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Research on Industrial Waste Heat Recovery and Multi-energy Coupling System

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Abstract: Aiming at the demand for efficient energy utilization and energy saving and carbon reduction in the industrial field, this paper investigates the synergistic mechanism of waste heat gradient utilization and multi-energy coupling system under the framework of thermal management through case studies in the iron and steel and chemical industries, and puts forward a heat recovery scheme based on the coupling system to realize a more efficient and energy-saving recycling and utilization of industrial waste heat. In the future, it is necessary to promote the development of waste heat recovery towards integration and low-carbonization through intelligent control, efficient material research and development and policy support, so as to provide technical support for industrial energy transformation.

1. Introduction

Against the backdrop of the intensifying global energy crisis and rising calls for environmental protection, it has become imperative to realize carbon emission reduction and the efficient use of energy at multiple levels. The industrial sector, as the core segment of energy consumption, especially the high energy-consuming industries such as iron and steel, chemical industry, etc., is facing great pressure to save energy and reduce carbon. Excess heat energy such as high-temperature flue gas, waste steam and waste water generated during industrial production is often not fully utilized, resulting in a large amount of wasted energy. Under the dual drive of tightening resource constraints and growing green demand, it is of great significance to promote the recovery and reuse of industrial waste heat. Industrial waste heat resources are rich and diverse, but the current utilization rate is generally low. From the point of view of enterprise practice, medium and high temperature waste heat and part of the low temperature waste heat has been utilized to a certain extent, but the comprehensive utilization rate of low-temperature waste heat is still at a low level. In this context, exploring the waste heat gradient utilization technology and combining it with phase change energy storage, heat pumps and other emerging technology means to enhance the utilization efficiency of waste heat resources provides a new solution.

This study focuses on key industries such as iron and steel, chemical industry, etc., systematically researches the synergistic application mechanism of waste heat cascade utilization technology and emerging technologies, and quantifies their energy-saving and emission reduction benefits through scientific assessment methods, so as to provide theoretical support and data basis for realizing the green and low-carbon transformation of the industrial field.

2. Industrial waste heat sources

Waste heat resource is the heat that is not fully utilized in the process of industrial production, energy conversion or other thermal energy utilization and emitted to the environment, it can also be regarded as the valuable energy generated by the fuel in the combustion process and remaining after the completion of a certain process, which is the by-product of combustible substances and primary energy conversion process[1].Waste heat resources are considered to be the fifth largest conventional energy source after coal, oil, natural gas and hydropower[2], which is characterized by a large total volume, wide distribution, high grade as well as huge utilization potential.

Industrial waste heat is the most important source of waste heat resources, including blast furnace gas sensible heat in iron and steel mills, converter flue gas waste heat, and kiln exhaust waste heat in cement plants, etc.; power machinery waste heat comes from internal combustion engines, gas turbines, and other equipment operation of the waste heat, such as automobile engine emissions of high-temperature exhaust gas. Data show that the total waste heat resources in petroleum, chemical, iron and steel, building materials and other industrial fields account for about 15%-67% of the total energy consumption, of which the recoverable utilization rate is about 60%.In 2023, the average value of the total recoverable waste heat resources in China reached 1.373 billion tons of standard coal. High-medium temperature waste heat is easier to recycle because of the higher temperature and concentrated heat, and has now become the object of enterprise priority recycling [3].For example, China National Offshore Oil Corporation (CNOOC) and China Shipbuilding Corporation (CSSC) have independently developed a 5MW-class offshore high-temperature flue gas waste heat power generation unit, which has made an important breakthrough in the field of flue gas waste heat utilization in China's offshore oil and gas fields. The device takes the high-temperature flue gas waste heat generated by the main power station as the heat source, and heats up the cyclopentane to form high-temperature steam to push the turbine expander to generate electricity through the intermediate heat transfer of heat-conducting oil, and the annual power generation capacity can reach 0.4 billion kilowatt-hours.

