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Comprehensive Evaluation of Three Major Heat Pump Technologies: Air-Source, Ground-Source, and Water-Source Heat Pump

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Abstract: Heat pump systems, recognized for their energy efficiency and low-carbon footprint, are pivotal in advancing the global shift toward sustainable energy. This research focuses on a thorough comparative analysis of three primary heat pump systems: air-source heat pumps (ASHP), ground-source heat pumps (GSHP), and water-source heat pumps (WSHP).The research begins with the fundamental theory of heat pump technology, then delves into the core technical characteristics, suitable application environments, and actual performance of each type of heat pump, highlighting their unique strengths and potential drawbacks. Air-source heat pumps are flexible to install and cost-effective but experience reduced efficiency in low-temperature environments; ground-source heat pumps provide excellent energy efficiency and consistent performance, though they involve greater upfront costs and are influenced by geological factors; water-source heat pumps have the highest efficiency but are constrained by hydrological conditions and may impact the ecological environment. Through these analyses, this study aims to contribute to the sustainable development and widespread application of heat pump technology, providing researchers and engineers in the field with a comprehensive and detailed evaluation report.

Keywords: Heat pump, Air-source heat pump, Ground-source heat pump, Water-source heat pump, Sustainable development

1. Introduction

Today, the heating methods for buildings still largely rely on fossil fuels, particularly natural gas. Against the backdrop of accelerating global carbon neutrality goals, the transformation of energy structures in the building and industrial sectors has become a hot topic. Heat pump technology, due to its ability to efficiently utilize environmental thermal energy, can provide stable and efficient energy supply for buildings and industries. It has been listed by the International Energy Agency (IEA) as one of the "Seven Key Pillar Technologies for Achieving Net-Zero Emissions." The European Union is taking significant steps to promote the transition to sustainable and renewable energy systems through the European Green Deal. As a result, the use of renewable energy is also increasing. Meanwhile, China is actively responding to the challenges of global climate change by promoting the development of low-carbon industries through its "Dual Carbon" policy. However, due to the diversity and application complexity of heat pump technologies, selecting the appropriate heat pump system has become an urgent issue to address. This study seeks to comprehensively examine the

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fundamental features of three heat pump systems, evaluate their strengths and weaknesses, and offer evidence-based guidance for selecting the most suitable technology in various applications.

2. Fundamentals of heat pump technology

Heat pumps are systems designed to move thermal energy from one location to another by utilizing electrical or mechanical power, facilitated by the circulation of refrigerants. Their working mechanism closely resembles that of refrigeration systems. Heat pumps (HP) have the capability to transform surplus renewable energy into usable heat, playing a important role in decreasing carbon emissions in the heating industry[1]. The principle of a heat pump is identical to that of a refrigerator. The function of a heat pump is to extract a certain amount of heat from a low-temperature heat source, raise its temperature, and then deliver it to a higher-temperature confined space to achieve heating. Heat pumps are divided into two main categories: absorption heat pumps and compression heat pumps. Absorption heat pumps use heat as the driving force to transfer heat from a low-temperature source to a high-temperature sink. Compression heat pumps, conversely, depend on electrical or mechanical energy to transfer heat from a cooler source to a warmer destination. By utilizing a minimal amount of work (transformed into heat), they extract ambient heat and deliver it alongside the generated heat to the end user[2].

The energy efficiency of heat pumps is typically measured using the Coefficient of Performance (COP) and the Seasonal Coefficient of Performance (SCOP). The Coefficient of Performance (COP) represents the ratio between the heating or cooling output, measured in kilowatts (Q), and the electrical power input, also measured in kilowatts (W), required by the heat pump[3].

$$\mathrm{COP} = \frac{\mathrm{Q}}{\mathrm{W}}$$

The effort required by a heat pump to maintain a comfortable indoor environment is influenced by various factors, such as the nature of the heat source and heat sink, the comfort preferences of the occupants, and the gap between the outdoor temperature and the desired indoor temperature[3]. Based on the type of heat source, heat pumps can be classified into ASHP, GSHP, and WSHP. The thermal properties of the heat source have a direct impact on the efficiency (COP), stability, and applicable scenarios of the heat pump system.

