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A Review on Key Technologies of Central Air Conditioning: Compressors, Heat Recovery, and AI-Driven Control

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***Abstract*—*In recent years, the central air conditioning industry has seen extensive technological advances, covering compressor technology, system energy efficiency optimization, intelligent control and other fields. Breakthroughs have been achieved in energy-saving technologies including magnetic levitation compressors, variable and wide-frequency operation modes, integrated heat pump and heat recovery systems, as well as independent temperature and humidity control. In terms of intelligent control, AI-enabled load forecasting, online optimization and digital twin technology have also made remarkable progress. Meanwhile, the replacement of environmentally friendly refrigerants and the trend of copper reduction in materials are steadily advancing, exerting profound impacts on the industrial supply chain. Relevant research indicates an obvious integration of two technical routes: continuous improvement of hardware energy efficiency, and in-depth integration of intelligent control technologies into systems. This dual transformation is upgrading products from standalone units to system-level solutions, and shifting business models from one-time equipment sales to long-term operation and maintenance services. However, the intersection of technological development also brings challenges, such as difficulties in implementing standards for high-efficiency machine rooms, generalization deviations of AI algorithms in actual building scenarios, and complex renovation demands in the existing market. This paper also prospects the potential paths of technological evolution.*

I. INTRODUCTION

Building energy consumption accounts for 30% to 40% of global final energy consumption, with HVAC systems being the largest single energy load. In China, air conditioning systems consume 21.7% of the country's total social energy use[1].Driven by stringent carbon emission reduction requirements and rising user demands for indoor comfort and health, central air conditioning technology has achieved rapid and steady upgrading in recent years. Globally, fueled by carbon neutrality policies, high-efficiency energy-saving products have become mainstream and variable frequency technology has gained dominance. China is now the world's largest producer and consumer of central air conditioners, with its market size projected to reach 230 billion yuan[2].Against these industrial changes, a core question emerges: Is the technological evolution of central air conditioners still following a linear path centered solely on energy efficiency indicators, or has it undergone fundamental structural changes?This paper reviews academic literature, industry reports and typical technical cases from 2020 to 2026, and finds that two technological development paths are evidently converging.The first path lies in continuous breakthroughs in hardware energy efficiency, mainly covering core compressor technological innovation, system-level heat recovery and independent temperature-humidity control, environmentally friendly refrigerant replacement, and copper-free material optimization. The second path refers to the in-depth integration of intelligent system control, represented by AI-driven load forecasting and online optimization, digital twin technology, and intelligent operation and maintenance, which has further promoted the restructuring of product forms and business models. These two development paths are not isolated. Their continuous integration has transformed central air conditioners from passively responsive temperature control equipment into active energy management nodes participating in energy dispatch.

It should be noted that the market data cited from industry reports, including penetration rates and market size forecasts, may vary across different sources due to inconsistent statistical criteria and sample coverage. Nevertheless, this study focuses on the general trends reflected by the data, which have been verified through cross-checking multiple sources of information.

II. SUSTAINED BREAKTHROUGHS INHARDWARE ENERGY EFFICIENCY

Improving the energy efficiency of central air conditioners cannot be achieved by optimizing individual components alone. Instead, it is a progressive process that evolves from component refinement to full-system coordination.This chapter analyzes the progress from three perspectives: compressors, system integration and fundamental materials.

2.1 EVOLUTION OF CORE COMPRESSOR TECHNOLOGIES

CIts widespread adoption marks a pivotal shift in the energy-saving philosophy for central air conditioning. Previously, the industry only pursued peak energy efficiency under rated operating conditions, while greater emphasis is now placed on overall efficiency during part-load operation.ompressor performance sets the upper limit of energy efficiency for central air conditioners.In recent years, technological upgrades have mainly focused on three directions: full popularization of variable frequency technology, large-scale application of oil-free magnetic levitation compressors, and optimization of wide-frequency operation technology for part-load conditions.This indicates that market focus is shifting from "maximum efficiency under rated conditions" to "comprehensive efficiency at part load". Supported by auxiliary technologies such as vapor injection and enthalpy enhancement, scroll compressors maintain high energy efficiency under both low and high temperature conditions, and all product lines have attained China’s national Level 1 energy efficiency standard in terms of APF [3]. Magnetic levitation compressors suspend the rotor above bearings via electromagnetic force, which fundamentally eliminates mechanical contact and friction losses to enable oil-free operation. Having moved beyond laboratory research, this technology has seen large-scale commercial deployment in recent years [27].

