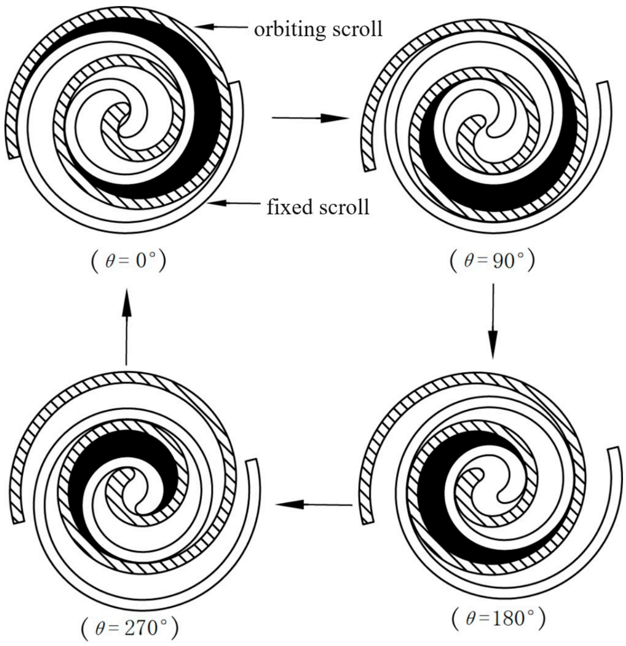

Figure 1. Working process of a scroll compressor.

A schematic diagram of the working process of the volumetric chamber corresponding to the compressor spindle angle at four specific positions (0°, 90°, 180°, 270°) is shown in Figure 1. When θ = 0°, the outermost working chamber is closed, and the volume of working fluid filling the outermost working chamber is the suction volume. As the spindle angle increases, the volume of the crescent-shaped working chamber gradually decreases, as indicated by the black parts corresponding to 90°, 180°, and 270° in the figure, thus achieving compression of the working fluid.

2.2. Research on Materials and Manufacturing of Scroll Compressors

With advancements in machining and material science, scroll machinery has seen notable enhancements in processing efficiency, accuracy, and application versatility. It has now become a crucial and indispensable piece of equipment in modern manufacturing industries. To minimize the weight of electric scroll compressors, aluminum alloy scroll plates are commonly utilized. These plates are typically made from a silicon aluminum alloy with specific hardness values to ensure wear resistance, with an aluminum content of 89.3% and silicon content of 7.54% [8]. Jiang et al. [9] proposed an integrated computer-aided design (CAD) and computer-aided engineering (CAE) approach for the design and manufacturing of scroll compressors. Park et al. [10] applied the Darveaux method, considering the

Bauschinger effect in ductile materials, to assess the fatigue life of aluminum alloy scroll compressors. Ji et al. [11,12] developed a technique for depositing diamond-like carbon films (DLCFs) onto scroll surfaces using unbalanced magnetron sputtering technology, while considering mechanical properties and surface treatment methods. Compared to anodized oxide film (AOF), DLCF provides a more uniform and compact surface, enhancing wear resistance. He et al. [13] utilized an unbalanced magnetron sputtering technique to sputter the orbital scrolls of scroll compressors and coated them with a Cr transition layer to improve bond strength.

2.3. Research on Experimental Methods of Electric Scroll Compressors

In order to test the efficiency and performance coefficient of the electric scroll compressor, researchers conducted experimental studies on the transmission system, control system, and durability of lubricating oil of the compressor under different environmental temperatures and compressor speeds.

Masahiko et al. [14] developed a small, lightweight, and efficient scroll compressor, where the motor and orbiting disk are integrated within a single housing. The total volume of an electric scroll compressor is reduced by 17% compared to a conventional scroll compressor connected to the engine via a belt. To adapt to the demanding working environment of EVs, the developed electric scroll compressor exhibits excellent heat resistance and vibration resistance, while also demonstrating low vibration and noise levels. Yu et al. [15] established a structure of the scroll compressor, which is shown in Figure 2 and consists of a fixed scroll plate, orbiting scroll plate, discharge port, and crank shaft.

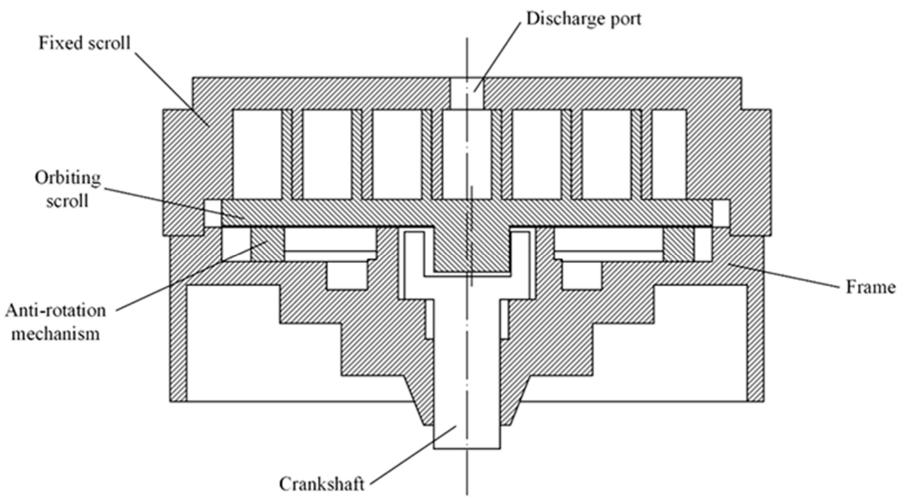

Figure 2. Structure of scroll compressor by Yu [15].

