

A Study on a Multifunctional Variable-Condition Heat Pump System for Mitigating Heat Stress in Deep Coal Mines and Utilizing Waste Heat

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Abstract: Against the backdrop of global climate change and the “dual carbon” strategy, mine waste heat—a low-grade energy source generated during coal mining—presents a key solution to addressing the conflicts between energy waste, environmental pollution, and production safety through its efficient recovery and utilization. Addressing issues such as high ventilation loads and waste of waste heat caused by high-temperature heat hazards in deep mines, existing research has largely focused on single technologies, lacking studies on multi-condition coupled systems. Based on this, this paper proposes a technical framework and engineering implementation path for a multifunctional, variable-condition mine waste heat pump system. The paper first analyzes the characteristics of deep-mine heat hazards and waste heat resources to clarify the necessity of system development; it then outlines the overall system architecture and proposes two technical pathways adapted to different exhaust air conditions; subsequently, it compares the core technical mechanisms and performance, and verifies the system’s feasibility through engineering case studies at the Hongliulin Coal Mine and Wanfu Mine; finally, it establishes selection criteria for mine waste heat technologies, forming a comprehensive system solution for multi-condition utilization of mine waste heat, thereby providing a reference for the large-scale and efficient utilization of mine waste heat resources.

Keywords: Mine Waste Heat; Multi-functional Variable-condition Heat Pump System; Co-current Tube-in-tube Heat Exchanger; Spray Heat Exchanger; Energy Conservation and Emissions Reduction; Dual Carbon Strategy.

1. Introduction

Global climate change is one of the most pressing challenges facing humanity today [1]. The implementation of the Paris Agreement has spurred countries to accelerate their emissions reduction efforts and move toward carbon neutrality [2], while the need for energy structure transformation and efficient resource utilization in China has become increasingly urgent [3]. With rapid industrial development and rising energy consumption, the depth of mining operations in China continues to increase, and the number of high-temperature deep mines is growing. While this has brought significant economic benefits, it has also raised prominent issues regarding energy utilization and production safety, creating a sharp contradiction with the energy conservation and emission reduction goals under the “Dual Carbon” strategy [4].

The high-temperature heat hazards caused by deep mining not only lead to a substantial increase in mine ventilation loads but also generate massive amounts of low-grade waste heat. Traditional methods of heat hazard management fail to effectively address production safety issues and result in significant waste of heat resources, creating an urgent need for systematic solutions for waste heat recovery and heat hazard mitigation. The high-temperature environment caused by mine waste heat not only seriously threatens the health of underground workers—increasing the risk of occupational diseases such as heat exhaustion and heatstroke [5]—but also accelerates equipment wear, reduces lubrication efficiency, disrupts production continuity, and may even lead to production shutdowns. This not only increases maintenance costs but also affects the stability of energy supply [6]. However, mine waste heat is not merely “waste energy”; rather, it is a low-grade energy source with immense potential

for resource utilization. After being upgraded through heat pump technology, it can replace traditional fossil fuels in applications such as wellhead freeze protection and heating for surface buildings [7]. This approach not only prevents energy waste but also reduces the additional consumption of coal resources to lower carbon emissions, aligning with China’s “dual carbon” strategic goals [7].

China’s development of heat pump technology began relatively late, with the study and introduction of European heat pump products only starting in 1997 [8]. However, research and development in mine waste heat utilization technology have advanced rapidly in recent years, and many domestic coal mining enterprises have gradually adopted this technology to reduce coal consumption and minimize pollution [9]. As mining operations extend deeper underground, the temperature of the surrounding rock increases significantly; at a vertical depth of 1,000 m, the surrounding rock temperature can reach 40°C [10, 11, 12]. Heat exchange between the airflow and the surrounding rock in the mine tunnels means that mine exhaust air contains abundant low-grade waste heat resources, and the efficient extraction of this heat has become a key technical challenge [13]. Through research and analysis of multiple coal mining regions, scholars such as Miao Shuyun and Huang Tao [14, 15, 16, 17] have confirmed that integrated systems for utilizing mine waste heat demonstrate excellent operational performance, economic benefits, and environmental benefits. These systems feature low operating costs, fully tap into waste heat potential, and help achieve energy conservation and emission reduction targets. Given that China’s energy structure remains dominated by coal, the development of mine waste heat resources using heat pump technology has become a critical pillar for achieving carbon peak and carbon neutrality targets on schedule [18].

