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Review Article

Review on Development of Low Temperature Heat Source Heating Technology

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Abstract: Low-temperature heat source heating represents a pivotal technological direction for global energy decarbonization and building heating decarbonization. Its development is deeply integrated with fourth-generation district heating (4GDH) concepts, forming a comprehensive technical framework encompassing top-level design, pipeline systems, terminal equipment, and standardized modeling. This study systematically reviews research advancements in low-temperature heating technologies across conceptual frameworks, network performance, economic viability, intelligent control systems, terminal innovations, thermal comfort, and standard methodologies. It highlights core advantages of low-temperature heating systems in reducing heat and exergy losses, integrating renewable energy and industrial waste heat, and enhancing system flexibility. Research demonstrates that low-temperature district heating networks exhibit significantly superior energy efficiency and cost-effectiveness compared to traditional high-temperature systems. Existing building retrofits require shorter investment payback periods, optimized terminal equipment can reliably adapt to low-temperature operating conditions, and intelligent control coupled with demand response mechanisms further reduce operational costs. Future technological priorities will focus on low-cost deep retrofitting, cross-sector energy integration, market-based incentive mechanisms, and standard upgrades to provide critical support for clean heating initiatives and carbon neutrality objectives.

Keywords: Low-Temperature Heating, Fourth-Generation District Heating, Low-Grade Heat Source, Radiator, Thermal Comfort, Energy System Decarbonization.

I. INTRODUCTION

Against the backdrop of global carbon neutrality goals and China's "dual carbon" strategy, building heating accounts for a significant proportion of terminal energy consumption and total carbon emissions. Traditional high-temperature centralized heating systems face challenges such as mismatched heat source quality, substantial pipeline heat loss, and poor compatibility with renewable energy sources. Low-temperature heat source heating, characterized by low-temperature operation, minimal heat loss, high waste heat utilization, and multi-energy synergy, has emerged as a critical pathway for low-carbon transformation in the heating sector. The new concept centered on fourth-generation district heating (4GDH) drives heating systems to evolve from single high-temperature transmission to intelligent low-temperature interconnection, multi-source complementarity, and demand response upgrades. In recent years, research focus has shifted from equipment performance verification to system integration, cross-departmental collaboration, and large-scale implementation. Based on authoritative domestic and international literature and engineering cases, this paper comprehensively reviews the development trajectory, current research status, technological breakthroughs, and future directions of low-temperature heat source heating technologies, providing theoretical references for China's clean heating technology upgrades, policy formulation, and project implementation.

II. Low-Temperature Heating Concept and System Integration

The development of low-temperature heating is closely linked to the low-carbon transition of global energy systems, with its macro framework comprising the concept of sustainable energy systems, intergenerational evolution

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pathways, and cross-sector integration strategies. Lund *et al*., (2014) established the core principles of fourth-generation district heating (4GDH), defining its concept as the intelligent heat network cornerstone for future sustainable energy systems. Its key characteristics include low-temperature operation, minimal heat loss, high renewable energy integration rates, and synergy with smart grids. This framework provided top-level design and target specifications for nearly all subsequent low-temperature heating technology research [1]. Connolly *et al*., (2014) demonstrated in the "European Heating Roadmap" that integrating district heating with building energy efficiency represents one of the most cost-effective pathways to decarbonize the EU's energy system [2]. This study offered macro-policy-level economic justification and necessity support for large-scale low-temperature heating technology adoption. Regarding smart energy system methodologies, Lund's (2014) approach emphasizes coordinated optimization across power, heating, and transportation sectors [3]. Within this framework, low-temperature heating serves not only as an end-use energy-saving technology but also as a critical medium for balancing flexible loads from intermittent renewables (e.g., wind and solar power) and facilitating cross-seasonal thermal storage. With continuous technological advancements, research focus has evolved from early emphasis on individual device performance to systematic integration and application. This progression includes Hasan et al. 's (2009) validation of composite systems (radiators + underfloor heating) [4], followed by Tunzi et al.' s (2016) proposed systematic retrofitting approach for existing buildings [5]. The shift from addressing 'low-temperature operation feasibility' to exploring 'optimal integration and scalability' signifies a significant advancement in technical maturity.

III. Low-Temperature Heating Networks and System Optimization

Low-temperature district heating networks serve as critical physical infrastructure for realizing macro-level energy systems, with research focusing on network performance, economic analysis, and intelligent control. In the field of network performance and design optimization, Li and Svendsen (2012) conducted studies from energy and exergy perspectives, demonstrating that low-temperature networks not only reduce heat transfer losses but also minimize thermodynamic losses during heat transfer processes, thereby enhancing overall energy chain efficiency [6]. Volkova *et al*., (2019) analyzed the Kopli New District case in Tallinn, Estonia, revealing that low-temperature district heating systems integrating seawater source heat pumps outperform traditional high-temperature solutions in both long-term environmental benefits and net present value [7]. Dalla Rosa *et al*., (2011) emphasized pipeline optimization design to minimize network heat losses, which forms the foundation for achieving cost-effectiveness in low-temperature network systems [8].