Wei et al. [16] conducted experimental research on the impact of swash plate variable displacement compressors and electric scroll compressors on the thermal HPAC system of EVs under various operating conditions. The results of this study show that as the ambient temperature rises to a particular level, the cabin temperature rises along with the compressor speed. Moreover, when the environmental temperature is above −5 °C, the electric scroll compressor system exhibits a higher average in-cabin temperature compared to the swash plate variable displacement compressor. Joerg et al. [17] comparatively analyzed the rotary piston, axial piston, and scroll compressors used in EVs. Detailed geometrical and physical numerical simulations of each compressor were also carried out to comparatively analyze the compressor efficiency and coefficient of performance (COP). Meanwhile, the electric motor (EM2) of the electric scroll compressor is connected to the drive motor (EM1) of the EVs through a belt, as shown in Figure 3. This new power system combines the advantages of traditional fuel vehicles and EVs, allowing for the more flexible adjustment of the power system's operation mode and selection of the most suitable driving mode according to demand. In urban transportation, if the motor efficiency (EM2) of the electric compressor is higher than that of the vehicle's main motor (EM1), then the compressor motor (EM2) can contribute to the vehicle's power system. This combined drive approach can further improve the whole power system efficiency [18]. The results of this study bring new possibilities to the development of energy conservation, emission reduction, and automotive power systems.

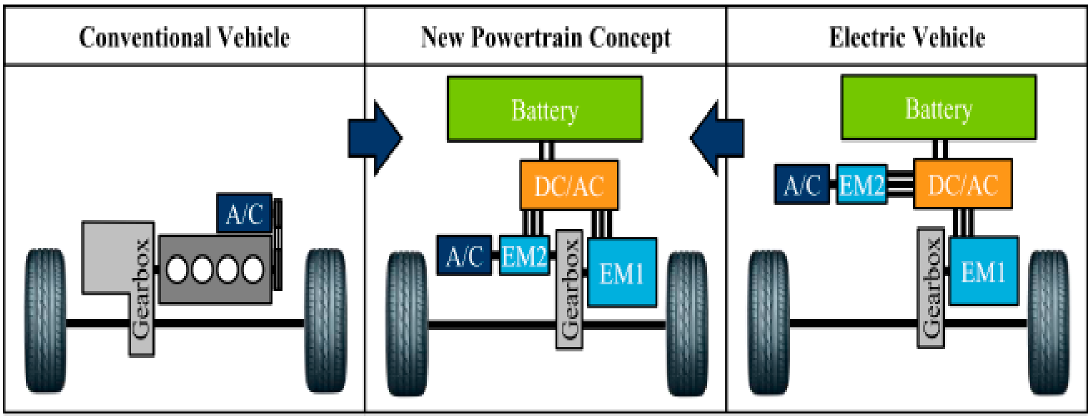

Figure 3. Drive train structure outlined by Joerg [18].

Kim et al. [19] developed an electric compressor driver based on a 3.5 kw switched reluctance motor to design and build a compact and energy-efficient scroll compressor. Similarly, Seong et al. [20] aimed to enhance the power block of a converter for the control system of a scroll compressor in a 48 V mild hybrid vehicle, encapsulating the electric motor, scroll mechanical structure, and three-phase inverter to improve system performance and achieve high reliability.

In order to optimize the oil charge of an electric scroll compressor, Nam et al. [21–23] conducted a system performance test by increasing the amount of POE lubricant from 40 g to 120 g at intervals of 20 g. Wang et al. [24] investigated the effect of two lubricants, PAG and POE, on the lubrication and durability of compressors. The experiment involved testing the compressors at different speeds. The test data revealed that the discharge temperature of the PAG compressor was consistently higher than that of the POE compressor. The studies indicated that POE lubricants exhibit better durability compared to PAG lubricants. Table 1 shows the reported performance of the electric scroll compressor (in chronological order).

Table 1. Reported performance of electric scroll compressor (in chronological order).

Authors	Year	Pressure Ratio	Isentropic Efficiency	Refrigerant	Oil
Cuevas Cristian [25]	2009	2~3	0.67	R134a	POE
Wang Dandong [26]	2018	4.5~6.2	0.85	R134a	--
Zheng Siyu [27]	2020	2.82	--	R744	oil-free
Pereira [28]	2020	0.2~0.9	--	R134a	--
Rak Jozef [29]	2020	1.62	--	CO_2	oil-free
Zheng Siyu [30]	2021	1.64~2.82	0.40~0.50	CO_2	oil-free
Sun Shuaihui [31]	2022	3.92~4.58	0.15~0.6	R134a	--
Zhang Shuai [32]	2023	14	--	R134a	POE

3. Theoretical Research on Electric Scroll Compressor

The research and development of electric scroll compressors is currently a popular and rapidly advancing area. This section provides a summary and analysis of the theoretical research progress in electric scroll compressors, with a focus on profile optimization studies, leakage studies, and computer simulation studies.

3.1. Research on Profile Optimization Theory

The profile design determines the technical performance level of the compressor, and researchers have been committed to improving the profile design to enhance the efficiency, stability, and reliability of scroll compressors. Common single profiles include circular involutes, involutes of variable circle radii, and algebraic spirals. The appropriate profile design can be selected according to the specific performance requirements. To improve the compression ratio and increase the stroke volume, researchers combine multiple single profiles of different types to form a combined profile, which takes into account the advantages of each single profile. Liu et al. [33] established a scroll compressor profile consisting of a variable-radius base circle involute and gave a volumetric expression for the scroll line. The scroll disk gradually reduces in size, resulting in better reliability and mechanical efficiency compared to scroll compressors with the same dimensions.