Danfoss MagLev series has been on the market for 30 years. Its active cooling function improves the operational stability of units under high-temperature and heavy-load conditions [4]. Haier led the development of China’s first national standard for oil-free levitation central air conditioners, and the IPLV of its magnetic levitation centrifugal units is well above the threshold for national Level 1 energy efficiency [5]. In the energy-saving renovation project of Nanjing Deji Plaza, TICA adopted magnetic levitation technology and raised the overall system energy efficiency by 75% [6]. At the end of 2025, InvoTech launched a magnetic levitation centrifugal compressor with a cooling capacity ranging from 150 to 600 RT. Equipped with actively controlled magnetic levitation bearings, it guarantees precise rotor suspension under extreme operating conditions [7].

In terms of application scenarios, magnetic levitation compressors have expanded from conventional water chillers to air-source heat pumps. Multiple manufacturers exhibited air-source heat pump magnetic levitation centrifugal units at the 2026 China Refrigeration Expo held in Beijing [8].Wide-frequency operation technology is designed to address the capacity mismatch of multi-split systems under low-load conditions. When only one indoor unit of a conventional multi-split air conditioner is running, the compressor output far exceeds actual demand, leading to frequent start-stop cycles, fluctuating room temperatures and unnecessary energy consumption. Haier's ultra-wide frequency technology extends the compressor operating frequency range to 4–160 Hz. At the ultra-low frequency of 4 Hz, its power consumption is merely 124 W, with a total power consumption of less than 5 kWh after 24 hours of continuous operation [9]. GMCC's wide-frequency, high-efficiency and low-noise technology cuts the power consumption of 12 kW small multi-split central air conditioners by 55% in ECO mode [10].

Magnetic levitation technology mainly boosts peak energy efficiency under extreme working conditions, while wide-frequency operation technology improves the matching efficiency across all operating scenarios. These two technical approaches expand the energy-saving potential of compressors from different dimensions.

2.2 SYSTEM-LEVEL ENERGY EFFICIENCY OPTIMIZATION: HEAT PUMPS, HEAT RECOVERY AND TEMPERATURE-HUMIDITY DECOUPLING

With continuous improvements, compressor efficiency has gradually approached the physical limits of current technologies. Accordingly, there is diminishing room for further energy savings by merely upgrading compressors, making system-level optimization a more viable solution. The core principle is to integrate air conditioning systems into the broader building energy network. Beyond enhancing the efficiency of individual equipment, greater focus is placed on system-wide coordination with heating, heat utilization, humidity control and other related processes.

Heat pumps operate by consuming a small amount of electricity to transfer heat from low-temperature sources to high-temperature areas, delivering much higher heating efficiency than direct electric heating. Their role in central air conditioning systems has undergone a notable shift: instead of merely serving as an auxiliary heating solution in winter, heat pumps have evolved into a core component for year-round energy management. Danfoss provides complete heat pump system solutions for clean heating and coal-to-electricity conversion projects, ranging from variable-frequency scroll compressors to high-efficiency plate heat exchangers [4]. Hisense has launched low-carbon solutions for industrial applications covering waste heat recovery, deep dehumidification and process cooling, forming a full technical chain that combines high-temperature heat pump heating and high-efficiency centrifugal refrigeration [11]. Driven by the energy crisis, heat pump adoption surged across Europe, with sales rising by 35% in 2022 compared with the previous year [12].

Heat recovery technology captures condensing heat and exhaust heat generated during the operation of central air conditioners and converts them into usable thermal energy, thereby cutting down excessive heat dissipation from cooling towers to the surroundings. Hitachi's four-pipe simultaneous cooling and heating units enable cooling and heating to run concurrently within a single system, offering a practical engineering approach to condensing heat recovery [13]. According to statistics from the China Refrigeration and Air-Conditioning Industry Association, the overall energy efficiency ratio of traditional central air conditioning systems has long remained between 3.0 and 3.5, while systems equipped with heat recovery technology can reach 5.6 [14]. Additionally, ultra-low-temperature waste heat recovery at 70–80 °C has emerged as a new research hotspot, with technical routes such as the Organic Rankine Cycle (ORC) being actively explored [15].

