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Industrial Waste Heat Recovery and Heat Pump System Integration: A Critical Review

Ze-Yang Chen, Yan-Zuo Chang*, Shun-Tian Huang, Zi-Shuo Liu, Hong-Yi Chen, Geng-Wen Cai, Hong-Fei Wu, Lin-Tao He, Zheng-Bo Hou

School of Energy and Power Engineering, Guangdong University of Petrochemical Technology, Maoming, Guangdong 525000,China
*Corresponding author : 3509025756@qq.com

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***Abstract*— Amid global energy restructuring toward low-carbon development and the steady advancement of China's dual-carbon strategic layout, industrial energy consumption consistently occupies a high proportion in total social energy usage. Mass quantities of low-grade residual heat generated during industrial production are directly discharged without effective recycling, which not only creates massive energy wastage but also aggravates regional greenhouse gas pollution and environmental load. By upgrading heat pump thermal utilization technologies, low-temperature low-quality residual heat can be captured and upgraded into high-grade heat medium suitable for factory production, which has become a core technical route to realize industrial energy conservation, carbon emission reduction and graded exploitation of residual heat resources. This paper comprehensively sorts out domestic and overseas existing research findings plus practical engineering examples, and conducts systematic reviews on full-chain core technologies linking industrial residual heat recycling and heat pump matching integration. Relevant research progress is classified from five dimensions including residual heat inherent properties, heat pump working principles, system matching schemes, core component technologies and multi-industry practical applications. The paper objectively summarizes existing technical bottlenecks, divergent academic viewpoints and blank research fields of current technologies. Combined with relevant industrial policy orientation, the paper further forecasts the development trend of high-temperature heat pump equipment, digital intelligent linkage and multi-energy complementary integrated technologies. Relevant research conclusions can provide theoretical reference and practical guidance for efficient recycling of industrial residual heat and low-carbon upgrading of manufacturing industries.*

I. INTRODUCTION

With increasingly tight global energy supply-demand balance and stricter ecological environment supervision worldwide, improving industrial energy efficiency and fully tapping residual heat resources have turned into key development directions of global energy industries, which also serves as an important guarantee to fulfill China's carbon peaking target by 2030 and carbon neutrality target by 2060 outlined in national strategies [1]. As the world's biggest manufacturing country, China's industrial terminal energy consumption accounts for more than 65% of national total energy consumption for a long period. During actual manufacturing processes, roughly 20%~55% input energy is eventually transformed into various types of low-grade residual heat such as flue gas waste heat, circulating cooling water heat, process condensate heat and equipment surface dissipating heat, most of which is emitted directly to ambient environment without utilization [2]. Such scattered, low-temperature and unstable residual heat cannot satisfy factory heating demands directly; conventional heat recovery equipment has limited temperature lifting capacity and narrow applicable working conditions, leading to an overall residual heat recycling rate below 30% and triggering serious energy loss and excess carbon emission problems.

Under such industrial background, heat pump cyclic technology follows the reverse Carnot cycle's heat transfer law, consuming a small amount of high-grade driving energy like electric power and industrial steam to upgrade low-temperature inferior residual heat into usable high-quality heat. This technology effectively resolves the mismatch between residual heat temperature and on-site production heat requirement restricting industrial residual heat reuse [3]. Deep fusion between heat pump units, residual heat recovery pipe networks and production heat supply processes can effectively broaden the available temperature range of industrial residual heat, raise the whole-cycle energy utilization efficiency of production lines, cut fossil fuel consumption for enterprises and lower carbon emissions and operating expenditure, matching the intelligent, low-carbon and high-efficiency development needs of process manufacturing under Industry 4.0 construction [4].

Global scholars have launched comprehensive research focusing on residual heat grade classification standards, heat pump operating mechanism, system parameter optimization, environment-friendly novel refrigerants and long-period stable running performance. At present, compression, absorption and transcritical CO_2 heat pump technologies have been put into demonstration construction across multiple fields including iron and steel production, chemical processing, paper making, municipal central heating and big data server base cooling [5]. Nevertheless, existing technical systems still face multiple practical obstacles: poor high-temperature adaptability of existing equipment, insufficient tolerance for corrosive heat sources in industrial waste, unstable collaborative performance under variable multi-heat-source working conditions, uneven full-life-cycle economic benefit and incomplete cross-industry standard formulation system [6].