Takahisa et al. [34] developed Perfect Meshing Profile (PMP) scroll profiles with essentially zero clearance volume at the end of the discharge, as shown in Figure 4. From the red circles in the figure, it can be seen that there is a gap in the volume present at the end of the discharge for conventional profiles compared to PMP profiles. Theoretical and experimental studies were also conducted to analyze the internal stress, performance, and noise of the scroll compressor with a PMP profile.

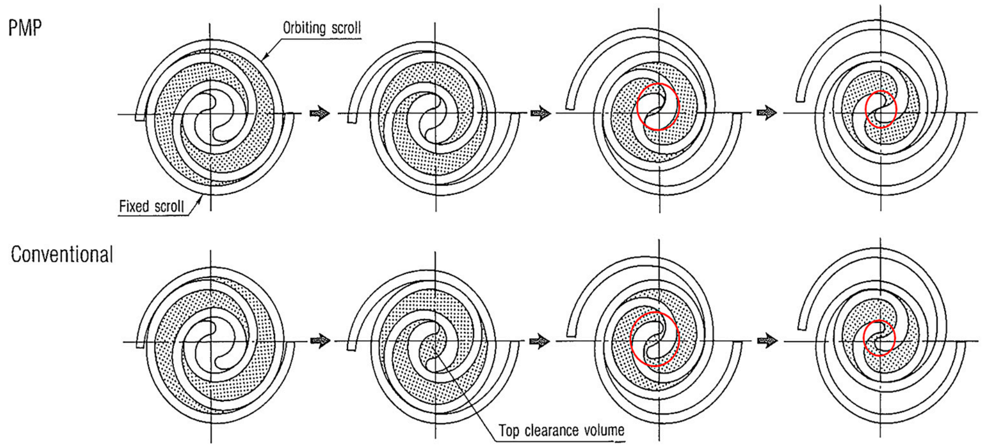

Figure 4. Characteristics of PMP and conventional profile described by Takahisa [34].

Wang et al. [35] established a unified form of general-function integral scroll profiles using Taylor series expansion for four common scroll profiles. This advancement has contributed to the improvement in the general function theory of scroll profiles. Additionally, the researchers investigated the method of determining the conjugate meshing curve using the envelope method and derived the conjugate meshing condition for the general-function integral scroll profile, and the expression of the conjugate profile in the right-angle coordinate system was also derived. Xiao et al. [36] proposed an optimization design for the geometrical parameters of the scroll compressor profile using a chaos particle swarm optimization (CPSO) approach. In their study, they simplified the leakage loss power and friction loss power of the scroll compressor into leakage line length and tangential gas force, which were then optimized. This optimization process resulted in a smooth convergence of parameters. Pin et al. [37,38] established a scroll disk profile composed of a circular involute, higher-order curve, and circular arc. The researchers analyzed the variation in the scroll disk working volume with spindle angle. Additionally, they established geometric, thermodynamic, and kinetic models for the variable-cross-section scroll compressor and built a test rig to validate their models. Wang et al. [39] developed a parametric model to determine the tangential angle coefficients based on the characteristic features of the general scroll profile, and also established a model for the cylindrical pin anti-rotation mechanism to address the dynamic characteristics of the anti-rotation structure. A virtual prototype model was created using UG software, which involved constructing a three-dimensional

(3D) solid model of the dynamic scroll disk and other components. Liu et al. [40,41] introduced a compound profile for calculating the pressure and temperature inside the compression chamber using computational fluid dynamics methods. In comparison to a single-profile (circular involute) equal-section scroll compressor, a variable-section scroll compressor with a combination of profiles (base circle involute plus variable base circle radius) exhibits superior geometric and mechanical properties. The uniform pressure distribution of the flow field inside the scroll chamber reduces refrigerant leakage and mass flow rate fluctuations. Zhang et al. [42] designed an electric scroll compressor with variable-wall-thickness scroll profiles, incorporating symmetrical circular and straight line corrections at the beginning of the scroll profile to improve the discharge port and minimize discharge loss. This study also introduced classification methods and evolution analysis techniques for various scroll cavities.

3.2. Research on Computer Simulation Optimization

In the field of fluid dynamics simulation, a 3D model of an electric scroll compressor can be created and analyzed using simulation software. By defining boundary conditions and operating parameters, the gas flow and pressure distribution inside the compressor can be analyzed. Grid generation technology plays a key role in the advancement of fluid mechanics. Through the computational fluid dynamics (CFD) simulation output, the evolution of the internal flow field in a scroll compressor over time, as well as the distribution of pressure, velocity, temperature, and density, can be understood. This, in turn, guides the optimized design of the scroll compressor and ensures that the compressor works efficiently [43].

Cuevas et al. [25,44] conducted modeling simulations and experiments to verify the operating characteristics of an electric scroll compressor. Liu et al. [45] proposed a profile with a variable base circle radius, consisting of an involute, and investigated the structure using finite element analysis. The newly designed scroll profile showed improved performance. Ahn et al. [46] analyzed the bearings of scroll compressors, taking into consideration the actual bearing geometry conditions. They proposed an 'overturning coefficient and thrust load map' to ensure proper operation of the thrust bearings. Kim et al. [47] developed a model for the quasi-dynamic lubrication of thrust bearings and provided a detailed discussion on the pressure distribution and friction losses on these bearings. Luo et al. [48] utilized Ansys simulation software to analyze the deformation and stress distribution of the scroll disk. Ding et al. [49] established a 3D transient flow model for an algebraic spiral scroll compressor with a pressure-reducing valve. Theoretical calculations and experimental verification were conducted on the simulation model, and the findings showed that compared with compressors without pressure-reducing valves, the maximum over-compression pressure can be reduced by 80 kPa. Abhishek et al. [50] developed a novel mixed-timescale heat transfer technique for simulating thermal loads. Zhang et al. [32] constructed a CFD model of the motor and inverter to study temperature distribution through simulation, while experimental measurements were conducted at three points on the compressor shell. The deviation between the simulation and measurement results does not exceed ± 3 °C.