Existing research on mine waste heat utilization has largely focused on the development and application of individual technologies, lacking studies on coupled systems tailored to different exhaust air conditions, making it difficult to adapt to the complex and variable characteristics of mine waste heat resources. Accordingly, this paper proposes a multifunctional, variable-condition mine waste heat heat pump system. Starting from the characteristics of deep-mine heat stress and waste heat resources, we construct the overall system architecture, compare the adaptability of core technologies, verify the system’s feasibility through engineering case studies, and establish criteria for technology selection, thereby forming a comprehensive technical framework and engineering implementation pathway.

2. Deep Well Heat Strain and Characteristics of Waste Heat Resources

During deep well mining operations, thermal hazards and waste heat resources exhibit distinct inherent characteristics. These characteristics not only pose challenges for mitigating thermal hazards in deep wells but also determine the technical direction for mine waste heat recovery; they serve as the core basis for the research and development of multifunctional, variable-condition mine waste heat heat pump systems.

2.1. Characteristics of Temperature Distribution in Deep Wells

Mine temperatures show a significant upward trend with increasing mining depth; at a vertical depth of 1,000 m, the temperature of the surrounding rock can reach 40°C [10, 11, 12]. The continuous heat exchange between the surrounding rock and the airflow causes the temperature of the underground airflow to be significantly higher than the ambient temperature at the surface, creating a typical high-temperature heat hazard environment in deep mines; At the same time, heat exchange occurs between the airflow and the surrounding rock throughout its entire flow through the mine tunnels, resulting in the return air maintaining a high temperature throughout its entire path. This provides a stable temperature foundation for waste heat recovery.

2.2. Return Air Temperature and Humidity Characteristics.

The temperature and humidity of mine return air are influenced by factors such as mining depth, geological conditions, and underground operations, resulting in two typical operating conditions: First, high-airflow, low-humidity conditions in mines located in arid northern regions, where return air humidity is low, airflow volume is large, and waste heat consists primarily of sensible heat; Second, high-temperature, high-humidity conditions in certain mining fields, such as the Wanfu Mine, where the average return air temperature is 31°C and humidity is 95% [25]. Here, the waste heat consists of both sensible and latent heat, exhibiting significant heat-humidity coupling characteristics.

2.3. Huge Airflow Volume, Low Waste Heat Quality, and Extremely Large Total Volume.

Mine ventilation is an essential measure for ensuring the safety of underground operations, and the scale of return

airflow far exceeds that of conventional industrial exhaust systems. For example, the return airflow at the Tangjiahui Mine reaches 8,520 m³/min [23], while the actual exhaust airflow at the Wanfu Mine ranges from 12,000 to 13,000 m³/min [25]. As a large-scale modern mine, the Hongliulin Coal Mine also features an exceptionally high return airflow volume. Mine waste heat is a low-grade energy source; while the thermal energy content of a single volume of return air is relatively low, the massive return air volume creates a vast total waste heat resource, making it valuable for large-scale recovery and utilization.

2.4. Optimizing the Utilization of Waste Heat through Heat Pump Technology.

Although mine waste heat has a low thermal grade, it is characterized by a stable temperature and a continuous supply, making it highly compatible with the technical principle of “upgrading and utilizing low-grade thermal energy” inherent in heat pump technology. Through heat pump systems, low-grade waste heat from mines can be converted into high-grade thermal energy to meet the demands of applications such as wellhead freeze protection, building heating, and hot water for bathing. This enables the resourceful utilization of waste heat. Simultaneously, by recovering waste heat to lower return air temperatures, the system alleviates heat-related issues in deep mines, achieving the dual objectives of “mitigating hazards” and “utilizing energy.”