The Temperature and Humidity Independent Control (THIC) system is designed to separate indoor sensible heat load and latent heat load, which are handled by respective subsystems. This design fundamentally eliminates the energy waste caused by over-dehumidification and subsequent reheating in conventional air conditioning systems. In typical configurations, radiant capillary tubes undertake most of the sensible heat load. They absorb heat via chilled water circulating at a temperature close to room temperature with nearly imperceptible airflow. Dedicated dehumidification systems, such as liquid desiccant dehumidification, rotary dehumidification and low-temperature air supply systems, are responsible for latent heat load.

Studies show that independent dehumidification can save over 30% of energy compared with conventional refrigeration dehumidification. It can even achieve zero-energy dehumidification when waste heat is available [16]. For a long time, the industry regarded energy efficiency and indoor comfort as conflicting objectives. Nevertheless, THIC technology has verified that refined control enables both goals to be achieved simultaneously within one system.

2.3 ECO-FRIENDLY REFRIGERANT REPLACEMENT AND COPPER REDUCTION IN MATERIALS

Technological upgrades have exerted profound impacts on fundamental materials and industrial supply chains. Globally, the phase-out of high-GWP HFC refrigerants is accelerating. For instance, the EU F-Gas Regulation mandates that low-GWP refrigerants account for more than 50% of newly installed air conditioning units by 2025 [31]. Chinese air conditioner manufacturers have fully launched products using R32 refrigerant, and some enterprises have begun to develop CO_2 heat pump air conditioners. The GWP of CO_2 is less than 1/3000 that of traditional HFC refrigerants [17]. Currently, products adopting R32 and R290 jointly hold over 40% of the global market share [2].

The adoption of natural refrigerants such as carbon dioxide, ammonia and hydrocarbons has set new requirements for system operating pressure ratings, safety protection measures and material compatibility. Take the HGX56 CO_2 compressor developed by BOCK GmbH as an example. It achieves a heating COP of 4.49 with a frequency range of 20 to 70 Hz, and its single-unit heating capacity ranges from 250 kW to 350 kW [18] (Data sourced from the manufacturer's official technical specifications).

Material substitution has also become a prominent trend, as stainless steel is gradually replacing copper tubes. This transition is driven by cost pressures arising from fluctuating copper prices and the continuous maturation of stainless steel processing technologies. The 2026 China Refrigeration Expo in Beijing clearly showed that stainless steel has evolved from an experimental solution for individual manufacturers to a standard configuration across the industry [8].

In Midea's V9 multi-split air conditioners, stainless steel is applied to compressor suction pipes, high-pressure pipes, vapor injection pipes, four-way valves and stop valves. Upstream heat exchanger manufacturers have also rolled out stainless steel heat exchangers. This material shift is not merely a cost-cutting measure; it signifies a systematic material upgrade across the entire supply chain of the central air conditioning industry.

III. DEEP INTEGRATION OF INTELLIGENT SYSTEM CONTROL

As the energy-saving potential of hardware for central air-conditioning systems is continuously tapped, the focus of industrial competition has shifted to algorithms and system intelligence. The positioning of central air-conditioning has evolved from a single hardware product to a data-driven long-term service, which marks the core of industrial transformation.

3.1 AI-ENABLED LOAD PREDICTION AND ONLINE OPTIMIZATION

Conventional central air-conditioning systems operate in a passive manner. The system adjusts operating parameters only after the actual cooling load changes, and such response lag has long been a prominent defect. With the introduction of artificial intelligence, the system can predict load variations in advance and adjust operating parameters proactively, eliminating the need for post-event adjustments.