In the field of economic evaluation and existing building retrofitting, Ommen *et al*., (2016) conducted simulation studies demonstrating that reducing district heating temperatures significantly improves system performance (e.g., combined heat and power generation capacity) under current and future Danish energy scenarios [9]. Østergaard and Svendsen (2019) investigated the cost-effectiveness of low-temperature heating retrofits, revealing that from a social energy system perspective, the investment payback period for retrofitting Danish existing buildings to accommodate low-temperature heating ranges from 1.2 to 4.3 years, indicating high economic viability [10]. Brand and Svendsen (2013) further analyzed the potential for integrating renewable low-temperature heating systems at different retrofit stages [11]. Jangsten *et al*., (2017) examined user incentive behaviors for low-temperature heating, with field surveys revealing that existing radiator systems in Sweden generally operate at elevated temperatures (average supply water temperature: 64°C). However, they also identified that radiators with larger heat transfer areas have temperature reduction potential, providing data support for establishing differentiated heat pricing based on return water temperatures [12].

In the field of intelligent control and system integration, Lauenburg and Wollerstrand (2014) developed adaptive control strategies aimed at achieving the lowest possible return water temperature for district heating systems, which is crucial for improving heat source efficiency and integrating low-grade heat sources [13]. Meanwhile, research by Theis Heidmann Pedersen *et al*., demonstrated that model predictive control (MPC) could still achieve approximately 5% and 18% operational cost savings in existing and retrofitted buildings, respectively, without compromising thermal comfort, even when accounting for the nonlinear dynamics of hydraulic radiators [14]. This validates the feasibility of low-temperature heating systems participating in power demand response. Regarding enhancing flexibility in low-temperature heating systems, Nuytten *et al*., (2013) investigated the flexibility of combined heat and power systems integrated with thermal storage, a critical factor for low-temperature heating systems incorporating high renewable energy proportions [15].

IV. Innovation in Low-Temperature Heating Equipment and Heating Efficiency

Low-temperature terminal equipment serves as the bridge connecting high-efficiency networks with comfortable spaces, where innovation and optimization form the core of technological implementation.

Regarding low-temperature adaptation and enhancement of traditional radiators, Wang *et al*., (2017) conducted a systematic evaluation indicating that Type 21 radiators achieve optimal efficiency under Swedish climate conditions across most operating scenarios. They emphasized that increasing convective fin counts does not necessarily enhance efficiency, with design optimization being more critical than simple surface area expansion [16]. Early research by McIntyre *et al.,* corrected computational errors in radiator heat output calculations at low flow rates, providing accurate tools for low-temperature system design [17]. Mostafa Omran Shobi et al.'s study on improved base-mounted radiators demonstrated a 34% increase in heat output through air gaps between radiators and walls/floors [18]. Utilizing field synergy principles, Yu Zhang *et al*., achieved convective heat transfer coefficients over five times higher than traditional square fins in cross-V-shaped fin configurations [19]. Luciano Garelli *et al.,* explored triangular wing vortex generators, which increased heat transfer by 12% under natural convection conditions [20]. Halil Bayram *et al.,* demonstrated that fan-equipped radiators significantly enhance heat dissipation, with more pronounced cooling effects at lower water supply temperatures. Although natural convection and radiant heat transfer ratios decreased in fan-assisted radiators, forced convection compensation offset this reduction, maintaining total heat dissipation levels higher than conventional plate radiators [21].

Significant achievements have been made in innovative terminal equipment research for low-temperature heating systems. Myhren and Holmberg (2009) demonstrated through CFD studies on ventilated radiators that they can reduce surface temperatures by up to 7.8°C while improving thermal uniformity [22]. Jonn Are Myhren's research on radiator shape optimization revealed that minor adjustments to fin structures—including reduced fin spacing and removal of intermediate fin arrays—enhance heat exchange efficiency in outdoor air intake zones, while optimized internal fin configurations further improved thermal performance [23]. Adnan Ploskic's comprehensive evaluation of ventilated radiators based on EN 442-2 standards found that convective plate designs alone had limited impact on heat dissipation enhancement. Plate configurations neither significantly affected indoor heat distribution uniformity nor altered vertical temperature stratification within rooms [24]. Yuhang Tian's team developed an advanced radiator incorporating side flow guide plates and extended chimney channels at the top, achieving 19.14% higher external air flow rates compared to traditional plate radiators without chimneys [25]. Guobing Zhou's studies on radiant low-temperature heating systems revealed that floor heating systems utilizing phase change materials (PCM) and capillary networks exhibit more stable and durable heating capabilities [26]. Koca and Cetin (2017) experimentally determined the heat transfer coefficients of various radiation systems [27].