To further investigate the impact of discharge ports on scroll compressors, Cavazzini et al. [51] conducted a study on optimizing the shape of the compressor's discharge port. The authors found that a non-circular shape, resembling a longer bean shape, was more effective for discharge. In a similar vein, Zhao et al. [52] built a 3D non-stationary CFD model to analyze the discharge port of an electric scroll compressor. Figure 5 illustrates three circular discharge ports positioned in different locations. In addition to the baseline position, two other positions are achieved by translating the baseline position along the x-axis by 2 mm and 4 mm, respectively. The study results indicated that the pressure variation during the discharge process was influenced by the time difference between the two central chambers of the conventional circular discharge port. Therefore, the design of the new discharge port should promote the advancement of the discharge time of the upper center chamber while delaying the discharge time of the lower center chamber. Zheng et al. [27] focused on a horizontal scroll compressor that used CO_2 as the working fluid. They conducted CFD simulations to examine the entire process of the CO_2 working mass within the compressor. The pressure in the suction chamber fluctuates due to the 'pre-compression' effect during the intake process. Additionally, the asymmetry of the discharge ports leads to the occurrence of 'over-compression'.

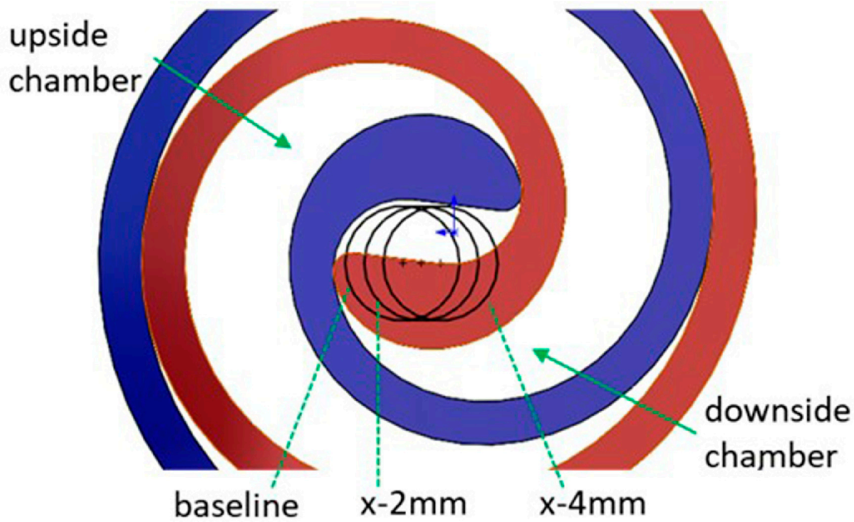

Figure 5. Three different discharge ports as described by Zhao [52].

3.3. Research on Leakage Sealing

The electric scroll compressor's orbiting scroll disk generates two types of leakage paths as it rotates alongside the main shaft: radial leakage and tangential leakage. The mixed mass leaks through the axial gap in the radial direction and through the radial gap in the tangential direction. To enhance the compressor's reliability, various sealing solutions can be employed based on the characteristics and geometry of these leakage paths.

Pereira et al. [28,53] developed numerical models for analyzing radial and tangential leakage in scroll compressors. Rak et al. [29] proposed a two-dimensional model that incorporates non-constant flow, including leakage between each chamber. Gao et al. [54] developed a novel template tool for simulating the non-constant flow field along the leakage path of the scroll disk tooth-top seal and radial leakage path A typical cross-section of the tip seal leakage path is shown in Figure 6. The simulation outcomes offer valuable flow information, such as pressure distribution and flow rate, which can be utilized to enhance the design of similar systems. Cavazzini et al. [55] conducted numerical simulations to investigate the internal fluid dynamics of a compressor, employing CFD software and various axial clearance modeling strategies. Zheng et al. [56] conducted a study on the control method for tangential leakage. The tangential leakage flow is observed as a jet in the suction chamber. In the compression chamber, the refrigerant main flow and tangential leakage flow combine to create a channel scroll and a secondary flow. The secondary flow is primarily responsible for the high temperature observed.

Sun et al. [31] conducted a study on the tangential leakage losses in compressors, noting that these losses become more severe at the initial discharge. On the other hand, radial leakage losses are found to be more significant towards the end of compression. Qin et al. [57] investigated the impact of axial and radial clearances on compressor performance. In a separate study, Li et al. [58] developed a 3D model for high-speed scroll compressors to perform numerical calculations and analysis, as depicted in Figure 7. It has been observed through research that the higher the rotational speed, the greater the pressure fluctuation in the compression chamber. Radial leakage occurs in the axial gap and tangential leakage occurs in the radial gap, and the tangential leakage velocity is higher than the radial leakage velocity.