3. Overall Architecture of a Multi-Functional, Variable-Condition Mine Waste Heat Heat Pump System

The multi-functional, adaptive mine waste heat heat pump system utilizes mine exhaust air as its primary waste heat source and employs heat pump units as the core for energy upgrading. Based on the varying operating conditions of the mine exhaust air, two distinct technical pathways are designed to enable precise waste heat recovery and efficient utilization across multiple scenarios. The core architecture of the system is as follows: exhaust air → adaptive heat exchange technology → heat pump units → multi-scenario thermal energy utilization. The system framework diagram is shown below(As shown in Figure 1):

The system matches dedicated heat exchange technology pathways to two typical operating conditions for mine exhaust air. It then uses heat pump units to upgrade the recovered low-grade waste heat. Finally, based on the actual needs of the mining area, the thermal energy is delivered to various application scenarios, achieving a full-cycle closed-loop process of “operating condition adaptation—waste heat recovery—energy upgrading—multi-point utilization.” The correspondence between operating conditions, technology pathways, and application scenarios is shown in the table below (As shown in Table 1):

Table 1. Correspondence Table of Operating Conditions, Technical Pathways, and Application Scenarios

Operating conditions	Core Technology Pathways	Key Use Cases
High airflow, low humidity	Coaxial tube heat exchanger	Wellhead Frost Protection
High temperature and high humidity	Spray heat exchanger	Heating/Hot Water/Multi-purpose Supply for Mining Areas

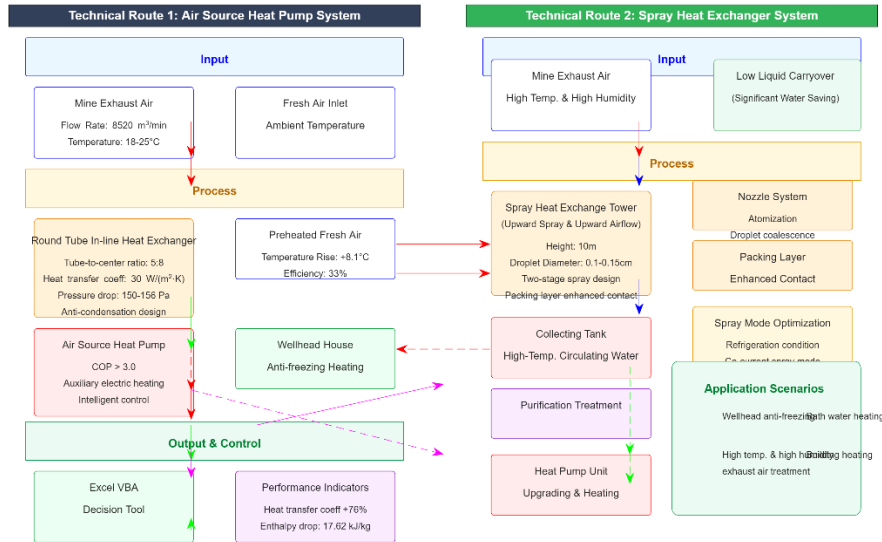


Fig 1. Two or more references

The core principle of the system design is adaptability to varying operating conditions. This approach overcomes the limitations of relying on a single heat exchange technology by selecting the appropriate heat exchange method based on the actual characteristics of the mine exhaust air—such as temperature, humidity, and airflow—to ensure efficient waste heat recovery while minimizing disruption to the mine’s existing ventilation system, thereby enabling the system to operate in harmony with mine production.

