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The Development and Research of Waste Heat Recovery Technology

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Abstract: In the context of advancing societal and technological landscapes, the global escalation in energy demand has underscored the looming threat of dwindling energy resources. Over recent years, China has consistently showcased its commitment to assuming the role of a responsible major nation by actively advocating for green and low-carbon development. This commitment is tangibly reflected in a series of green initiatives that progressively prioritize and incentivize enterprises to partake in the recovery and utilization of waste heat. This paper offers a comprehensive review of extensively researched waste heat recovery technologies within China, elucidating their operational principles and highlighting contributions made by relevant scholars. Currently, waste heat utilization stands as a focal point for intensive research, with simultaneous benefits including heightened energy efficiency, resource conservation, and the mitigation of thermal energy wastage, thereby addressing environmental concerns. The implications of such advancements extend significantly to the enhancement of China's societal, ecological, and economic spheres.

Keywords: Heat exchange; Heat exchanger; Thermodynamic conversion; Waste heat refrigeration; Waste heat heating.

1. Introduction

The world is currently facing an energy crisis, and energy-saving technologies have emerged in response to the rapid consumption of energy resources. Approximately 43% to 70% of the world's energy is primarily lost in the form of waste heat[1]. China, endowed with abundant waste heat resources, particularly in the construction industry, witnesses substantial wastage, with recoverable waste heat accounting for 60% of the total waste heat[2]. Therefore, the utilization of waste heat recovery is an effective approach to reducing energy consumption and achieving the goals of "dual carbon" reduction.

Numerous devices discharge significant amounts of untreated waste heat directly into the environment during operation, resulting in severe thermal pollution. Additionally, the energy consumption for heating domestic water constitutes 3%-9% of the total societal energy consumption. By recovering and utilizing waste heat, not only can energy be conserved and environmental impacts mitigated, but it can also enhance energy utilization efficiency, alleviate the heat island effect, and contribute to sustainable practices. Currently, avenues for waste heat utilization primarily include direct heat exchange technologies, thermodynamic conversion technologies, and waste heat refrigeration and heating technologies. This paper will expound upon waste heat utilization based on these three aspects[3].

2. Heat Exchange Technology

Heat exchange involves the transfer of heat between two objects with different temperature differentials or between different sections of the same object. Heat exchange technology utilizes this principle, employing heat exchange equipment to transfer the waste heat from high-temperature objects to low-temperature ones, facilitating the recovery and utilization of waste heat. This technology can directly apply recovered waste heat to its own processes, thereby enhancing the efficiency of primary energy utilization and facilitating both heating and cooling processes.

At the core of heat exchange technology lies the heat exchange equipment. Common types of heat exchange equipment include shell-and-tube heat exchangers, heat pipe heat recovery devices, and heat storage exchangers[4]. Although there are slight differences in waste heat recovery temperature and recovery efficiency among different heat exchange equipment, heat exchange technology is widely applied due to its cost-effectiveness.

2.1. Shell-and-Tube Heat Exchanger

The primary working principles of shell-and-tube heat exchangers involve heat conduction and heat convection. A solid wall is added inside the heat exchanger, separating the hot and cold fluids. The two fluids of different temperatures do not come into direct contact; instead, the high-temperature fluid transfers heat to the solid wall, which then conveys the heat to the low-temperature fluid, completing the heat exchange process[5].

As the most commonly used heat exchanger in waste heat recovery, shell-and-tube heat exchangers dominate the market[6]. They boast advantages such as simple structure and fast heat exchange, making them suitable for scenarios with high temperatures and significant pressure differentials. However, their heat efficiency is lower compared to other types of heat exchangers. Under the same pressure loss conditions, the heat transfer coefficient of shell-and-tube heat exchangers is 3-5 times smaller than that of plate heat exchangers[7]. Plate heat exchangers, especially gasketed plate heat exchangers, can recover 90% or more of waste heat[8]. Shell-and-tube heat exchangers find wide applications, such as Ni Shaojun[9] is utilization in the waste heat recovery of mine ventilation, addressing the issue of wellbore freezing, and Li Chunrong[10] is application of shell-and-tube dryers in municipal sludge thermodynamic drying, revealing an increase in gas pollutant emissions with rising drying temperatures.