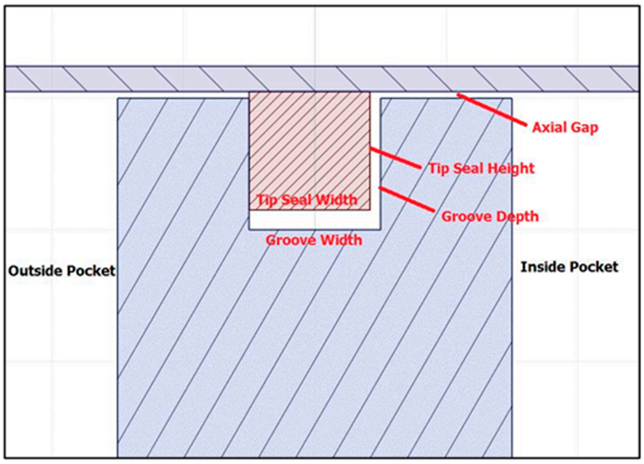

Figure 6. A typical cross-section of tip seal leakage path by Gao [54].

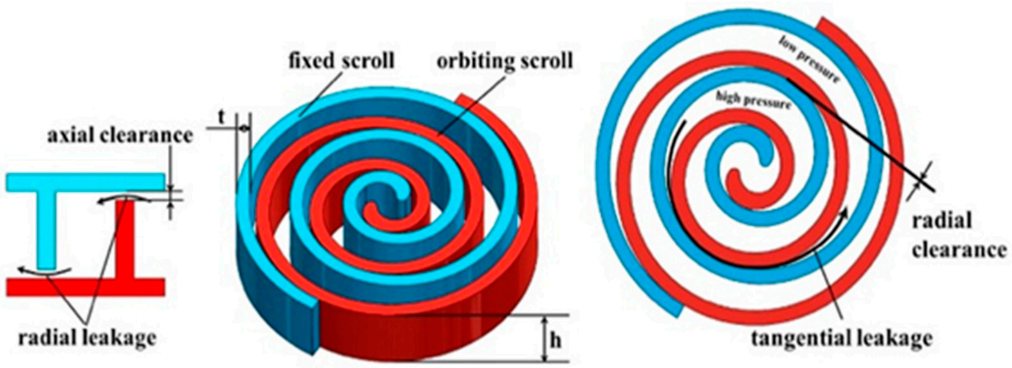

Figure 7. Scroll compressor leakage model devised by Li [58].

In their study, Sun et al. [59] focused on modeling radial gap lubrication to optimize the radial flexible mechanisms in the scroll compressor of the HPAC system for EVs. The researchers conducted performance test experiments and discovered that the swing phase angle of the flexible mechanism β should be set between 40° and 42° for achieving optimal clearance and rotational equilibrium of the orbiting scroll disk. Furthermore, Wang et al. [60] observed that the average radial leakage gap increases with the involute angle during a rotation cycle. The authors also found that the radial leakage gap can be controlled by gradually reducing the scroll disk height from the outside to the interior.

Due to machining errors and design considerations, there exists a gap between the orbiting scroll and the fixed scroll of the scroll compressor, resulting in unavoidable losses through these clearances. Radial and tangential leakages occur in each compression chamber, which are the main contributors to the overall leakage and have a significant impact on the cooling capacity and power consumption of the scroll compressor.

4. Research on Vapor-Injection Scroll Compressor

Researchers have developed the technique of vapor injection technology to address the issues of high discharge port temperatures and inefficiencies in electric scroll compressors at low temperatures. The compressor is equipped with a vapor injection port, strategically positioned in the compression process to introduce a refrigerant of mid-pressure and mid-temperature into the compressor. Enhancing the compressor's circulation flow ensures optimal performance [61,62].

Navarro et al. [63] examined the impact of vapor injection ports on system performance and found that compressors with the ports achieved a 10% higher COP compared to single-stage compressors at high pressure ratios. Even under extreme conditions, the discharge temperature of the SCVI remained consistently low. Zaber et al. [64] conducted a thermodynamic analysis of the SCVI, while Jung et al. [65] investigated the use of single/dual-injection port technology to improve the reliability of scroll compressors and the performance of EV-HPAC systems. In their experimental HPAC system, the scroll compressor was equipped with vapor injection from a flash tank. The test results showed that compared to a non-injected HPAC, the COP increased by 7.5% and 9.8% for single- and dual-injection ports, respectively. James et al. [66] studied a two-cavity (N = 2) scroll compressor with a small pressure ratio and a short profile. A test bench was set up to measure the performance of an HPAC using the second refrigerant calorimeter method. Experimental studies and analyses were conducted under different heat pump operating conditions and make-up air pressures. The findings indicated that an increase in make-up air pressure leads to a higher heat output from the system. Kim et al. [67] developed a numerical model to predict the performance of an SCVI in heating mode based on various operating characteristics. Xu et al. [68] conducted a study on the SCVI scroll disk, which utilizes a circular involute profile with a thickness ranging from 3 mm to 6 mm. The circular vapor injection ports are symmetrically positioned on the compression chamber, as shown in Figure 8. It was determined that the size of the vapor injection ports should be smaller than the thickness of the scroll. This study revealed that the most favorable position for the compressor's vapor injection ports is when the suction chamber is just closed.

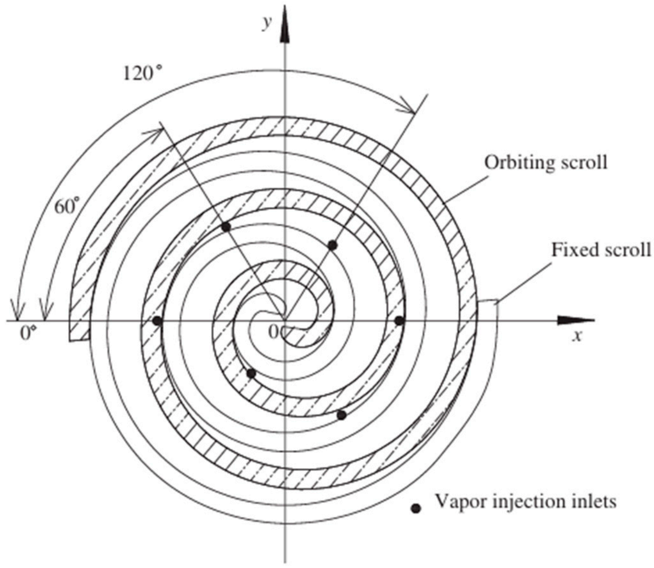

Figure 8. Position of scroll disk and vapor injection ports by Xu [68].