4. Comparison of the Mechanisms and Performance of Two Core Technologies

There are two technical approaches for a multifunctional, variable-condition mine waste heat heat pump system. One uses a co-current round-tube heat exchanger as its core heat exchange equipment, while the other employs a spray heat exchanger. These two systems exhibit significant differences in their heat transfer mechanisms, structural designs, and performance characteristics, making them ideally suited for two typical operating conditions of mine exhaust air. The following analysis compares and evaluates these systems based on three dimensions: core mechanisms, key performance metrics, and suitability.

4.1. Core Technical Mechanism

4.1.1. Coaxial Tube Heat Exchanger (Suitable for High-Airflow, Low-Humidity Applications)

The co-current round-tube heat exchanger is the core component of an air-source heat pump system dedicated to mine exhaust air. It employs an air-to-air indirect heat exchange mechanism and features a structural design with a vertical-to-horizontal tube center-to-center ratio of 5:8 [22], transferring thermal energy from the mine exhaust air to the fresh air. The preheated fresh air is then directly conveyed to the shaft head building to prevent freezing at the shaft head; When ambient temperatures are too low and the fresh air does not receive sufficient heat, the system supplements the heat deficit through electric auxiliary heating. Some optimized designs incorporate wet-type basalt fiber grids (spacing ratio

8, water-to-air ratio 0.73), combined with the NTU_m -Le series heat and moisture transfer model to enhance heat exchange efficiency [22]. This heat exchange process involves no gas-liquid contact; heat transfer occurs solely through the heat exchanger tube walls, making it suitable for sensible heat recovery from low-humidity, low-flow air. As shown in Figure 2

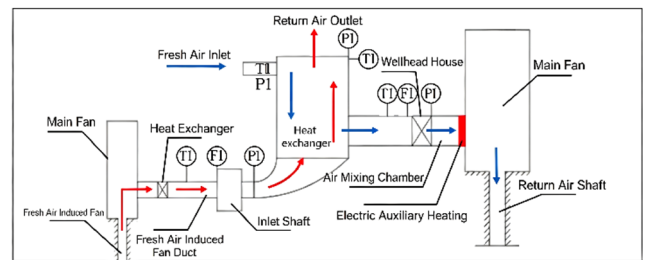


Fig 2. Schematic of a Co-current Round Tube Heat Exchanger

4.1.2. Spray Heat Exchanger (Suitable for High-Temperature, High-Humidity Conditions)

Spray heat exchangers utilize a gas-liquid direct contact heat transfer mechanism, with the mainstream design employing an upward spray and upward air inlet configuration [24]. Low-temperature spray circulation water is atomized upward through nozzles to form a cluster of fine droplets, which come into direct contact with high-temperature, high-humidity exhaust air. Heat and moisture transfer is achieved through sensible heat exchange (driven by temperature differences) and latent heat exchange (regulated by differences in water vapor concentration). The circulation water, heated after heat exchange, enters the heat pump unit for shell-and-tube heat exchange; after being upgraded, it supplies energy to various applications, while the cooled circulation water is purified and recirculated for spraying [24]. This heat exchange process fully utilizes the latent heat resources of the high-temperature, high-humidity exhaust air while also serving a dust suppression function, making it suitable for heat and humidity coupled waste heat recovery requirements. A comparison of the key performance indicators for the two systems is shown in Table 2 below:

Table 2. Comparison of Core Technical Mechanisms Between Co-current Round Tube Heat Exchangers and Spray Heat Exchangers [22] [24] [25]