Based on above background, this review systematically combs the latest research progress and mature industrial application cases of residual heat-heat pump integrated technology at home and abroad, compares advantages, drawbacks and applicable boundary of different technical paths, objectively analyzes existing academic disputes, on-site application constraints and undiscovered research fields, summarizes technical evolution laws and pins down future research priorities. The sorted research results can offer systematic literature support for subsequent academic exploration, enterprise energy-saving transformation projects and industrial specification revision.

II. RESEARCH PROGRESS CLASSIFICATION AND SUMMARY

This chapter synthesizes the latest research achievements over the past 15 years, categorizing them into five pivotal domains: the graded characteristics of residual heat, operational principles of heat pumps, system integration architectures, core component technologies, and cross-industry applications. Rather than a mere accumulation of literature, this section integrates experimental data and academic viewpoints to reveal the evolutionary trajectory of this technological field.

2.1 Study on Grading Feature of Industrial Residual Heat and Corresponding Recycling Mode

Domestic scholar Wang Ruzhu's research team pioneered comprehensive statistical investigation and temperature grading classification targeting residual heat resources of China's process industry [7]. According to exhaust temperature difference, industrial residual heat is split into four grades: high-temperature waste heat (>500°C), medium-temperature waste heat (200~500°C), low-temperature waste heat (80~200°C) and ultra-low-temperature waste heat (<80°C). Meanwhile, the research group specified corresponding emission industries, heat carrier types, impurity characteristics and recycling technical difficulties for each temperature grade. He Yaling academician's research team built an evaluation system to judge residual heat utilization value, putting forward four core assessment indicators: heat source temperature stability, fluid corrosivity, space-time distribution concentration and load fluctuation amplitude, establishing a comprehensive evaluation system for industrial residual heat development potential [8]. Relevant statistical results prove over 80% domestic industrial residual heat belongs to scattered low/ultra-low temperature type, which cannot be recycled via traditional direct heat exchange and needs heat pump upgrading technology to realize resource recovery.

Sun Jian and other researchers analyzed intermittent heat emission rules of chemical and steel industries [9], discovering production parameter fluctuation in process factories leads to daily variation of residual heat flow rate and temperature exceeding 40%. Fixed-parameter single-set residual heat recycling equipment cannot maintain long-term stable and high-efficiency operation; it is necessary to equip heat storage modules and adjustable heat pump units for collaborative matching. Guo Feng explored physical properties of high-dust industrial flue gas and strong acid-base corrosive industrial wastewater with residual heat [10], pointing out complicated working conditions easily cause rapid corrosion on conventional heat exchanger components, shorten equipment service life and raise running cost, which becomes a key bottleneck restricting large-scale popularization of residual heat heat pump. Arpagaus C and overseas research partners finished global residual heat resource statistical analysis, confirming low-grade industrial residual heat can cover over 30% worldwide industrial heating demand, and heat pump technology is the only technical solution applicable for all sorts of residual heat working conditions [11]. Besides, Luo's research team completed multi-scale space-time distribution simulation on steel industry residual heat, providing fundamental data for heat pump parameter design under dynamic variable load [12].

2.2 Working Mechanism and Technical Routes of Various Industrial Heat Pumps

By distinguishing driving energy types and internal operation principles, industrial residual heat recycling heat pumps are mainly divided into four mainstream technical categories: vapor compression heat pump, lithium bromide absorption heat pump, solid adsorption heat pump and transcritical CO_2 heat pump. Global researchers have carried out contrast tests on energy efficiency, applicable temperature range and investment economy of above four types of equipment [13]. Li Jianhui performed numerical simulation for electrically driven compression heat pump [14], which relies on compressor to drive refrigerant circulation with heating COP ranging from 3.0 to 5.0 and applicable working temperature between -20°C~150°C. Featuring compact layout, flexible load adjustment and quick start-stop response, such equipment is most widely used in low-temperature residual heat recycling projects. Ge Yu's team researched steam-driven lithium bromide absorption heat pump [15], which takes low-pressure waste steam and high-temperature flue gas as driving heat source with low power consumption and COP within 1.5~2.5, suited to recycle 60~200°C medium-temperature residual heat in steel and petrochemical factories with abundant waste steam output. Li Yongtian focused on adsorption heat pump used under ultra-low-temperature conditions [16]; the equipment completes thermal cycle via solid adsorbent without mechanical moving parts and possesses ultra-low failure probability, yet its operating efficiency is limited (COP=0.5~1.2), only suitable for special ultra-low-grade residual heat recovery scenarios.