Researchers from Shandong Jianzhu University established a multi-modal lightweight prediction model. Based on multi-dimensional dynamic data, this model maintains the prediction accuracy of cooling load above 95% steadily. The ArchiPilot platform adopts a similar technical approach. By analyzing historical energy consumption data, meteorological parameters and user behavior patterns, it realizes load prediction ranging from minute-level to daily scale, and further adjusts operational strategies in real time accordingly. Accurate prediction of energy demand in advance creates sufficient margin for subsequent system optimization.

In terms of online optimization, Xie and his colleagues proposed and verified an AI-based online control optimization technology. Hardware-in-the-loop tests proved that this technology achieves an energy-saving rate of 7.66%. The deep learning algorithm adopted in the research optimizes genetic algorithms, which accelerates the solution speed and reduces the occupancy of CPU and memory resources. The favorable performance has also been verified in practical building applications. The AI energy efficiency monitoring solution for multi-split air conditioners developed by Haier was applied to the renovation project of Jinjiang Times Building in Hangzhou. After implementation, the coefficient of performance (COP) of the units rose from 2.52 to 4.07, with a payback period of approximately 3.7 years.

Generative artificial intelligence has also been applied to the control of heating, ventilation and air conditioning (HVAC) systems. A research team from Mitsubishi Electric in Japan put forward the Office-in-the-Loop scheme. The system takes real-time data from environmental sensors, indoor occupants' thermal comfort feedback and historical operating information as prompts for generative AI, so as to dynamically determine the optimal temperature setpoint. Experiments conducted in a real office environment show that this system delivers a maximum energy-saving rate of 47.92%, while the indoor thermal comfort level is improved by 26.36%. This research proposes a novel control paradigm based on data-driven reasoning. By importing basic principles of data-driven operation into AI, the prediction stability is enhanced. The system is capable of independently inferring dynamic characteristics and cost functions, which omits the complicated design of reward functions required by traditional reinforcement learning methods.

3.2 DIGITAL TWIN AND INTELLIGENT OPERATION & MAINTENANCE

Digital twin technology establishes virtual models that interact with physical systems in real time, allowing operators to test and optimize operational strategies in a risk-free digital environment. Trane Technologies integrates artificial intelligence and digital twin into the full-lifecycle management of central air-conditioning cooling plants. This approach helps high-end manufacturing sectors such as semiconductor production, which demand stringent temperature control accuracy, to shift from experience-based temperature regulation to data-driven management. Gree Electric launched the Taishan intelligent building platform, which integrates building intelligent control and full-process high-efficiency plant systems. According to publicly released corporate documents, the platform adopts AI algorithms to dynamically optimize electromechanical systems and cuts energy consumption by 40%. It should be noted that this figure is sourced from corporate publicity and has not been verified by independent third parties. The ArchiPilot platform features high modeling efficiency and can rapidly generate digital twin models. It is capable of simulating the coordinated operation of main units, water pumps, valves and other subsystems, thereby lowering risks during on-site deployment. A core shift in intelligent operation and maintenance lies in the transition from periodic preventive maintenance to real-time data-based predictive maintenance. Continuous operational data collected by sensors is processed via big data analytics and AI algorithms to realize fault early warning, energy efficiency diagnosis and optimized control. Practical application results indicate that digital operation and maintenance systems can reduce manual inspection costs by approximately 60%. Predictive maintenance helps lower equipment failure rates by around 40% and cuts the overall lifecycle maintenance cost by roughly 25%.

3.3 RESTRUCTURING OF PRODUCT FORMS AND BUSINESS MODELS

The evolution of technical solutions has also brought profound changes to product configurations and business models. In terms of products, the market trend has shifted from the procurement of individual equipment to the adoption of systematic solutions. Meanwhile, system-level products including residential central air conditioners, multi-split systems and district energy stations have seen a rapid growth in market share.