Comparison criteria	Coaxial tube heat exchanger	Spray heat exchanger
Heat transfer coefficient	30 W/(m ² ·K), a 76% improvement over traditional stacked square tube heat exchangers	High heat and moisture transfer efficiency; heat transfer efficiency is optimal when droplet diameters range from 0.1 to 0.15 cm
Air Temperature/Enthalpy Drop Effect	Maximum air temperature drop: 8.1°C ; Air-side heat transfer efficiency: 33%; Enthalpy drop: 17.62 kJ/kg	At the Wanfu Mine, the average temperature increase of spray droplets was 7 K, and the enthalpy drop in the exhaust air was significant.
Effects of Ventilation Air Pressure	Supply air pressure drop: 150–156 Pa ; ≤200 Pa (mine ventilation limit)	The average air pressure increases by only 3 Pa, causing virtually no disruption to the ventilation system
Additional Features	No extra features—focused solely on waste heat recovery	It also serves as a dust collector and can handle contaminated air streams
Auxiliary energy consumption	Electric auxiliary heating is required to provide additional heat in low-temperature conditions	Equipment for circulating water purification and spray systems must be provided
Comparison Criteria	Coaxial tube heat exchanger	Spray heat exchanger
Heat Transfer Coefficient	30 W/(m ² ·K), a 76% improvement over traditional stacked square tube heat exchangers	High heat and mass transfer efficiency; heat transfer efficiency is optimal when droplet diameters range from 0.1 to 0.15 cm
Air Temperature/Enthalpy Drop Effect	Maximum air temperature drop: 8.1°C; air-side heat transfer efficiency: 33%; enthalpy drop: 17.62 kJ/kg	At the Wanfu Mine, the average temperature of the spray droplets increased by 7 K, and the enthalpy of the exhaust air decreased significantly.
Effects of Ventilation Air Pressure	Supply air pressure drop: 150–156 Pa; ≤200 Pa (mine ventilation limit)	The average air pressure increases by only 3 Pa , causing virtually no disruption to the ventilation system
Additional Features	No extra features—focused solely on waste heat recovery	It also serves as a dust collector and can handle contaminated air streams

4.2. Demonstration of Operational Compatibility

1. Co-current tube-in-tube heat exchangers are well-suited for high-airflow, low-humidity conditions: The waste heat in high-airflow, low-humidity exhaust air consists primarily of sensible heat, eliminating the need for complex thermal-humidity coupling treatment. The gas-to-gas indirect heat exchange mechanism of the co-current tube-in-tube heat exchanger enables highly efficient sensible heat recovery; Its structural design is optimized for high-airflow conditions, with pressure drop controlled within the limits of mine ventilation, ensuring it does not interfere with normal mine ventilation. Additionally, automated design software enables the optimal configuration of structural parameters [22], accommodating the high-airflow requirements of different mines. The recovered waste heat, after being upgraded by a heat pump, can precisely meet the specific, continuous heating demands for wellhead freeze protection.

2. Spray heat exchangers are suitable for high-temperature, high-humidity conditions: The waste heat in high-temperature, high-humidity exhaust air contains a large amount of latent heat. The direct gas-liquid contact mechanism of the spray heat exchanger enables simultaneous recovery of both sensible and latent heat, resulting in higher waste heat utilization efficiency; its impact on air pressure is minimal, making it suitable for ventilation-sensitive mines [24], and the heat exchange process reduces dust and humidity in the exhaust air, further improving the mine’s exhaust ventilation environment; The total recovered thermal energy, after being upgraded by a heat pump, can meet diverse heating demands across multiple scenarios—such as space heating, bathing, and combined heat and power (CHP)—aligning with the advantage of the high total waste heat volume in high-temperature, high-humidity mines.

5. Project Case Studies

Using Hongliulin Coal Mine (high-airflow, low-humidity conditions) and Wanfu Mine (high-temperature, high-humidity conditions) as representative case studies, this study verifies the feasibility and effectiveness of two technical approaches for a multifunctional, variable-condition mine waste heat heat pump system. The results ultimately confirm that the overall system methodology can be adapted to the actual operating conditions of different mines, thereby achieving the dual objectives of mitigating heat-related hazards in deep mines and utilizing waste heat as a renewable energy resource.

