The Thermoelectric Cooler Technology and Its Applications in Athletic Field

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Abstract. Thermoelectric Cooling (TEC) technology has emerged as a crucial foundation for the development of modern society in various aspects. This paper begins by introducing the development of general refrigeration technology, noting that TEC has evolved as an innovative system due to its effectively combination between semiconductor materials and scientific theories, particularly in response to the design and reliability limitations of traditional refrigeration methods. Then it explains the three thermo electric effects—the Seebeck effect, Peltier effect and Thomson effect ---examines the interrelationships among them, which builds the solid scientific foundation for TEC. Next, the paper concentrates on TEC's numerous advantages, such as precise temperature control, adaptability in harsh circumstances, vibration and noise eliminating. These attributes give TEC a competitive edge in comprehensive fields like medical, commercial and military, ranging from grand industry to individuals. After that, the paper specifically takes athletic field as a representative example. Inventions like cooling vests, handheld fans, the intellectual national football league (NFL) helmet developed at Purdue University, and the TEC embedded seats have enhanced people's life quality and contributed to advancements in scientific practices. In conclusion, while challenges still remain, the prospects of TEC technology are promising and bright.

Keywords: Thermoelectric cooling, Seebeck effect, Peltier effect, Thomson effect, athletic applications.

1. Introduction

The thermoelectric cooler technology has been perceived as the cornerstone and foundation of modern engineering by removing heat from a specific and designated spot and maintaining lower temperature conditions than its surrounding circumstance. It satisfies various cooling requirements throughout history from individuals to industries.

The food industry was the earliest field to adopt refrigeration technology. Its application enabled the long-term preservation and long-distance transportation of perishable foods, greatly enriching human dietary structures [1]. The application of refrigeration technology in the industrial sector is equally extensive and profound. In mechanical manufacturing, cryogenic treatment can alter the metal structure of steel, improving hardness and strength [2]. In medicine, vacuum freeze-drying technology preserves biological products and is also applied in cryogenic anesthesia and organ transplants [3]. Additionally, special construction techniques like frozen soil excavation and dam concrete pouring also rely on refrigeration technology

In 1834, British inventor Jacob Perkins built the first ether-based refrigeration machine, which laid the foundation for modern refrigeration cycle. Later around 1874, German engineer Carl von Linde invented the first ammonia compressor, establishing a complete ammonia compression refrigeration system, bringing refrigeration technology into large scale practical application [4]. Throughout centuries, though great contributions have been made by vapor compression refrigeration technology as being the absolute mainstream representing traditional refrigeration technique for human society, the increasingly apparent rising environmental awareness and energy crisis have gradually turned into non-negligible limitations which are becoming bottlenecks for sustainable development.

Traditional systems also suffer from design complexity and reliability issues. For example, some refrigeration systems are overly complex for automation, increasing costs and maintenance difficulty. Freezing equipment using thermal expansion valves faces uneven refrigerant distribution and liquid return problems. In VRV systems, bypass heat exchangers make refrigerant charge prediction

difficult, requiring large separators and receivers that trap oil and hinder compressor lubrication, reducing reliability [5]. These limitations drive researchers and engineers to explore alternative refrigeration technologies. For efficiency, new principles breaking Carnot cycle limits must be developed. System design requires simpler, more reliable architectures. Thermoelectric cooling—a solid-state technology avoiding traditional refrigerants and mechanical compression—offers promising solutions. In this essay, thermoelectric cooling technique will be introduced in comprehensive aspects. Firstly, illustrate the fundamental theories of the thermoelectric cooling technology by introducing three major effects: Seebeck effect, Peltire effect and Thomson effect and how those scientific principles successfully combined with social demands to develop thermoelectric coolers, which holds overwhelming superiority compared to traditional cooling system. Then several representative applications in athletic fields will be examined, Finally, based on its current performance, the future prospects of thermoelectric cooling technology will be predicted from different perspectives.