In contrast, low-temperature waste heat resources account for about 54% of China's total waste heat resources, but due to the low-temperature waste heat recovery technology has not yet matured, a large number of low-temperature industrial waste heat is still not effectively utilized. Although some enterprises have achieved significant results in waste heat recovery, but still faces many challenges: on the one hand, part of the waste heat utilization technology has efficiency bottlenecks, energy efficiency level needs to be improved.

3. Waste heat gradient utilization technology for high energy-consuming industries such as iron and steel, chemical industry

3.1 Waste Heat Stage Utilization Technology in Iron and Steel Industry

China's iron and steel enterprises are mostly based on long process, and the whole process includes coking, sintering, blast furnace ironmaking, converter steelmaking, steel rolling, etc. Table 1 shows the distribution of major waste heat resources within the process.

Taking Jinxi Steel Plant as the research object, an efficient waste heat power supply scheme is proposed, which fully utilizes the waste heat resources of blast furnace slag flushing water, blast furnace cooling water and waste heat power generation cooling water. The study shows that the blast furnace cooling circulating water waste heat its system by connecting different cooling branches in parallel and then centralized to the cooling tower for cooling. The cooling water is cooled down by heat extraction equipment and then sent to the cooling tower pool for recycling. The advantage of this design is that the cooling water temperature can be precisely controlled by adjusting the cooling tower's cooling capacity[4].

Table 1 Distribution of waste heat resources in the steel industry

process	Waste heat resources	temperature
Distill	Coke sensible heat	950-1050℃
	Waste flue gas sensible heat	200-300℃
	Desert gas sensible heat	650-700℃
Sintering	Sinter Ore Apparent Heat	700-800℃
	Sintering waste flue gas sensible heat	100-450℃
Blast Furnace	Blast furnace slag sensible heat	1500℃
	Blast furnace gas sensible heat	200-300℃
Converter steelmaking	Converter flue gas heat development	800-1200℃
	Furnace slag heat development	1500-1600℃
Steel Rolling	Heating furnace waste gas heat development	900-1150℃

3.2 Waste Heat Stage Utilization Technology in the Chemical Industry

In the chemical industry, waste heat gradient utilization technology has important application value. Take inorganic chemical industry as an example, the waste heat generated in the production process mainly comes from four categories: exothermic chemical reaction, heat loss of equipment, cooling water and cold air reflux, and exhaust gas emission. These waste heat contains both high-temperature and low-temperature waste heat, and has a strong instability, subject to the production process and equipment operation. Waste heat release sites are decentralized, which increases the overall recovery difficulty [5].

Organic Rankine Cycle (ORC) is an effective low and medium temperature waste heat recovery technology. The technology converts thermal energy into mechanical or electrical energy through the absorption of waste heat by an organic work material, which then undergoes four sequential steps: evaporation, expansion work, condensation and pumping.Compared with the conventional steam Rankine cycle, the ORC has a lower boiling point of the work material and is suitable for low and medium temperature heat sources in the range of 100-300 ℃. The ORC system is designed to produce electricity at a low temperature and at a high temperature. The study shows that the adopted ORC waste heat power generation system is configured with three parallel 560kW gensets, with a total installed capacity of 1,680kW and a net generator power of 1,206kW. the annual power generation hours of the system are 8,000 hours, and the annual net power generation capacity reaches 9,648,000 kWh. As shown in Figure1,this solution not only helped the enterprise to save expenditure on air-conditioning equipment, but also realized the goal of energy saving and carbon reduction [6].

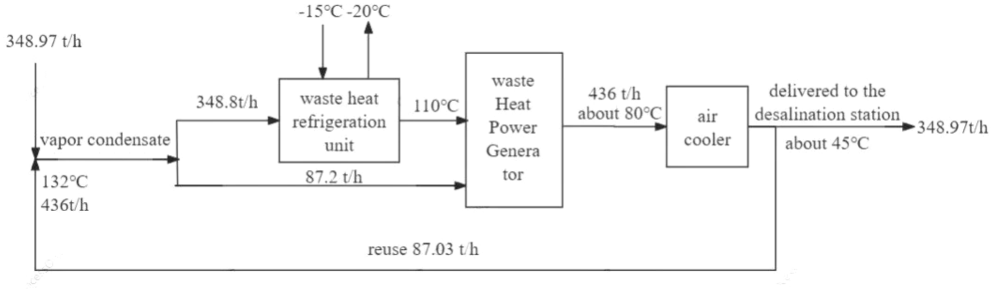

Fig. 1 Flowchart of waste heat power generation in Salt Red Square[6]