5.1. Hongliulin Coal Mine: Validation of Technical Approaches for High-Airflow, Low-Humidity Operating Conditions

5.1.1. Mine Conditions and Project Background

The Hongliulin Coal Mine is located in Shenmu County, Yulin City, Shaanxi Province, within a region characterized by an arid desert-plateau climate [26]. The mine’s exhaust air exhibits typical characteristics of high volume and low humidity. The original frost-protection system at the No. 2 ventilation shaft of this mine utilized a natural gas boiler with a capacity of 10 t/d [22]. Due to its high consumption of fossil fuels and significant carbon emissions, there is an urgent need to upgrade the system through waste heat recovery technology.

5.1.2. Application of Technical Approaches

To address the high-airflow, low-humidity conditions in mines, a technical approach combining “circular tube parallel-flow heat exchangers” with a “dedicated air-source heat pump system for exhaust air” was adopted. After comparing the performance and construction feasibility of stacked square-tube heat exchangers with circular tube

parallel-flow heat exchangers, a circular tube parallel-flow heat exchanger with a vertical-to-horizontal tube center-to-center ratio of 5:8 was selected as the core equipment [30]; Concurrently, we developed automated design software based on multivariate optimization to achieve the optimal configuration of the heat exchanger's structural parameters [22], thereby ensuring both waste heat recovery efficiency and ventilation safety.

5.1.3. Engineering Validation Results

The application of this technical approach at the Hongliulin Coal Mine has achieved three core objectives: 1) Significant waste heat recovery efficiency, with a heat transfer coefficient of 30 W/(m²·K) in the heat exchanger and a maximum air temperature reduction of 8.1°C [22]; the preheated fresh air fully meets the frost protection requirements at the mine entrance, replacing traditional natural gas boilers; 2) There was no interference with mine ventilation, as the exhaust air pressure drop was controlled between 150 and 156 Pa [22], meeting the mine's ventilation limit requirements; 3) Energy conservation and emission reduction effects were outstanding, reducing fossil fuel consumption and carbon emissions while lowering the operating costs of wellhead freeze protection. This case study fully validated the engineering feasibility of this technical approach under high-airflow, low-humidity conditions.

5.2. Wanfu Mine: Validation of Technical Approaches for High-Temperature, High-Humidity Operating Conditions

5.2.1. Mine Conditions and Project Background

The Wanfu Kida Mine is located in Heze City, Shandong Province. The mine's exhaust air exhibits typical high-temperature, high-humidity conditions, with an actual exhaust airflow rate of 12,000–13,000 m³/min, an average return air temperature of 31°C, and a humidity of 95% [25]. Given the large volume of waste heat and the pronounced thermal-humidity coupling characteristics, the site possesses ideal conditions for the application of spray heat exchangers.

5.2.2. Application of Technical Approaches

To address the high-temperature and high-humidity conditions in mines, a technical approach combining a “spray heat exchanger and heat pump unit” was adopted. Based on the structural parameters of the mine return air diffusion tower, a 6 m × 12 m × 12 m spray heat exchanger model was designed [25], and the nozzle arrangement was optimized (9 conical nozzles, droplet diameter 0.0015 m, spray height 9 m) [25], and a three-dimensional discrete phase model (DPM) was employed for numerical simulation and engineering design [25].

5.2.3. Engineering Validation Results

Numerical simulations and engineering design results indicate that this technical approach demonstrates outstanding adaptability and feasibility: 1) The waste heat recovery performance is excellent; after thorough heat exchange between the spray droplets and the exhaust air, the average temperature increase is 7 K [25], effectively absorbing both the sensible and latent heat from the exhaust air; 2) Ventilation interference is minimal; after the heat exchanger is activated, the average air pressure increases by only 3 Pa [25], fully meeting the operational requirements of the mine ventilation system; 3) The system operates stably, with controllable droplet condensation and coalescence; there are no issues with large-scale droplet escape or pipeline

blockage, and the recirculating water can be purified and reused [25]. This case study verifies the engineering feasibility of this technical approach under high-temperature and high-humidity conditions, providing a design reference for similar mines.