2. The principle of the thermoelectric cooler technology

2.1. The Seebeck Effect

The Seebeck effect, firstly discovered by German physicist Thomas Seebeck in 1821, is one of the fundamental theories of thermoelectric conversion. It happens when two semiconductors made by different materials create potential differences while encounter temperature gradient. The schematic diagram of the Seebeck principle is shown in Figure 1. In Figure 1, metal A and metal B form into a closed circuit, a thermoelectromotive force V_0 is generated when two connecting points are at different temperatures respectively, where Th represents the hot end while Tc represents the cold end, therefore inducing an electric current known as a thermal current

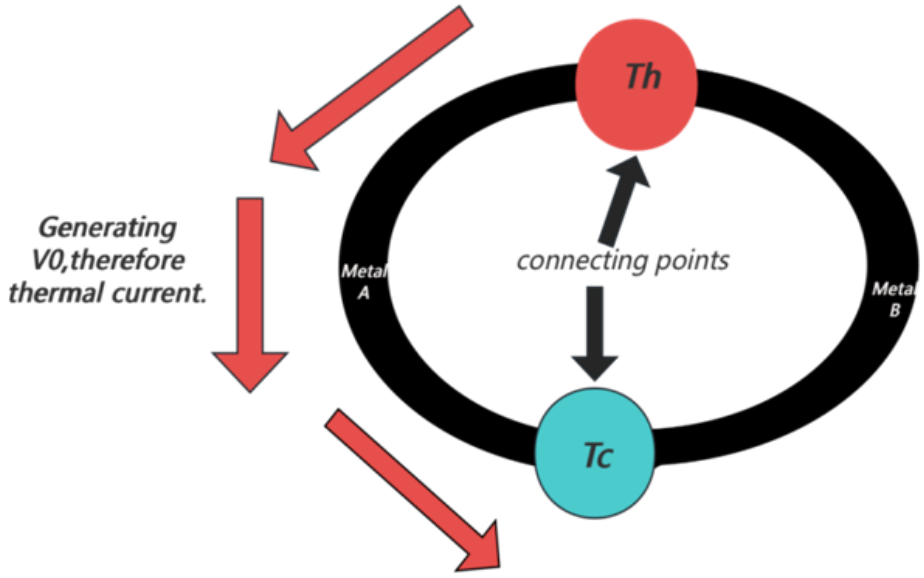


Fig. 1 The schematic diagram of the Seebeck principle (Picture credit: Original)

The math formula for that phenomenon is shown in equation (1).

$$V_0 = \alpha_{xy} \times (T_h - T_C) \tag{1}$$

Where α_{xy} is the Seebeck coefficient of the material which is generally determined by its carrier type including electrons or holes and its material characteristics.

The cause of the Seebeck effect can be depicted simply as the charge carriers within the conductor move from the hot end to cold end under a temperature gradient and accumulate in the cold end,

thereby forming a potential difference within the material. Meanwhile, this potential difference creates a reversed charge flow Eventually when the electron flow driven by thermal motion achieves a dynamic balance with the internal electric field, a stable thermoelectromotive force is formed between the two ends of the semiconductor. The force can be applied as a thermoelectric generator.

2.2. The Peltier Effect

The Peltier effect is the reversed process of the Seebeck effect. Discovered by J.C.A Peltier in 1834, when the electric current flows through a pair of thermocouples composed by N-type and P-type materials, despite producing irreversible joules heat, heat absorption and heat release phenomena also occur at the junction of different kinds of materials depending on different directions of the current.

The movement of charge carriers creates the current in the conductors. Since those carriers are at different energy levels in different types of materials, extra energy would be emitted when moving from higher energy level to lower level. Vice versa, the carriers absorb energy from the outside when moving in the opposite direction. This explains why the energy is either gained or lost at the interface of the materials through the form of heat. In conclusions, under the influence of an externally applied electric field, electrons bring a portion of energy to the other side of the electric field through their directional movement.

2.3. The Thomson Effect

The Thomson effect refers to the phenomenon when an electric current is induced in a conductor made of one single material with temperature gradient, the conductor generates or releases heat except for Joules heat created by resistors.

This effect comes from the redistribution of energy of charge carriers under the temperature gradient--the kinetic energy of the charge carriers at the high-temperature end is higher, and when they diffuse to the low-temperature end, the energy is released and is absorbed in the opposite case.

2.4. Relationships between three effects

The Seebeck effect and the Peltier effect are both thermoelectric effects, and are counterproductive to each other. The Seebeck effect means that electromotive potential will be generated when a temperature difference occurs in the electric couple, while the Peltier effect indicates that a temperature difference will be created when an electric current passes through the electric couple.