2.2. Heat Storage Heat Exchanger

The core equipment of a heat storage heat exchanger is the heat storage body. The temperature of the heat storage body rises by absorbing heat from the hot fluid and decreases after transferring heat to the cold fluid, thus completing the cyclic heat exchange process.

Chen Qiang[11] utilized aluminum as the material for the heat storage chamber and adopted a plate array heat storage body. The results indicated a heat recovery efficiency of up to 66%. When the length of the heat storage body is less than 600mm, each additional 100mm in length increases the heat recovery rate by 16%. Chen Zhichao and Li Chaoxiang employed orthogonal experimental methods to numerically simulate and analyze honeycomb ceramic heat storage bodies, determining optimal heat storage body structures and operating parameters [12-14].

2.3. Heat Pipe Heat Recovery

A heat pipe is a high heat-transfer component that combines condensation and boiling characteristics. In the evaporator section of the pipe, the liquid medium is heated and vaporized, and the gaseous medium flows to the heat dissipation area, releasing latent heat. After condensation, it returns to a liquid state under the capillary force within the pipe, forming a closed-loop cycle. When a micro heat pipe array is employed in an air-air heat exchanger, it can recover over 80% of the total waste heat[15].

Wu Qiang[16] et al. compared the overall performance and economics of three-dimensional heat pipe exhaust heat recovery, dehumidifying heat pipes, and systems simultaneously using exhaust and dehumidifying heat recovery. They provided an optimal operating scheme. Xiang Zhaopeng[17] et al. introduced a closed-loop dehumidification drying system with an independent unit gravity-type heat pipe heat recovery heat pump. The heat pipe energy efficiency ratio reached 6.4, and the system energy efficiency ratio reached 4.8, demonstrating higher energy utilization efficiency compared to common drying systems.

3. Thermodynamic Conversion Technology

Thermodynamic conversion involves the direct utilization of excess thermal energy to drive a turbine for power generation, achieving dynamic output. In comparison to conventional thermal power generation techniques, where low-temperature waste heat is utilized, low-temperature turbine power generation units operate at lower waste heat temperatures and smaller capacities. The technology, such as the low-temperature waste heat power generation in a new dry-process cement kiln, is an example of low-temperature turbine power generation with medium to low temperature parameters.

4. Waste Heat Refrigeration and Heating Technology

4.1. Waste Heat Refrigeration

Waste heat refrigeration utilizes production waste heat as a heat source, employing absorption or adsorption refrigeration technologies with preheating. This technology offers the advantages of reducing primary energy consumption and improving energy utilization efficiency.

Currently, a portion of low-temperature waste heat is reused through lithium bromide absorption refrigeration. Bai Yun[18] et al. utilized a lithium bromide unit to provide cooling, replacing some functions of the J-T valve. They proposed and demonstrated the feasibility of waste heat refrigeration technology in offshore platforms, reducing energy losses caused by pressure drop during the J-T valve throttling process.

While lithium bromide systems can utilize low-grade thermal energy for cooling, they face limitations in meeting refrigeration demands below 0°C[19]. Zhao Sai[20] addressed this issue by replacing waste heat refrigeration technology with a cascade ammonia-water absorption chiller. This improved system efficiency using low-temperature waste heat resources and reduced overall electricity consumption.

4.2. Heat Pump Recovery

4.2.1. Partial Heat Recovery

As shown in Figure 1, a partial heat recovery system is established between the condenser and the compressor. This system recovers the sensible heat of the refrigerant as it cools from superheated vapor to the saturated condensation temperature. Some partial heat recovery devices can recover up to 70% of the condensation heat[21]. The heat recovery unit has a pre-cooling effect on the condenser, enhancing cooling efficiency. When the demand for hot water is low, the control system is simple, and the outlet temperature can be adjusted accordingly. However, it can only recover the sensible heat of superheated cooling, and the recovery of some latent heat of condensation may decrease due to lower heat recovery unit heat transfer capacity or higher heating water temperature. The recovered heat is limited, and recovery is only possible during the refrigeration and heating operation states.