For high-end residential buildings, the traditional mode of simply combining central air conditioners with floor heating systems is gradually phased out. As a key driving factor, temperature and humidity independent control (THIC) technology has long attracted extensive attention from academic and engineering communities. The principle of THIC is straightforward. Rather than adopting a single integrated system to handle both sensible and latent heat loads indoors, this technology separates the two types of heat loads and addresses them through independent approaches. Specifically, high-temperature cold sources coupled with radiant terminals such as capillary radiant ceilings are applied to reduce indoor temperature and deal with sensible heat loads；In terms of humidity regulation, a dedicated outdoor air system (DOAS) is deployed to eliminate latent heat loads and supply fresh air. The two subsystems operate in a coordinated manner. This configuration effectively avoids cold and heat losses caused by excessive cooling and reheating during the dehumidification process of conventional air conditioning systems, and markedly improves the overall energy efficiency. In engineering practice, the application scope of temperature and humidity independent control (THIC) systems keeps expanding. Focusing on office buildings under the hot and humid climate of Hong Kong, Wen et al. (2026) proposed an integrated solution combining radiant ceiling cooling and dedicated outdoor air systems equipped with air-to-air sensible heat exchangers. The results show that compared with conventional fan coil units, this integrated scheme reduces total energy consumption by 19.8%. Meanwhile, the proportion of thermal discomfort time indoors drops sharply from 54.0% to below 0.8%. The findings provide solid practical data to support the application of THIC technology in high-end residential buildings. Furthermore, the application scenarios of THIC systems are being continuously extended. Relevant studies regard THIC as a flexible energy resource for collaborative scheduling with photovoltaic and energy storage systems. This combination increases the on-site consumption rate of building photovoltaic power by 21% and the self-sufficiency rate by 22.5%. It proves that THIC can not only optimize indoor thermal and humid environment, but also possesses great potential for the overall optimization of building energy systems. For commercial buildings, central air conditioning systems equipped with magnetic levitation compressors achieve an energy saving rate of approximately 40% and cut the full-lifecycle cost by around 25% when compared with traditional systems.

Business models are also undergoing continuous iteration. Service modes such as full-lifecycle operation and maintenance and energy performance contracting have gained rapid popularity and been widely adopted in large public buildings including airports and hospitals. The economic rationale behind this transition is evident. A cost analysis of an office building in Shenzhen reveals that the initial procurement cost of air conditioning equipment merely accounts for 12% of the total cost of ownership over a 20-year period. By contrast, energy consumption and maintenance expenses together make up as much as 83% of the total cost. This indicates that the core value no longer lies in selling high-priced equipment, but in delivering comprehensive service solutions that can steadily cut operational costs.

IV. CURRENT CHALLENGES AND FUTURE OUTLOOK

The technological advances described above should not obscure the real-world challenges facing this paradigm shift.

4.1 BOTTLENECKS IN IMPLEMENTING HIGH-EFFICIENCY PLANT ROOM STANDARDS

The development of energy efficiency evaluation standards for high-efficiency chiller plants has entered an accelerated phase. Local technical standards for high-efficiency cooling plant rooms have already been published in regions such as Jiangsu and Henan, and the technical review of the national standard Test and Evaluation Method for Energy Efficiency of Centralized Air-Conditioning Cold (Heat) Source Systems has also been completed [14]. Nevertheless, the practical promotion of these standards still faces considerable resistance. On the one hand, small and medium-sized enterprises lack mandatory regulatory constraints, and their intrinsic economic motivation to proactively pursue energy efficiency certification is inherently insufficient. On the other hand, end users have varying levels of understanding of whole-life cycle costs, which severely limits the premium space for high-performance products in markets that are highly sensitive to initial investment.

4.2 REAL-WORLD GENERALIZATION BARRIERS FOR AI ALGORITHMS

Although academic research on AI technology for central air-conditioning control has yielded significant achievements, moving from the laboratory to real building applications remains quite difficult.

A prominent problem is the cross-scenario generalization capability of models. AI control algorithms that perform excellently in the lab often suffer from performance degradation when deployed in actual buildings, primarily due to sensor noise, data discontinuities, network latency, and the stochastic nature of occupant behavior. Specific studies have pointed out that some AI control research suffers from sample bias and data integrity issues, affecting the generalizability of the conclusions [24]. Another review notes that AI models deployed online must cope with data distribution drift and the operational constraints imposed by real-world system maintenance cycles [15].