Choi et al. [69] developed a mathematical model and conducted experiments on the steam injection cycle of an electric scroll compressor. The experiments revealed that the system achieves optimal heating ability when the injection port is positioned around 300° and the mid-pressure ratio is below 0.25. Qin et al. [70,71] conducted theoretical analysis and experimental research on two different types of SCVIs for EVs. The injection porthole shapes studied were a single porthole (SP) and an abnormal shape with three interlinked portholes (TP), as depicted in Figure 9, the green line represents the orbiting scroll, and the black line represents the fixed scroll. The experiment demonstrated that the heating capacity of the SCVI system increased by 28.6%, with the TP configuration exhibiting a higher heating capacity.

Jung et al. [72] optimized the angle of the SCVI injection port by using the COP as the evaluation index. The supplemental injection ports were positioned at 320°, 360°, 400°, and 440°, as depicted in Figure 10. This study concluded that the optimal position for the injection port is at 400°.

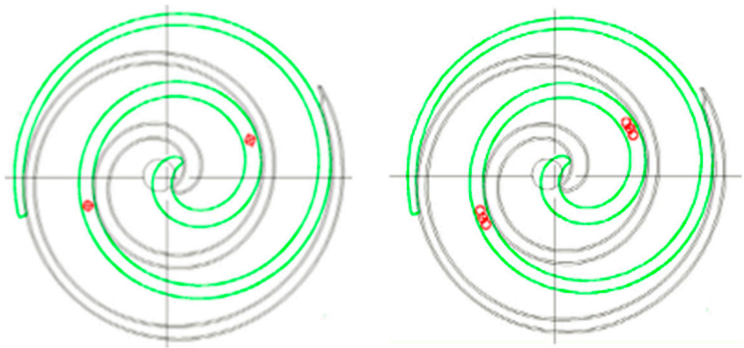

Figure 9. Two different injection ports [70]. (**a**) Single porthole; (**b**) three interlinked portholes.

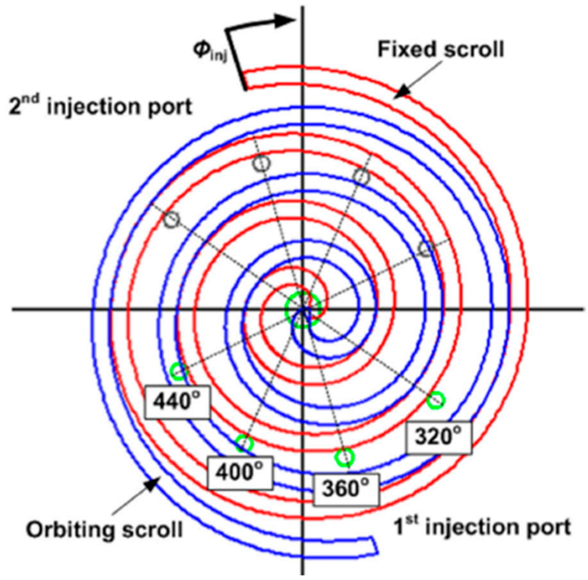

Figure 10. Two different injection ports [72].

To address the decline in performance of the EV-HPAC system in low-temperature regions, Kwon et al. [73] proposed an HPAC system with an SCVI. Fernando et al. [74] conducted a comparative analysis between an SCVI and a two-stage scroll compressor (TSSC). The researchers found that the SCVI system should be used when the pressure ratio is below 5, while the TSSC system is more suitable for higher pressure ratios. Kim et al. [75] compared and analyzed the impact of liquid refrigerants, vapor refrigerants, and two-phase mixed refrigerants on the performance of scroll compressors, and they found that the two-phase mixed refrigerant, at exhaust temperatures of −5 °C, exhibits the highest COP and injection capability, suggesting that it can maximize system efficiency and performance under specific conditions. Zhang et al. [76,77] proposed a lower-compression-ratio SCVI, as illustrated in Figure 11. This study indicated that at higher compressor speeds, the system heating performance is improved as the injection pressure increases and the scroll compressor discharge port temperature decreases. At a temperature of −22 °C, compared to the scroll compressor without the vapor injection system, the heat pump system equipped with the vapor injection scroll compressor has a 16% improvement in heating performance and an 8 °C decrease in discharge temperature.

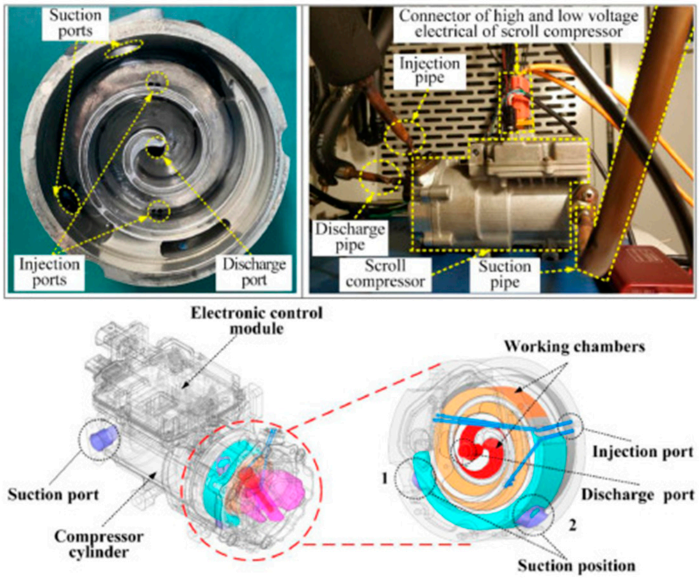

Figure 11. SCVI diagram created by Zhang [76].