4. Application of heat pump and phase change energy storage technology in industrial waste heat recovery

4.1 Application of heat pump technology in waste heat recovery

The second law of thermodynamics states that heat cannot be transferred spontaneously from a low-temperature object to a high-temperature object, but the process can be accomplished by external work.Heat pumps are based on the principle of thermodynamics, driven by consuming a small amount of high-grade electricity, absorbing energy from a low-temperature heat source and transporting it to a high-temperature heat source so as to realize the transfer of heat energy. The principle of heat pump operation is shown in Figure 2.

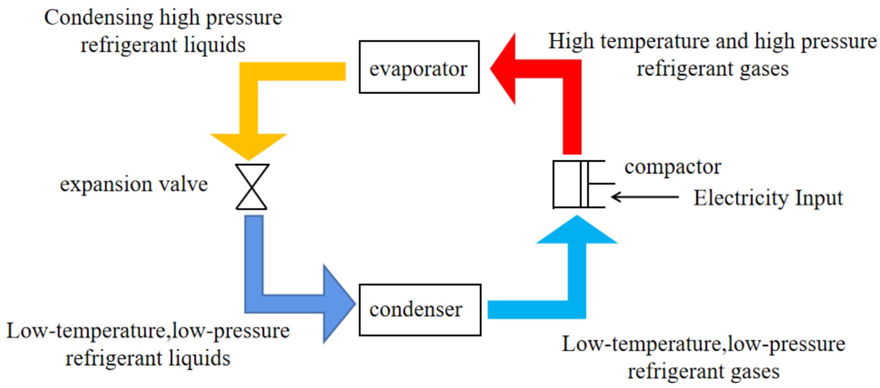

Fig. 2 Heat pump working principle diagram

The core principle of heat pump technology is based on the inverse Carnot cycle, which consists of four main stages: evaporation, compression, condensation and throttling.In the evaporation process, a low-temperature, low-pressure refrigerant absorbs heat from a low-temperature heat source (such as outdoor air, groundwater or soil) and evaporates into a gas;The compressor then compresses the low-temperature, low-pressure refrigerant gas into a high-temperature, high-pressure gas, a process that consumes external energy (e.g. electricity);Then, in the condensation process, the high-temperature, high-pressure refrigerant exchanges heat with a high-temperature heat source (such as indoor air or hot water) and liquefies into a high-pressure liquid;Finally, the refrigerant is throttled and depressurized to a low-temperature, low-pressure liquid through an expansion valve and enters the evaporator to begin the next cycle [5].The performance of a heat pump is usually measured by its COP (ratio of heat supplied to power consumed). An ideal COP value greater than 1 means that the heat pump supplies more heat than it consumes power and has high energy efficiency.According to the different heat sources, heat pumps can be divided into three categories: (1) Air-source heat pumps: using outdoor air as a low-temperature heat source, featuring simple installation, lower cost and wide range of application. However, its efficiency decreases significantly in low-temperature environments (e.g., below -5 ℃), and the amount of heat produced decreases. It is widely used for heating and cooling in residential and commercial buildings. (2) Water source heat pump: using groundwater, surface water or seawater as the low-temperature heat source, it has high efficiency and stability and is not affected by outdoor air temperature. However, installation and maintenance costs are high, and need to consider the protection of water sources and sustainable utilization. It is commonly used in large buildings or centralized heating systems. (3) Ground source heat pump (ground-coupled heat pump): using the soil as a low-temperature heat source, and exchanging heat with the soil by burying underground pipes. Its high efficiency, stable performance, long service life and almost independent of seasonal and climatic influences. However, the installation cost is high, requires a large land area for burying pipes and is complicated in construction. It is suitable for buildings with high requirements for energy saving and comfort, such as high-grade houses, villas and large commercial buildings [7].In the field of waste heat recovery, heat pump technology shows significant application value. For example, air compressors, as commonly used equipment in industrial production such as coal mines, produce a large amount of waste heat from year-round operation, which has a huge recovery potential [8].Deng Qiang et al [9] found that air energy heat pumps in coal mine air compressor waste heat recovery can effectively improve the economic efficiency of enterprises and save electricity. Zhang Jiexiong[10]and others designed a centrifugal compressor waste heat recovery and water source heat pump bath system, which successfully solved the problem of waste heat from the air compressor in Dongpang Coal Mine and significantly improved the comprehensive energy utilization efficiency. Zhou Jiaojiao et al [11] proposed a scheme of using high-temperature heat pumps to recover the waste heat of cooling water to prepare medium- and high-temperature hot water, and through the analysis of economic energy saving and environmental protection showed that the high-temperature heat pumps have higher economic and environmental benefits compared with the traditional steam heating. Qin Jingling et al [12] designed a system based on high-temperature heat pump to recover waste heat and use it for heating air supply in response to the problem of waste heat emission from cooling towers in thermal power plants. The results show that compared with the traditional coal-fired boiler heating method, the system can reduce 1137.4 tons of CO2 and other pollutant emissions per year, which is in line with the national “dual-carbon” policy guidance.