The mathematical relation between the Seebeck coefficient α and the Peltier coefficient π is shown in Equation (2), where T is the temperature at the junction.

$$\pi = \alpha \times T \tag{2}$$

The Thomson effect can be regarded as a differential manifestation of the Seebeck effect. Both involve the transformation between a temperature gradient and an electric potential or heat flow. The Peltier effect occurs at the interface between two different conductors, while the Thomson effect exists within the region of a temperature gradient in a single, homogeneous conductor [6]. The mathematical relation between the Thomson coefficient μ and Seebeck coefficient α is shown in Equation (3), where T is the temperature of the single conductor.

$$\mu = T \times \frac{d\alpha}{dT} \tag{3}$$

Those three major effects together base the solid foundation of thermo electric effect by revealing the direct transitions between heat energy and electricity.

The theory of thermoelectric cooler is established on the physical basis of thermo electric effects, especially the core role of the Peltier effect and is closely connected with the Seebeck effect and Thomson effect.

Semiconductor chilling plate, as the core component of a thermoelectric cooler, is composed of numerous particles of N-type and P-type semiconductors arranged alternately and its working

principle is based on Peltier effect [7]. The basic working principle of chilling plate is shown in Figure 2. When an electric current flows through the circuit composed by N-type semiconductor and P-type semiconductor, heat transfer will take place at the junction of the two materials. Specifically, electrons in N-type semiconductors combine with holes in P-type semiconductors to absorb heat at the cold junction point, while at the hot junction point the electrons separate from the holes to distribute heat.

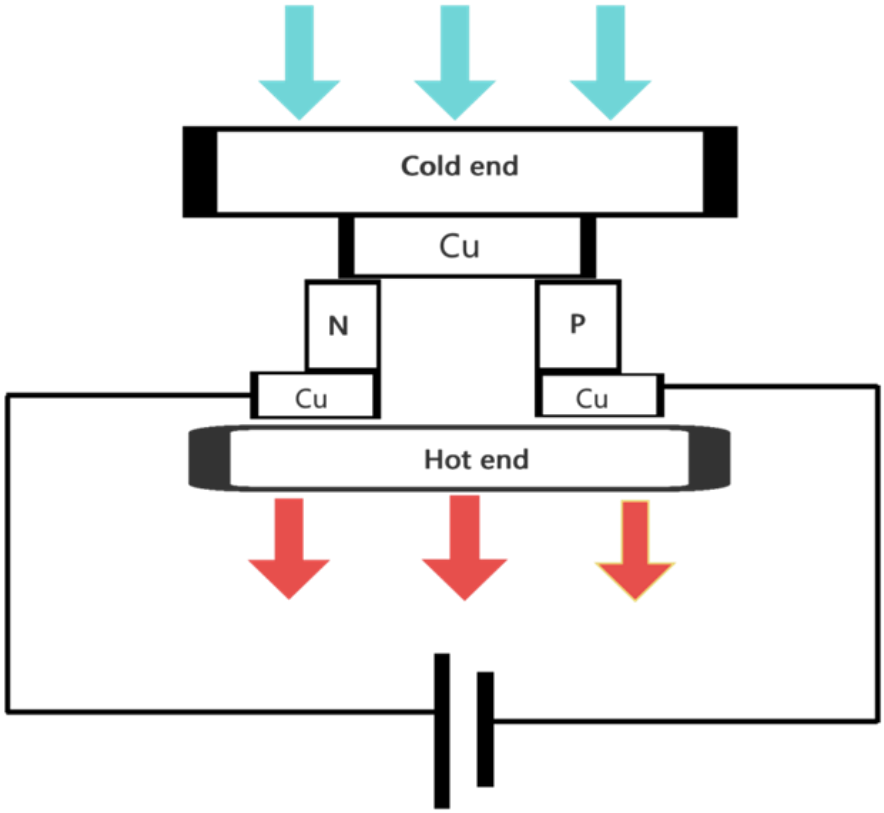


Fig. 2 The basic working principle of chilling plate (Picture credit: Original)

The refrigerating efficiency of the chilling plate is determined by the following equation:

$$Q = \pi \times I \tag{4}$$

$$Q = (\alpha_p - \alpha_n) \times T \times I \tag{5}$$

Since the α_p and α_n respectively refers to the Seebeck coefficients of both P/N semiconductor, it is evident that the refrigerating efficiency is directly proportional to the difference between the two coefficients. This implies that materials with a great Seebeck coefficient undoubtedly contains strong Peltier refrigerating potential.