Peng et al. [78] created a 3D model of an SCVI to investigate the flow properties of refrigerant R134a within the working chamber. The study results demonstrated that the isentropic efficiency of the SCVI increased from 8.51% to 9.35% compared to the conventional scroll compressor. Li et al. [79] examined the impact of oil circulation rate (OCR) on the performance of an SCVI. The findings revealed that the system COP is highest at an OCR of 3.5%. Furthermore, as the OCR increases, there is a significant decrease in the compressor discharge temperature.

Compared to conventional scroll compressors, SCVIs demonstrate better performance and have the potential to enhance system efficiency and refrigeration capability. Table 2 presents the parameters associated with the injection port, as documented by various researchers. These research findings are highly valuable in guiding the optimization of scroll compressor design and enhancing the performance of refrigeration systems.

Table 2. Relevant parameters of the injection ports established by researchers.

Author(s)	Compressor Volume	Injection-Port Diameter	Injection-Port Angle	Single/Dual-Injection Ports
Jung Jongho	27 cm^3	5.725 mm	240°~440°	dual-injection ports
Kim Dongwoo	66 cm^3	3.5 mm	365°	dual-injection ports
Xu Shuxue	80 cm^3	2.4 mm	0°~120°	single-injection ports
Choi Young Uk	33 cm^3	1.25 mm	300°	single-injection ports
Qin Fei	27 cm^3	8 mm	774°	dual-injection ports
Kwon Chunkyu	--	4 mm	240°	single-injection ports
Zhang Xinxin	38 cm^3	2 mm	134°	dual-injection ports
Peng Mengbo	--	2.4 mm	165°	single/dual-injection ports
Li Kang	38 cm^3	2 mm	143°	dual-injection ports

5. Research on CO_2 Scroll Compressor

As environmental policies become more stringent, the Montreal Protocol aims to phase out ozone-depleting refrigerants, while the Kyoto Protocol emphasizes the control of HFCs [80]. Consequently, there is a growing focus on researching and utilizing new natural refrigerants [81]. When choosing refrigerants for practical purposes, factors such as flammability, corrosiveness, toxicity, ozone depletion potential (ODP), and global warming potential (GWP) need to be considered. Table 3 presents a comparison of the physical properties of different refrigerants. Notably, CO_2, as a next-generation natural refrigerant, does not harm the ozone layer or contribute to the greenhouse effect. The use of CO_2 scroll compressors can effectively reduce greenhouse gas emissions, in line with environmental protection requirements [82–84]. At the same time, promoting the development and application of CO_2 refrigeration technology can promote technological innovation, promote the development of the clean energy industry, and comply with the EU's policy goals in sustainable development and green economy. CO_2 scroll compressors operate in 'transcritical' cycles, with suction pressures ranging from 3.4 to 4.0 MPa and discharge pressures as high as 8.0–11.0 MPa. Due to the unique characteristics of CO_2, the structural design of CO_2 scroll compressors needs to be carefully reconsidered to ensure their safe operation in high-pressure environments [85,86].

Table 3. Comparison of physical properties of refrigerants.

Refrigerant	R410a	R134a	R744(CO_2)
ODP	0	0	0
GWP	2100	1300	1
Critical temperature °C	70.45	101.06	30.97
Critical Pressure MPa	4.81	4.07	7.37

Professor Lorentzen put forward the 'transcritical' cycle theory and developed the first prototype of an AC system using a 'transcritical' cycle system [87]. Takeuchi et al. [88] designed a CO_2 scroll compressor and studied the impact of leakage losses and mechanical losses on power consumption. Brown et al. [89] used entropy calculations to demonstrate that CO_2 performs slightly better than R134a in the evaporator, but falls significantly short of the performance of R134a in a condenser. Tamura et al. [90] achieved superior performance with their CO_2 HPAC system compared to existing HFC134a air conditioning systems.

The refrigerant CO_2 exhibits a significant difference between suction and discharge pressures in the compressor, resulting in an increase in thrust load. In order to address this issue, Yano et al. [91] developed a CO_2 scroll compressor with a new thrust-bearing structure that effectively reduces friction losses and improves compressor efficiency by 2%. Additionally, Ishii et al. [92,93] discovered that increasing the surface roughness can greatly enhance the volumetric efficiency of scroll compressors. Wang et al. [26,94–96] also observed that HPAC systems using the CO_2 refrigerant perform well in cold climates. Song et al. [97] proposed a geometrical model of a CO_2 scroll compressor that effectively described the volume changes in each working chamber. The authors also conducted transient flux modeling and performance evaluation. The research revealed that using a waist-shaped discharge port instead of a circular discharge port reduced the asymmetry of the discharge pressure and shortened the discharge time, as shown in Figure 12.