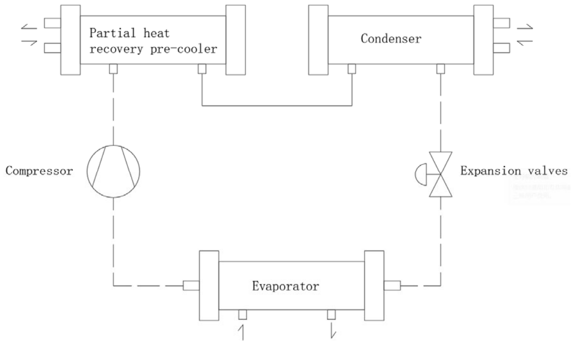

Figure 1. Schematic Diagram of Partial Heat Recovery

4.2.2. Full Heat Recovery

Full heat recovery technology involves the addition of a complete heat recovery unit, typically in parallel with the condenser, as illustrated in Figure 2. The recoverable rate of condensation heat is 100% during refrigeration. In heating mode, it can produce domestic hot water and air conditioning hot water, demonstrating significant energy-saving effects and high waste heat utilization efficiency. However, when producing hot water above 55°C, the condensation temperature needs to be raised to around 60°C for the unit to operate[22]. In this condition, it cannot be considered true full heat recovery, as the power consumption of the compressor increases, and the refrigeration capacity and condensation heat significantly decrease, which is not conducive to the normal operation of the unit.

4.2.3. Compound Condenser

As shown in Figure 3, the compound condenser combines the heat recovery condenser with the regular condenser. The heat recovery loop and the cooling water loop function as two independent branches, allowing heat exchange with the same refrigerant. In the water branch, the heat recovery condenser and the regular condenser act as two parallel water coils, while in the refrigerant branch, there is a single condenser. Compared to the other two forms of condensers, the control strategy and refrigerant quantity in the compound condenser remain unchanged. It can conveniently adjust the proportion according to flow requirements, achieving different proportions of heat recovery distribution to ensure the stable operation of the unit. Moreover, the cost of the compound condenser is lower than that of two independent condensers, demonstrating clear advantages[1][23].

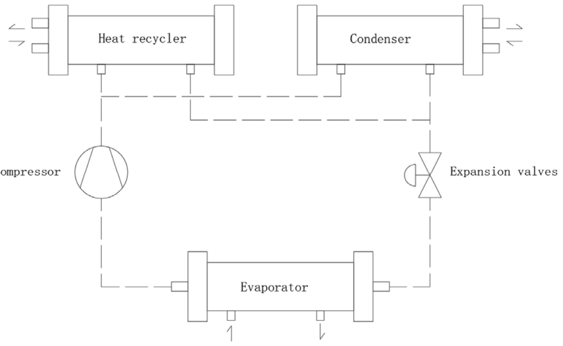

Figure 2. Parallel Full Heat Recovery Schematic Diagram

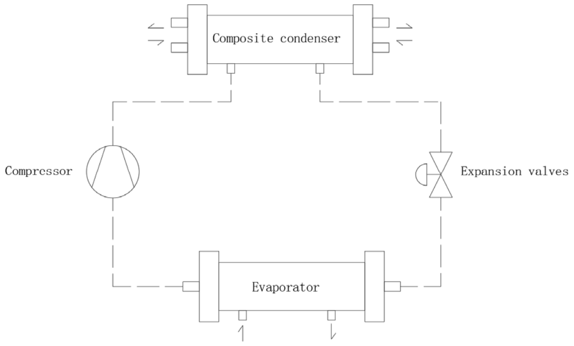

Figure 3. Compound-Type Full Heat Recovery Schematic Diagram

5. Conclusion

With the advancement of technology, waste heat recovery methods have become more sophisticated, and their applications have expanded. However, there is still room for the development of waste heat recovery technologies in China. For instance, the utilization of medium to high-temperature waste heat needs further refinement, and the utilization of low-temperature waste heat is not comprehensive enough. Therefore, it is essential to promote the use of waste heat in different temperature ranges. While actively promoting the use of green energy and responding to the goal of carbon peaking, efforts should also be directed towards continuously optimizing the efficiency of industrial equipment. In-depth research on condensation heat recovery technology should be conducted to recover and utilize waste heat, contributing to the realization of the "dual carbon" goals.

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