Ma Shicai devoted to developing transcritical CO_2 high-temperature heat pump [17]. CO_2 refrigerant has zero ozone depletion potential and extremely low greenhouse effect coefficient compared with traditional organic refrigerants, enabling equipment to break the previous 150°C heating limit and satisfy 120~200°C high-temperature industrial heat supply, becoming a key developing direction of future high-temperature residual heat utilization. Wang J.Y.'s cross-regional comparative experiments verified CO_2 transcritical heat pump runs more stably in long-term high-temperature residual heat environment than organic refrigerant heat pump, cutting full-cycle carbon emission by more than 40% [18]. Bamigbetan's theoretical calculation indicates two-stage compression CO_2 heat pump can lift system COP by 15%~20% under evaporation temperature of -10°C~40°C [19]. Dong Xiaobo compared component matching characteristics of heat pump units, proving parameter coordination among evaporator, frequency-variable compressor, high-pressure condenser and throttling valve directly determines overall operating efficiency of residual heat heat pump [20].

2.3 Matching Integration Modes Between Residual Heat Source and Heat Pump System

Based on the heat exchange connection methods between waste heat media and heat pump units, China's academic research categorizes the integration modes into three mainstream approaches: direct waste heat recovery, indirect heat exchange recovery, and multi-source hybrid coupling recovery. These modes exhibit significant differences in application scenarios, heat exchange efficiency, and equipment costs [21].

Scholar Zhou Xiaosan [22] investigated the direct heat exchange integration model, where the heat pump evaporator directly exchanges heat with industrial waste heat sources, featuring fewer process steps, minimal thermal energy loss, low initial system investment, and high heat transfer efficiency. However, this approach requires extremely high cleanliness of the waste heat medium and is unsuitable for waste heat from dust-containing, highly corrosive, or impurity-rich flue gases and wastewater. Scholar Ge Zhihua [23] optimized the indirect heat exchange integration model by adding an intermediate isolation heat exchanger between the waste heat source and the heat pump, effectively isolating corrosive and highly impure waste heat media to protect the core heat pump components while significantly expanding compatibility with complex operating conditions; however, this increases the first-stage heat exchange temperature difference, resulting in an overall system COP reduction of 8%–12%.

Scholar Zhang Huan [24] proposed a multi-waste heat source hybrid integration model that combines the advantages of both direct and indirect heat exchange methods, enabling simultaneous recovery of dispersed waste heat from multiple locations, different types, and varying temperatures within industrial facilities—making it the mainstream design solution for comprehensive waste heat utilization in large-scale industrial parks.

Meanwhile, numerous scholars have conducted in-depth research on system temperature matching optimization. Scholar Sun Jian [25] employed the T-Q thermodynamic enthalpy diagram matching method to optimize the residual heat evaporation temperature and the temperature difference between process heating and condensation, maintaining the heat exchange temperature differential within the optimal range of 5–10°C, thereby significantly reducing irreversible thermal energy losses and improving the system's overall energy efficiency by over 15% under identical operating conditions. To address fluctuations in waste heat load, relevant studies have proposed solutions such as variable-frequency regulation of heat pumps, parallel operation of multiple units, and coupling with phase-change thermal storage systems, effectively mitigating parameter variations caused by production fluctuations and ensuring stable, efficient year-round system operation [26]. Scholars Jensen et al. [27] further demonstrated that integration of phase-change thermal storage modules can increase the partial load energy efficiency ratio (IPLR) of heat pump systems by approximately 25%, making it particularly suitable for intermittent production processes.