As for Thomson effect, it occurs when an electric current flows through the interior of a semiconductor with a temperature gradient, which acts as an additional influence factor. It usually performs as a "parasitic heat effect" along with Joules heat by resistors in the conductors that reduce efficiency.

Based on the narration above, the actual working principle of the refrigerating efficiency is present as:

$$Q = \pi \times I \times T - \frac{1}{2} I^2 R - K\Delta T \tag{6}$$

In short, semiconductor cooling is a process of converting the thermoelectric effect (especially the Peltier-Seebeck coupling) into a practical thermal management technology. Its development is highly dependent on the advancement of thermoelectric material science.

3. Advantages and Applications of the Thermoelectric Cooling

Due to its distinctive working principles, thermoelectric cooling demonstrates unique advantages in specific application scenarios such as medicine, healthcare, agriculture, communication and national defense. Numerous products depending on thermoelectric cooling technology have been invented and thriving in a broad breadth from high-tech industry to daily life.

3.1. The Advantages of the Thermoelectric Cooling

First is the material advantage. The N/P type combined semiconductor can form a significant thermoelectric potential difference, strengthening the heat pumping capacity. Since the Peltier effect of metals is extremely weak, with a Seebeck coefficient $\alpha \approx 1 - 10\ \mu V/K$, semiconductors (such as Bi_2Te_3) can reach 200—300 μV/K, enhancing the cooling efficiency by tens of times.

Secondly, thermoelectric cooling requires no compressors or refrigerant circulation pumps, thus completely eliminating vibration and noise. In the military field, it provides reliable cooling/heating support for portable electronic devices, communication equipment, and small medical devices.

Besides, it features a temperature control precision reaching ±0.1℃ (suitable for medical/laboratory-grade requirements), making it suitable for precise instrument temperature stabilization. Due to its stable temperature control within a fluctuation between 0.1 Celsius, thermoelectric cooling can be utilized as a necessary component of laser devices which satisfies its sensitive temperature demands for waves length and power outputs. Additionally, in scenarios requiring precise temperature control, it can also cold down heat generating equipment like central processing units (CPUs) and graphics processing units (GPUs). In biochemistry and medical fields, thermoelectric coolers achieve rapid thermal cycling in different temperatures for Polymerase Chain Reaction (PCR) instruments. For cell culture equipment, it provides stable culture temperatures for small culture dishes or micro-bioreactors. Some medical aesthetic devices like pain relief devices use semiconductor cooling to cool the skin surface, reducing discomfort during treatment or protecting the epidermis [8].

Fourth, thermoelectric cooling can operate in environments such as vacuum, zero gravity (space), and strong magnetic fields. In the extreme space environment --characterized by vacuum, zero gravity, and high reliability requirements--thermoelectric cooling is the ideal choice for cooling precision electronic equipment [9].

Recently, innovative applications start emerging by combing thermoelectric cooling with advanced technologies. For instance, the combination of photovoltaic power generation to drive cooling, providing refrigeration solutions for remote areas without power grids like vaccine preservation [10].

In conclusion, thermoelectric cooling clearly holds a dominant advantage in the fields of medium and small power, precise temperature control, low noise, and special environments. It is a solution that cannot be replaced by traditional cooling technologies.

3.2. The Applications in Athletic Field

Nowadays, the sports market has gradually taken an increasingly important status among more and more countries due to its broad appeal and widespread participation. Appropriate athletic facilities and equipment extremely matter since they not only take protections for athletes' bodies, but also in enabling them to reach their full potential. This section will elaborate on several applications of thermoelectric cooling technology in the Athletic field.