In terms of solutions, transfer learning is regarded as a promising direction. By adapting a model trained on a source building and transferring it to a target building, it reduces the reliance on large amounts of training data for the new building [30]. Existing studies have verified the feasibility of transfer learning in the field of building energy consumption prediction. However, a common limitation of current research is that most work examines the impact of only a single factor (e.g., envelope differences, functional use differences, or climate differences) on transfer effectiveness in isolation, whereas in real buildings these factors are typically coupled. The lack of systematic analysis of multi-factor coupling effects means that the current understanding of the applicable boundaries of transfer learning is still incomplete. Seasonal differences in cooling load patterns also have a certain impact on the generalization capability of the transfer model. Regarding whether a certain "transferability threshold" exists between the source and target building, existing research has yet to provide a clear answer. In summary, transfer learning in the field of air-conditioning control is still at the stage of "clear direction but insufficient engineering validation," and its large-scale reliability requires further verification through more long-term, cross-building empirical studies. Robust control and online learning have also been identified as potential supplementary technical pathways. Robust control strives to maintain control stability under conditions of noise and data loss, while online learning allows models to continuously adapt to changing environments during operation. The practical deployment of both also faces engineering constraints such as sensor quality, computing resources, and user acceptance.

4.3 SPECIAL REQUIREMENTS OF THE EXISTING BUILDING RETROFIT MARKET

In the first three quarters of 2025, the domestic sales volume of central air-conditioning in China was RMB 88.67 billion, a year-on-year decline of 6.7%, with the new construction supporting market entering a growth plateau [21]. Meanwhile, the existing building floor area has exceeded 60 billion square meters, and the demand for building energy-saving retrofits within this stock is growing rapidly. The market focus is shifting from "incremental new construction" to "existing building retrofits." This shift imposes special requirements on technical solutions that differ from new construction projects: first, rapid deployment capability; second, minimal disruption to normal building operations during construction; and third, the flexibility for on-demand, phased upgrades. The Hitachi SET-FREE RIII series, through its piping adaptation and pressure adaptive technologies, enables the continued use of existing system piping [13]. The design philosophy of "retrofit with minimal operational disruption" embodied in this is a technological response to the demands of the existing building market.

4.4 FUTURE DIRECTIONS

Based on the current technological trajectory and the challenges faced, the subsequent development of central air-conditioning technology may need to deepen along three directions. First, the native integration of AI and energy efficiency — AI is no longer an "intelligent plug-in" added to hardware as an afterthought, but a native capability embedded into the system architecture at the equipment design stage. The industry's first large-model AI multi-split VRF system, launched by Haier, adopts a dual-chip design with an MCU and NPU, carries a HVAC vertical domain large model, and Haier reports that the product achieves 30% energy savings (compared to the energy consumption of a non-AI version of the same model under identical operating conditions; data sourced from the manufacturer, not independently verified by a third party) [5]. Second, multi-energy coordination and flexible load management — central air-conditioning systems will gradually integrate into "PV-storage-air conditioning" integrated energy systems centered on photovoltaic power, energy storage, and smart grids. Central air-conditioning can dynamically adjust its operating strategy based on grid peak-shaving demands and electricity market price signals [10]. Third, the restructuring of the global industrial landscape — Chinese central air-conditioning enterprises have transitioned from technology followers to technology exporters in some technical fields, a role change that will have a profound impact on international standard-setting and the balance of market power.

V. CONCLUSION

The analysis in this paper demonstrates that central air-conditioning technology has moved beyond the phase of gradual optimization measured solely by a single energy efficiency indicator. The industry has entered a new phase of deep integration between hardware energy efficiency improvement and intelligent control. Hardware technologies such as magnetic bearing compressors, wide-frequency operation, heat recovery, and temperature-humidity decoupling continue to iterate. Meanwhile, AI-driven load forecasting, digital twin-based operation and maintenance, and the service-oriented transformation of business models are reshaping the design logic and usage patterns of central air-conditioning. These two technological trajectories are not mutually exclusive but deeply coupled: the hardware provides the physical foundation for system intelligence, and system intelligence, in turn, unlocks the energy-saving potential previously constrained by traditional control logic. The focus of competition has expanded from a contest of single hardware parameters to the comprehensive capability of synergizing "high-efficiency hardware, AI algorithms, and scenario-based solutions." Understanding the internal logic of this transformation is crucial for grasping the industry's current core development context and future direction.

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