5.3. Conclusion on the Overall Feasibility of the System

The engineering case studies of the Hongliulin Coal Mine and the Wanfu Mine represent two distinct technical approaches for multi-functional, variable-condition mine waste heat heat pump systems. Both have achieved the goals of efficient waste heat recovery, effective mitigation of heat-related hazards, and no interference with the ventilation system. This demonstrates the engineering feasibility of the system's core concept of “operating condition adaptation and differentiated design.” It also validates that the system can effectively address the challenges posed by traditional single-technology approaches—namely, their inability to adapt to complex operating conditions and the resulting waste of waste heat. Consequently, it represents an effective system solution for heat-related hazard mitigation in deep mines and the resource utilization of mine waste heat.

6. Technical Comparison and Criteria for Suitability

Based on the engineering validation of the two core technologies and a comprehensive comparison of their technical characteristics, we have developed a selection criteria matrix for mine waste heat technologies. This has resulted in a practical methodology for selecting waste heat utilization technologies under various operating conditions, providing a clear basis for different mines to choose the most suitable waste heat recovery technology pathways. It also serves as a reference for the widespread adoption of multifunctional, variable-condition waste heat heat pump systems in mines.

6.1. Comprehensive Comparison of Core Technologies

Rather than focusing on a simple comparison of the performance of individual technologies, this analysis centers on the core requirements of actual mine applications. It examines multiple dimensions—including operating conditions, heat exchange, performance, engineering, and economics—to clearly identify the strengths and weaknesses of the two core technologies, their applicable boundaries, and key considerations for their implementation, as detailed in Table 3 below:

6.2. Table of Selection Criteria for Mine Waste Heat Technologies

By integrating key factors such as core operating parameters of mine exhaust air, application requirements in mining areas, and mine ventilation conditions, we have closely aligned technology selection with actual mine needs to develop a decision-making matrix for selecting mine waste heat recovery technologies. The criteria are divided into core criteria (mandatory requirements) and auxiliary criteria (optimization requirements), as detailed in Table 4 below:

Table 3. Comprehensive Comparison of the Two Core Technologies [22][24][25]

Comparison criteria	Coaxial Tube Heat Exchanger + Air-Source Heat Pump System for Exhaust Air	Spray Heat Exchanger + Heat Pump Unit
Core Heat Transfer Mechanism	Gas-to-gas indirect heat exchange	Direct gas-liquid heat transfer
Suitable for low-airflow conditions	High airflow, low humidity, with waste heat consisting primarily of sensible heat	High temperature, high humidity, and heat-moisture coupling in waste heat
Types of Waste Heat Recovery	Sensible heat recovery only	Dual recovery of sensible and latent heat
Key Performance Indicators	Heat transfer coefficient: 30 W/(m ² ·K); pressure drop: 150–156 Pa	High heat and moisture exchange efficiency, with a pressure drop of approximately 3 Pa
Key Use Cases	Wellhead freeze protection (single-source heat demand)	Heating/Hot Water/Multi-purpose Supply for Mining Areas (Diverse Heating Needs)
Additional Features	None	Removes dust and reduces humidity; treats contaminated air streams
Construction Difficulty	The piping layout needs to be optimized using automated design software	It is necessary to optimize the nozzle arrangement and droplet parameters, and design a recirculating water system
Key Operational Issues	The piping layout needs to be optimized using automated design software.	Control droplet coalescence and ensure proper purification of the recirculating water
Operating Cost Characteristics	Electric auxiliary heating is required to provide additional heat in low-temperature conditions	The operating and maintenance costs of the circulating water system are relatively high, but its waste heat recovery efficiency is high.
Impact of Mine Ventilation	Smaller, in compliance with ventilation limits	Extremely small, suitable for ventilation-sensitive mines