2.4 Key Supporting Technology of Residual Heat Heat Pump Equipment

a) 2.4.1 High-efficiency Anti-corrosion Enhanced Heat Exchange Technology

Corrosion, scaling and pipeline blockage are common faults restricting long-period stable operation of industrial residual heat heat exchangers, resulting in continuous heat transfer attenuation. Researchers developed micro-channel finned tube and corrugated tube enhanced heat exchange structure to promote unit-area heat transfer coefficient. Adopting titanium alloy, Hastelloy alloy and duplex stainless steel as heat exchanger manufacturing materials significantly strengthens corrosion resistance when facing acidic, alkaline and chloride-containing industrial medium [28]. Besides, nano self-cleaning coating technology applied on heat exchange surface effectively inhibits dirt accumulation and pipe blockage from flue gas and wastewater heat source, prolonging equipment maintenance cycle and lowering later-stage maintenance cost [29]. Uhlmann M and collaborators utilized CFD flow field simulation to optimize internal runner layout of heat exchanger, reducing fluid flow resistance while lifting overall heat exchange performance and operational stability [30].

2.4.2 High-efficiency Compression Equipment and Intelligent Control Technology

Oil-free magnetic suspension frequency conversion compressor is gradually replacing traditional fixed-frequency piston compressor. Such compressor reduces mechanical abrasion, vibration and running noise under non-lubrication working mode and presents superior partial-load efficiency, matching variable residual heat load characteristics well [31]. Besides, IoT, machine learning and digital twin technology have been introduced into heat pump intelligent control system, realizing residual heat supply prediction, real-time parameter automatic optimization, early fault pre-warning and remote online maintenance, replacing original artificial fixed-value regulation mode and boosting annual comprehensive energy-saving rate above 20% [32]. In terms of control algorithm upgrading, Starke’s research team designed MPC model predictive control scheduling strategy for residual heat heat pump, and practical test proves this control method can save 12% energy consumption compared with conventional PID control [33].

2.4.3 Environment-friendly Low-carbon Novel Heat Pump Working Medium Technology

With increasingly stringent global environmental restriction on high-GWP traditional refrigerants, low-environmental-hazard natural refrigerants and low-GWP mixed non-azeotropic refrigerant become core research hotspot in refrigerant field. Natural medium such as ammonia and CO_2 has zero ozone damage risk and outstanding environmental performance; customized mixed refrigerant features temperature slip characteristic, perfectly adapting to non-isothermal industrial residual heat recycling process and lifting cycle efficiency under wide working temperature range [34]. Nano-fluid modification technology mixes ultrafine nanoparticle into circulating medium to strengthen heat transfer capacity, decrease pipeline flow loss and upgrade whole-system energy efficiency [35]. Mota-Babiloni systematically summarized application prospect of multiple low-GWP alternative refrigerants for high-temperature heat pump, confirming R1233zd(E) and R1336mzz(Z) possess prominent development potential for medium-high temperature heating projects [36].

2.5 Engineering Demonstration Application Progress in Typical Industries

Domestic researchers have finished field test of residual heat heat pump transformation projects targeting four key industries: steel coking, petrochemical synthesis, papermaking light industry and IDC data center.

Petrochemical rectifying tower low-temperature condensate heat recycling project adopts two-stage compression heat pump scheme with steady system COP up to 3.8, cutting annual carbon dioxide emission over 6000 tons per single project and recovering construction investment within 4.2 years [37]. Steel coking wastewater absorption heat pump renovation reduces factory heating power consumption by 29.2% and corresponding carbon emission more than 30%. Papermaking drying tail gas transcritical CO_2 heat pump saves over 65% energy compared with traditional electric boiler heating. Data center cooling waste heat matched with heat storage-type heat pump lifts overall energy utilization efficiency by 45% [38]. Above practical projects fully verify the technical feasibility and economic benefits of residual heat-heat pump integrated scheme. Globally, Denmark Dronninglund municipal heating project builds large absorption heat pump unit to recover nearby factory residual heat for residential central heating, covering more than 1000 household heating demands and proving cross-industry residual heat supply's development potential [39].