Around 1980s-2000s, a cooling vest was invented. Through its TEC chip powered heat dissipation system, cold energy is transferred to the wearer's back via ventilated pads, achieving 8–10°C perceived temperature reduction. This technology is used for heat prevention for outdoor workers, supports athletic recovery during training, and helps reduce heat stress reactions [11]. It is also worth to mention that Fuxin Tech's 4th- generation cooling garment adopts a gel-based main unit combined

with air-cooling system, featuring lighter weight and extended battery life, making it suitable for light sports like hiking and fishing.

Another key invention, emerged around 2010s, is the TEC-Powered Handheld Fan. It integrates micro-semiconductor cooling chips that deliver cold airflow within 3 seconds, functioning as a portable air conditioning solution for summer outdoor activities. It is ideally for use at concerts, tourism, and similar scenarios.

Currently, a badminton shuttlecock humidification device has been developed. It utilizes the condensation principle at the cold end of TEC chips combined with water-absorbing materials for evaporative humidification, maintaining a constant humidity (above 70% RH) within the tube. It can also prevent brittleness and breakage of feather shaft, extending the shuttlecock's lifespan by over 30%, which solves the issue of "surface moisture without internal penetration" commonly associated with traditional steam humidification methods [12].

As evident, TEC technology has evolved from laboratory curiosities to essential sports tools, driven by material breakthroughs and cross-disciplinary research. Universities remain pivotal in refining these technologies for both elite performance and athlete safety. Below are some specific examples in universities.