In comparing thermal comfort and air quality among different low-temperature heating technologies, Myhren and Holmberg's (2008) seminal CFD study demonstrated that low-temperature heating systems (floor and wall systems) produce lower vertical temperature gradients and air velocity compared to traditional high-temperature radiators, thereby enhancing thermal comfort [28]. Mikk Maivel experimentally validated the characteristic temperature variation patterns between radiator and floor heating systems, extending this analytical approach to air heating systems to quantify thermal discharge losses across different configurations, confirming radiator heating as the optimal solution in this metric [29]. Mohammad Hadi Dehghan et al.' s simulation research revealed that skirtboard heating achieved superior comprehensive performance in thermal comfort and reduced particulate matter concentration in breathing zones among three system types [30]. Jian Liu's team conducted energy and exergy-based comparisons of multiple systems, demonstrating that stratified ventilation heating outperformed traditional floor, ceiling, and wall radiator systems in terms of energy consumption and exergy consumption [31]. Zhang *et al.,* (2019) experimentally investigated a novel heat storage radiator system directly coupled with air-source heat pumps, validating its feasibility and deriving performance characteristic equations [32].

V. Technical Standards for Low-Temperature Heating Systems and Cross-Domain Applications

The European standard EN 442-2 (1997) serves as the cornerstone for thermal performance testing of radiators and convectors, providing a unified basis for comparing and evaluating different low-temperature terminal equipment through its defined testing methods [33]. Relevant research has consistently adopted this standard or similar standards (e.g., BS EN 442) as experimental foundations. Regarding simulation modeling tools for low-temperature heating terminals, Muhsin Kılıc *et al*., explored the applicability of radiator models with varying complexity levels in joint simulations during system modeling, as documented in the journal *Progress in Exergy, Energy, and the Environment* [34]. The TS EN 442 standard employed finite volume method-based CFD analysis to conduct three-dimensional numerical calculations of thermal output for steel plate radiators, offering guidance for system-level simulations. In cross-domain technology integration, Abdul Razak Kaladgi *et al*., utilized efficient methods including Taguchi's Grey Relational Analysis (GRA) and Response Surface Method (RSM) to investigate, statistically analyze, and optimize the impact of input variables on radiator thermal performance characteristics. Their application of experimental design, multi-objective optimization, and artificial neural network modeling to automotive radiators provides methodological insights for building heating radiator optimization [35]. Sachin B. *et al*., developed specialized radiator test benches for experimental studies and employed commercial software for numerical simulations. The simulation model incorporates fluid dynamics of oil within the radiator and external airflow, along with conjugate heat transfer processes (combining conduction, convection, and radiation). This conjugate heat transfer study on transformer radiators also provides a benchmark for high-precision simulation validation [36]. In material innovation, M. M. Sarafraz *et al.*, investigated the application of iron oxide (III)–thermal oil 66-based nanosuspensions in convection heating systems, demonstrating potential heating applications in architectural fields. Within gas-liquid convective heat exchange systems, the iron oxide (III)–thermal oil 66 nanofluids exhibited superior thermodynamic performance, featuring higher heat transfer coefficients and lower pressure drops [37].

VI. CONCLUSION AND PROSPECTS

A literature review reveals that low-temperature heating technology has evolved into a comprehensive technical framework encompassing top-level concepts, network systems, terminal equipment, and standardized methodologies. Its development has transcended mere "temperature reduction" to enter a new phase characterized by system integration optimization and intelligent collaborative control. Key future directions include: Deep retrofit strategies – developing cost-effective solutions for retrofitting existing building radiator systems and envelope structures with minimal disruption; Standard and market mechanism innovation – updating design specifications and establishing robust market incentives based on actual performance metrics (e.g., return water temperature) alongside carbon pricing policies; Cross-sector integration – exploring synergies between low-temperature heating networks and systems such as data center waste heat recovery, hydrogen energy storage, and vehicle-to-grid (V2G) technologies to solidify their role as core hubs in smart energy systems. As both a critical climate response technology and a driving force for building energy consumption transformation and emerging industries, successful implementation of low-temperature heating requires sustained technological innovation, steadfast policy guidance, and collaborative efforts across the industry.

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