2.6. Synthesis and Evolution Trend

A critical analysis of Section 2 reveals a clear technological trajectory:From Simple Exchange to Thermal Upgrading: The focus has shifted from merely transferring heat to actively upgrading low-grade energy.From Isolated Units to Integrated Systems: There is a move towards hybrid systems that combine multiple heat sources and storage.From Manual to Autonomous: Control systems are evolving from fixed-parameter PID to AI-driven predictive control.This evolution sets the stage for the discussion in Section 3, where we will address the remaining bottlenecks in high-temperature adaptation and economic viability.

III. DISCUSSION AND IN-DEPTH ANALYSIS

Based on comprehensive literature sorting, this chapter objectively discusses divergent academic viewpoints, practical application defects, industrial development bottlenecks and blank research fields of existing technologies without subjective biased evaluation.

3.1 Current Existing Academic Technical Disputes

Existing published literatures mainly focus on two core disputed directions: high-temperature working condition heat pump type selection and anti-corrosion utilization scheme decision for impurity-rich corrosive residual heat source.

For industrial waste heat above 150°C, three alternative technical paths including transcritical CO_2 heat pump, high-temperature organic refrigerant compression heat pump and absorption heat pump remain controversial among academic researchers: organic refrigerant heat pump runs with high cycle efficiency yet suffers poor high-temperature stability and fails to satisfy updated environmental protection requirements; CO_2 transcritical equipment is eco-friendly but requires ultra-high system operating pressure, leading to soaring equipment manufacturing cost and safety protection investment; absorption heat pump fits high-temperature working environment yet must rely on factory self-produced waste steam as driving source and cannot run independently without matching residual heat resource. Different scholars' experimental data lead to inconsistent optimal design conclusion, lacking unified industry design standard up to now.

When processing high-dust flue gas, high-salinity chemical wastewater and sulfur-containing corrosive residual heat, academic circles cannot reach a consensus on three processing routes: direct heat transfer, intermediate indirect heat exchange or preprocessing + heat exchange compound scheme. Preprocessing technology greatly raises upfront project investment; indirect heat exchange sacrifices partial heat utilization efficiency; direct heat exchange faces accelerated equipment corrosion and unexpected shutdown risk. At present, targeted cost-benefit comparison research aiming at different industrial working conditions is still insufficient.

3.2 Practical Application Deficiencies of Existing Technology

Current mature heat pump products mostly apply to residual heat below 150°C, lacking available technical solutions for high-temperature residual heat recovery from chemical evaporation and rectification procedures; key technologies such as high-temperature resistant sealing material, environment-specific high-temperature refrigerant and high-pressure circulation equipment remain immature and restrict large-scale industrial popularization. Scattered intermittent residual heat cannot be fully utilized efficiently: numerous small and medium-sized manufacturers generate fragmented intermittent residual heat, while large-scale centralized integrated heat pump equipment is not suitable for small decentralized heat source, and relevant research about cross-factory regional residual heat interconnection sharing system is scarce. Uneven full-life-cycle economic return hinders market promotion: residual heat heat pump transformation requires large upfront capital input, some small-scale projects need more than six years to recover investment, resulting in low renovation willingness among SMEs. Besides, relevant profit model and government subsidy financing research are insufficient. Industrial standard system is incomplete, lacking targeted design, construction acceptance and energy efficiency evaluation specification for steel, chemical and papermaking residual heat heat pump, leading to uneven project design quality and inconsistent system running efficiency.

3.3 Unfilled Research Gaps in Present Research Field

Multi-energy complementary collaborative coupling research is insufficient; few researches focus on cascade utilization combining photovoltaic power generation, energy storage device, organic Rankine cycle power generation and residual heat heat pump, and the theoretical framework of renewable energy + industrial waste heat combined heating has not been perfected. Long-term equipment aging degradation research is inadequate; existing studies rarely discuss performance attenuation rule and service life prediction model of heat exchanger, refrigerant and core parts under long-term high-temperature, corrosive and variable-load industrial environment. Research about regional residual heat market-oriented allocation is almost blank, covering cross-workshop and cross-enterprise heat resource transaction rule, pricing standard and overall scheduling mechanism. Meanwhile, ultra-low-temperature residual heat (<40°C) recycling technology development falls behind, lacking high-efficiency recovery equipment for such widely distributed residual heat resource with the lowest utilization rate.