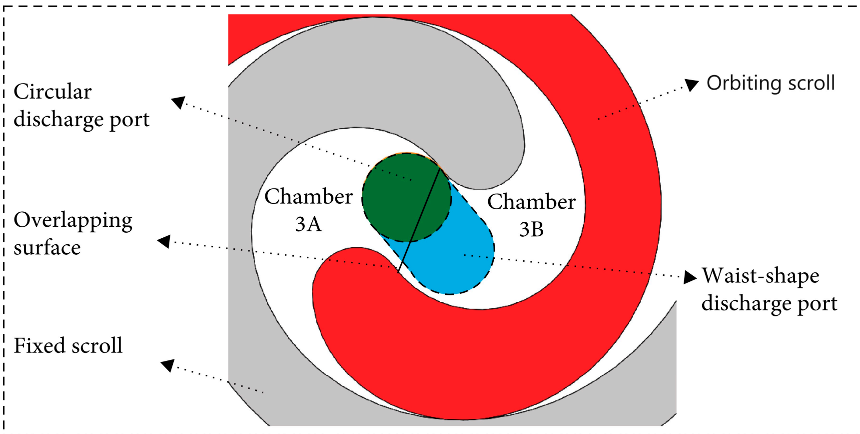

Figure 12. Circular and waist-shaped discharge port proposed by Song [97].

Zheng et al. [30,98] proposed a solution to the radial leakage problem in CO_2 scroll compressors by introducing micro-grooves on the top of the scroll disk to reduce leakage, as shown in Figure 13. The researchers investigated the impact of varying the number and depth of micro-grooves on controlling radial leakage. After careful evaluation, they determined that a quadruple groove with a groove width of 0.5 mm and groove depth of 100 microns yielded the best results. This configuration led to a 2.1% increase in the volumetric efficiency and a 1% increase in the isentropic efficiency of the compressor.

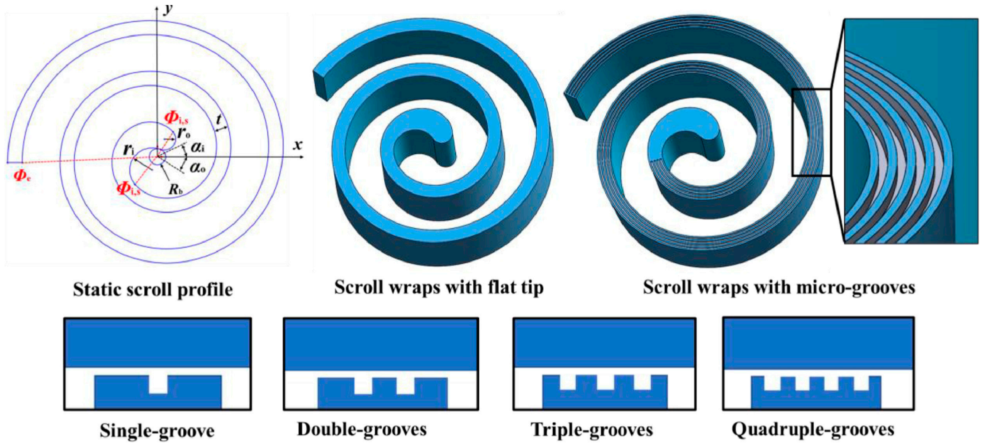

Figure 13. Micro-groove schemes proposed by Zheng [30].

6. Conclusions

This review paper examines the various applications and research advancements of electric scroll compressors. The section on profile optimization highlights that utilizing a variable-cross-section scroll profile can enhance the compression ratio and increase the stroke volume following the implementation of the optimization algorithm (CPSO) and profile modification (PMP). CFD is employed to analyze the stress, strain, flow field, and leakage within the compression chamber. This study reveals that the maximum stress occurs at the root of the orbiting scroll plate, with the top of the fixed scroll plate experiencing the most deformation. Research on discharge ports suggests that non-circular (longer bean) discharge ports result in smoother discharge flow. Furthermore, compared to single-stage compressors, the SCVI demonstrates significantly improved COP and consistently maintains lower discharge temperatures. The heating capacity of heat pump systems increases with higher replenishment pressure. Notably, the CO_2 electric scroll compressor in HPAC systems performs well in cold climates, with the overall efficiency of the refrigerant CO_2 scroll compressor surpassing that of the refrigerant R134a scroll compressor.

7. Outlook

In the future, the field of electric scroll compressors will continue to develop and innovate, achieving more technological breakthroughs and application results. The following points outline the future development outlook for electric scroll compressors:

1. The design of the compressor profile significantly impacts its technical performance index, with the variable-cross-section (combined profile) profile emerging as a key area of research.

2. Introducing an electric scroll compressor with vapor injection to increase enthalpy has shown promise in enhancing compression efficiency and improving operational reliability under adverse conditions. However, the efficiency of the compressor is greatly influenced by factors such as the form of vapor injection, shape of vapor injection ports, and vapor injection pressure, necessitating further research.

3. The electric scroll compressor, powered by a motor and capable of frequency control, is adaptable to more complex working conditions. As cloud control technology

and artificial intelligence continue to evolve, the future may see direct cloud control to enhance the intelligence level of the entire machine.

4. A breakthrough in the research of the relevant CO_2 electric scroll compressor is expected to realize the efficient operation of supercritical CO_2 HPAC systems in low-temperature environments, thus promoting the performance improvement and energy-efficiency optimization of the refrigeration and heating systems of EVs.

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Nomenclature

SCVI	vapor-injection scroll compressor
EVs	electric vehicles
HPAC	heat pump air conditioning
CAD	computer-aided design
CAE	computer-aided engineering
DLCF	diamond-like carbon films
AOF	anodized oxide film
COP	coefficient of performance
PMP	Perfect Meshing Profile
CPSO	chaos particle swarm optimization
IHX	internal heat exchanger
3D	three-dimensional
CFD	computational fluid dynamics
TSSC	two-stage scroll compressor
ODP	ozone depletion potential
GWP	global warming potential
OCR	oil circulation rate

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