Table 4. Selection Criteria for Mine Waste Heat Recovery Technologies

Selection Levels	Criteria indicators	Technical Approach for Co-current Round Tube Heat Exchangers	Technical Approach for Spray Heat Exchangers
Key criteria	Characteristics of air temperature and humidity	Low humidity (<60%), with minimal temperature fluctuations	High humidity (≥80%), high temperature (≥28°C)
	Types of Waste Heat	Predominantly sensible heat	Sensible and latent heat coupling
Supplementary criteria	Primary heat demand	Wellhead freeze protection (single, continuous heat demand)	Heating/Hot Water/Multi-Function Systems (Diverse, High-Load Heating Demands)
	Mine Ventilation Sensitivity	The ventilation system has moderate pressure drop tolerance (≥200 Pa)	Sensitive ventilation system (pressure drop requirement < 10 Pa)
	Environmental Protection Requirements for Mining Areas	Just heat recovery	Both waste heat recovery and dust/moisture removal from exhaust air must be achieved simultaneously.
	Operations and Maintenance Capabilities	Moderate operational and maintenance skills; prefers simple systems	Strong operational and maintenance capabilities, capable of managing the circulation water system
	Requirements for Waste Heat Utilization Efficiency	High efficiency in sensible heat recovery is required	High overall waste heat recovery efficiency is required

7. Conclusion

To address the issues of high ventilation loads and waste of waste heat caused by high-temperature heat stress in deep mines, as well as the shortcomings of existing research regarding the lack of multi-condition coupled systems, this paper proposes a technical framework and engineering implementation path for a multifunctional, variable-condition mine waste heat heat pump system. Through systematic analysis and engineering validation, the following core conclusions are drawn:

1. The inherent characteristics of deep-well thermal hazards and waste heat resources necessitate the development of such a system. Features such as rising temperatures with depth, two typical operating conditions for return air, massive airflow volumes with low-grade but substantial waste heat, and the potential for heat pump-based upgrading provide the core basis for designing a multifunctional variable-condition system.

2. The multifunctional variable-condition mine waste heat heat pump system establishes an overall architecture of “exhaust air—adaptive heat exchange—heat pump—multi-scenario utilization.” To address the two typical operating conditions—high-volume, low-humidity exhaust air and high-temperature, high-humidity exhaust air—two distinct technical pathways were designed: a co-current heat exchanger with circular tubes and a spray heat exchanger. This achieves precise recovery and multi-point utilization of waste heat.

3. The mechanisms and performance of the two core heat exchange technologies are highly suited to their respective operating conditions. The gas-to-gas indirect heat exchange characteristic of the co-current round-tube heat exchanger is suitable for sensible heat recovery from high-volume, low-humidity exhaust air, while the gas-to-liquid direct heat exchange characteristic of the spray heat exchanger is suitable for heat-moisture coupled recovery from high-temperature, high-humidity exhaust air. Furthermore, both technologies can keep interference with the mine ventilation system within

acceptable limits.

4. Engineering case studies at the Hongliulin Coal Mine and Wanfu Mine have respectively validated the engineering feasibility of the two technical pathways, confirming the effectiveness of the “operating condition adaptation and differentiated design” approach for multifunctional, variable-condition mine waste heat heat pump systems. This has achieved the dual objectives of mitigating heat-related hazards in deep mines and utilizing waste heat resources.

5. The developed selection criteria table for mine waste heat technologies clarifies the core and auxiliary criteria for selecting the two core technologies, establishing a practical technology selection method that provides a key reference for the widespread application of the system. Additionally, the design concept of the coupling and switching system can be further adapted to complex scenarios involving alternating mine operating conditions.

The multifunctional, variable-condition mine waste heat heat pump system proposed in this study constitutes a comprehensive solution for the multi-condition utilization of mine waste heat. It effectively addresses the limitations of existing single-technology approaches and provides a new technical pathway for mitigating high-temperature heat hazards in deep mines and utilizing mine waste heat as a resource. Against the backdrop of the ongoing advancement of the “Dual Carbon” strategy, future efforts can focus on optimizing heat exchanger structures, enhancing intelligent control, and constructing multi-energy coupling systems to further improve the system’s efficiency and adaptability, thereby driving the green and low-carbon transformation of the coal industry.

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