IV. RESEARCH CONCLUSION AND FUTURE PROSPECT

4.1 Main Research Conclusions

After sorting more than 40 relevant published papers about residual heat-heat pump integration technology, the core research findings are summarized as below: Industrial low-grade residual heat is China’s largest undeveloped renewable thermal resource; conventional heat exchange equipment cannot realize efficient recycling for low-temperature residual heat, hence heat pump integrated technology becomes the most feasible technical route to promote industrial energy conservation and carbon reduction. Currently compression, absorption and transcritical CO_2 three types of heat pump have formed complete theoretical system; direct, indirect and hybrid three matching integration modes can cover most industrial application scenarios; high-efficiency heat transfer, intelligent digital control and environment-friendly novel refrigerant three core technologies keep upgrading continuously. Multiple demonstration projects in steel, chemical, papermaking and data center industries verify prominent energy-saving and decarbonization value plus favorable economic return, most projects realize cost recovery within 3~5 years with large-scale popularization prospect.

However, the whole industry still faces multiple restrictive factors including insufficient high-temperature adaptability, difficulty in scattered residual heat centralized recycling, high initial construction cost, imperfect industrial standard and incomplete multi-system matching theory; related technical routes remain in academic debate and many targeted application fields are still vacant. Generally speaking, residual heat heat pump technology stays in rapid improvement stage with huge upgrading space before full-scale industrial popularization.

4.2 Future Key Research Direction and Development Trend

Combining existing technical defects and national industrial policy trend, residual heat-heat pump integration technology will develop toward four directions:

High-temperature heat pump upgrading: develop low-GWP environment-friendly special refrigerant applicable above 200°C, optimize two-stage compression transcritical cycle structure, break high-temperature high-pressure component material bottleneck and expand heat pump’s full-temperature residual heat recovery capacity;

Full-process digital intelligent transformation: promote digital twin, AI predictive scheduling and IoT online monitoring technology application to build all-link intelligent operation framework adapting to scattered intermittent residual heat and raise annual operating efficiency;

Multi-energy complementary integrated system construction: couple photovoltaic, wind power, heat storage and organic Rankine cycle equipment with residual heat heat pump to build graded energy utilization network for further energy conservation and cost cutting;

Regional residual heat networking construction: build cross-factory cross-industry residual heat sharing network inside industrial parks, perfect heat resource market trading mechanism and realize centralized utilization of fragmented residual heat, shifting from single-factory independent transformation toward regional overall energy optimization.

In the future, with continuous breakthrough of new material, intelligent control and multi-energy integration technology plus perfected national subsidy and financing policy, residual heat heat pump integrated technology will greatly boost domestic process industry’s low-carbon transformation and play an indispensable role in implementing dual-carbon strategy and securing national energy supply safety.

Low utilization ratio of massive industrial low-grade residual heat is a core obstacle restricting China’s manufacturing green upgrading and high-quality development. Heat pump can upgrade low-grade waste heat energy level; deep combination with residual heat recovery system helps improve factory energy efficiency and reduce fossil fuel consumption and greenhouse gas emission. This paper systematically reviews domestic and overseas research about residual heat classification feature, mainstream heat pump operating principle, system matching mode, core equipment and industrial application, sorts different technical research progress, analyzes academic divergence, practical engineering obstacles and blank research content, summarizes technical evolution law and puts forward four future developing directions including high-temperature heat pump, digital intelligent control, multi-energy complementation and regional residual heat networking. Relevant application examples prove residual heat heat pump technology has remarkable energy-saving decarbonization benefit and acceptable economy, yet shortcomings on high-temperature adaptability, scattered heat utilization and industrial standard construction still exist. Follow-up researches need joint efforts of universities, research institutes and production enterprises to perfect whole technical system and accelerate large-scale high-efficiency exploitation of industrial residual heat resources.

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