In summary, heat pump technology, as an efficient and clean energy conversion equipment, shows a broad application prospect in the field of waste heat recovery. Despite certain technical and economic challenges, its role in industrial energy conservation and low-carbon development will be further highlighted through technological innovation and policy support.

4.2 Application of phase change energy storage technology in waste heat recovery

Phase change materials (PCMs) are new chemical materials that achieve latent heat storage through a phase change process, characterized by high latent heat performance, high energy storage density, and near-constant temperature during the phase change process.The selection of PCMs requires comprehensive consideration of thermophysical properties (e.g., phase change temperature, latent enthalpy, thermal conductivity), physical properties (e.g., volume change, subcooling), chemical properties (e.g., stability, compatibility), and economic feasibility. Their performance advantages include high latent heat storage, temperature stability, recyclability and versatility, which makes them suitable for renewable energy storage, industrial waste heat recovery and other fields.For example, in the metallurgical industry, phase change energy storage technology recovers intermittent waste heat through thermal storage heat exchangers, which significantly improves the efficiency of energy utilization; while in the building sector, PCMs can be used to achieve stable temperature control. Meanwhile, heat pump technology, as another energy-efficient means of waste heat recovery, is based on the principle of the inverse Carnot cycle, which realizes the conversion of low-grade heat energy to high-grade heat energy through four stages: evaporation, compression, condensation and throttling.The advantages are high energy efficiency (COP values usually above 3), cleanliness and applicability, but are limited by high initial investment, ambient temperature impacts and specialized maintenance requirements. Both phase change energy storage and heat pump technologies show great promise in the field of waste heat recovery, but also face technical and economic challenges, such as material stability, equipment complexity and cost issues.

5. Conclusions and Perspective

Industrial waste heat recovery and multi-energy coupling system has significant advantages in energy utilization efficiency improvement and energy saving and emission reduction.Through the study of different industrial waste heat recovery technologies, it is found that heat pump technology and phase change energy storage technology have their own advantages and disadvantages in the recycling of industrial waste heat, but their combined application can effectively overcome the limitations of a single technology and realize more efficient waste heat utilization.In the future, the application of new materials and intelligent control technologies will drive the performance of waste heat recovery equipment, such as the development of highly efficient phase change energy storage materials and advanced heat exchangers to improve the efficiency of waste heat collection and storage. The integration and intelligence of the multi-energy coupling system will be further deepened to realize the gradient utilization of energy and the dynamic balance of supply and demand through optimized system design and operation strategy. At the same time, the government and enterprises will increase investment and policy support for waste heat recovery projects, encourage technological innovation and the promotion of demonstration projects, and promote the large-scale application of industrial waste heat recovery and multi-energy coupling technologies, so as to make a greater contribution to the realization of energy transformation and sustainable development goals.

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