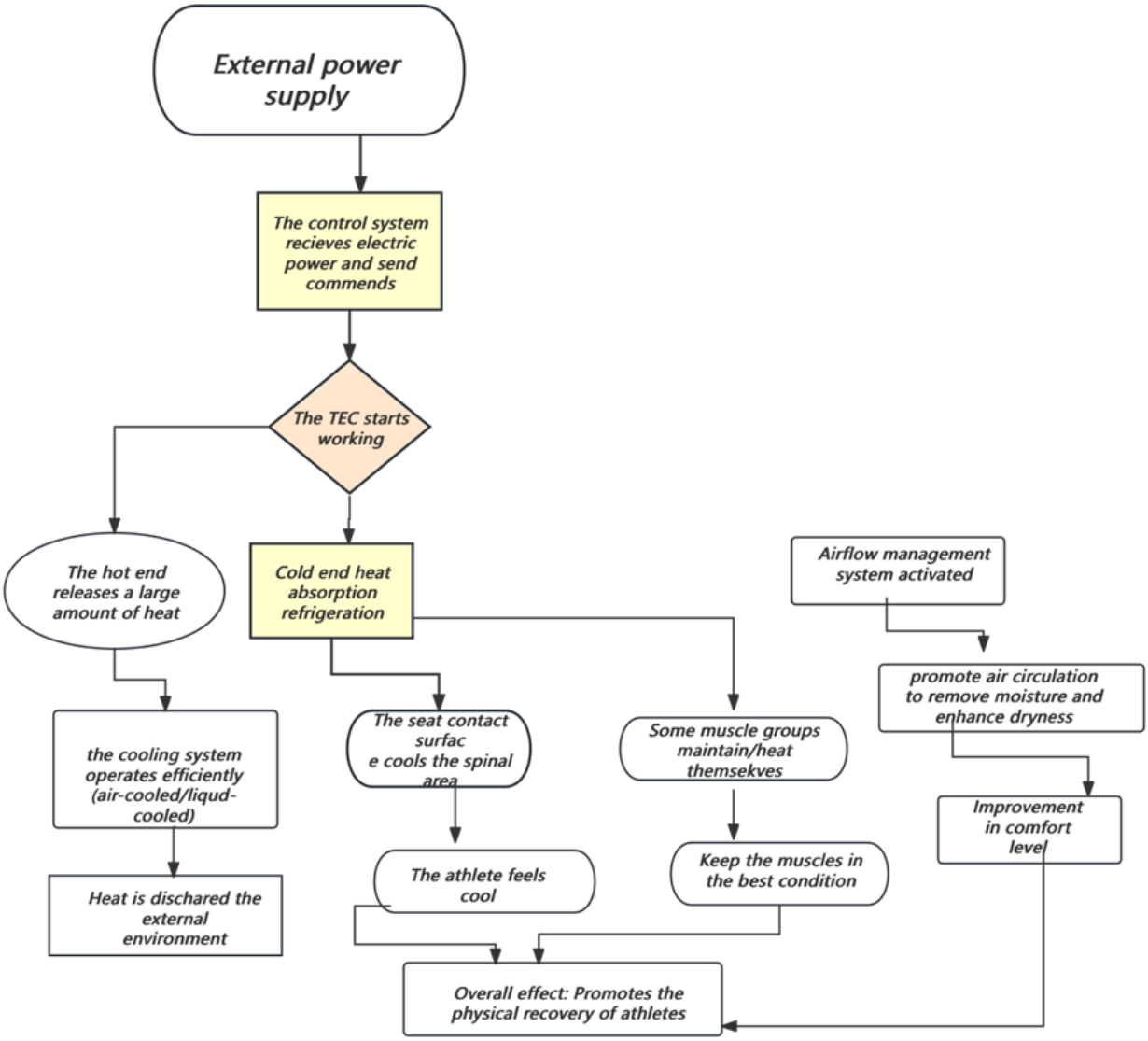


Fig. 3 The process of TEC embedded seat in UCLA Mo Ostin (Picture credit: Original)

Purdue University's Sports Engineering Master's Program (MSE), collaborated with the NFL, has designed smart helmets integrated with micro TEC chips. This can reduce athletes' core body temperature by 3–5°C, effectively preventing heat stress response in high-temperature environments.

The development of lightweight TEC modules also combined with phase-change materials (PCMs) to optimize thermal management in sports equipment. Figure 3 illustrates a simple process of TEC embedded seats in variable refrigerant volume (VRV) Mo Ostin.

The last example is Mo Ostin Basketball center at UCLA university. Not only is it renowned for utilizing natural airflow from skylights to reduce the usage of artificial air conditioning, but it also features a unique design element: TEC-embedded seats. These seats provide localized cooling through air channels, maintaining 24°C in spectator zones and 18°C on courts while reducing energy consumption by 30%. This system greatly enhances the comfortability for audiences.

4. The Future Development

TEC technology is an innovative field with promising prospects. Moving forward, scientists will focus on the following core directions for its future development.

The first is Enhancement of Technical Performance. Efforts will be devoted to the research and development of high-performance thermoelectric materials, such as bismuth telluride-based materials with ZT values exceed 1.2, along with improving thermal conductivity and reducing thermal resistance. There will also be a strong emphasis on increasing the coefficient of performance, addressing the current bottleneck of low efficiency (typically in the range of 0.3 - 0.5), and expanding the scope of application scope.

Secondly, TEC technology is expanding from traditional uses in medical and communication equipment to emerging fields such as CPO optical modules, humanoid robots and new energy vehicles. It aims to meet precise temperature control demands in high-power consumption, high-density integration, and extreme environments, becoming an "invisible necessity" in high-end manufacturing.

Furthermore, TEC systems will be deeply integrated with AI algorithms to achieve dynamic intelligent temperature control such as remote monitoring and adaptive adjustment. This integration is expected to reduce energy consumption by 15%, enable predictive maintenance, and meet the requirements of complex scenarios for precise temperature management.

Overall, the future of semiconductor refrigeration technology is expecting. It will gradually evolve from a supporting component to a key enabling technology for applications in diverse industries. Its advancement will be driven by high-end demands, supported by innovations in materials and breakthroughs in integration processes. It will continuously overcome challenges and move towards broader application horizons.

5. Conclusion

Overall, as the statement above, this article began by introducing the fundamental theories of thermoelectric cooling technology, comparing its advantages with traditional refrigeration tech. Then it discussed the three major effects: the Seebeck effect, the Peltier effect and the Thomson effect, and examined how scientists discoveries were applied to the invention of thermoelectric cooler. This paper also highlighted how those scientific principles successfully combined with social demands to develop thermoelectric coolers, which holds overwhelming superiority compared to traditional cooling system. Then the article explored the practical applications of TEC in diverse aspects and several representative applications in athletic fields were examined and listed. Finally, based on current performance, the future prospects of thermoelectric cooling technology are predicted from different perspectives. While certain limitations remain, continuous scientific efforts and technological progress are steadily addressing these deficiencies, indicating strong potential for broader future application.

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