3. In-depth analysis of three major heat pump technologies

3.1. Air-Source Heat Pump (ASHP)

3.1.1. Technical characteristics

The Air Source Heat Pump (ASHP) operates on the principle of the reverse Carnot cycle, utilizing air as its primary heat source. The heat pump, by absorbing a minimal quantity of electrical power, is capable of converting low-grade air thermal energy into high-grade thermal energy, facilitating the provision of heating and hot water. ASHPs present significant energy conservation advantages over traditional heating techniques such as electric, gas, and coal boilers[4].

The appearance of air-source heat pumps is very similar to traditional air conditioning outdoor units, occupying a small footprint. They are suitable for centralized cooling and heating in buildings, can be used year-round, and are less affected by weather conditions. Throughout the entire operation process, there is no combustion or exhaust emissions. Although air-source heat pumps require electricity, their working principle differs from the "electric-to-heat" conversion of electric heaters.

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The electricity in heat pumps is primarily used for driving the system, and it is not directly used for heating during the actual heating process, making them highly energy-efficient.

As the outside temperature drops, the heating demand of buildings rises. For air-source heat pumps, the external temperature serves as the evaporator side of the reverse Carnot cycle. If the condensing temperature stays constant (for example, when providing 50°C hot water), a decline in the evaporating temperature results in a higher specific volume of suction gas, lower volumetric efficiency, and reduced heating capacity per unit mass. As a result, the overall heating capacity of the air-source heat pump diminishes[5]. Due to the reasons mentioned above, the heating capacity of air-source heat pumps decreases under low-temperature conditions, affecting their heating efficiency. Moreover, in regions with temperatures of -35°C or lower, they generally cannot be used. Therefore, to ensure system reliability, researchers have chosen to integrate vapor injection technology with heat pump technology to improve the heating performance of the system under low ambient temperature conditions [6]. The application of vapor injection technology not only increases the degree of subcooling and the circulation flow rate, thereby enhancing the heating capacity, but also extends the operating temperature range of the system for heating under low ambient temperatures to some extent [7].

3.1.2. Applicable regions

ASHP (Air Source Heat Pump) is suitable for temperate climate regions where winter temperatures are typically above -10°C and summer temperatures are moderate. Currently, ASHPs are widely used in cities like Tianjin and Xi'an in China [8]. Research in Canada has shown that the equivalent COP (Coefficient of Performance) of ASHPs in various heating systems ranges from 2.3 to 3.5 [9]. An analysis of ASHP systems in a single-family home in Latvia revealed that the system's COP was at its lowest in January, the coldest month, at 2.6. These studies indicate that during the colder months, under such climate conditions, the COP can reach 2.5-3.5, meaning that only 1 kW of electrical energy is needed to produce 2.5-3.5 kW of heat energy.

Present advancements in the technology of ASHP units continue to indicate their potential as auxiliary heating sources in colder regions. In many situations, ASHP systems require supplementary electric heaters or alternative energy sources to ensure reliable operation during the coldest winter periods[10].

In addition, due to the energy efficiency and environmental friendliness of air-source heat pumps, they have been widely adopted in some regions and countries across Europe, North America, and Asia. Particularly in southern China, where winter temperatures are relatively mild, air-source heat pumps have become one of the primary heating solutions. In these areas, air-source heat pumps not only provide stable heating but also effectively reduce energy consumption and carbon emissions, aligning with the Chinese government's "Dual Carbon" policy goals.

3.2. Ground-Source Heat Pump (GSHP)

3.2.1. Technical characteristics

Ground-source or geothermal heat pumps present an exceptionally effective and environmentally friendly method for managing heating and cooling systems. This innovation leverages the Earth's steady subterranean temperature, elevated above the air during winter and reduced in summer. During the winter months, the system extracts heat from the earth to warm the structure, while in the summer, it releases heat from the structure into the soil to cool it down[11]. During operation, there is no need for combustion, exhaust emissions, or waste disposal, making it compatible with the transition to sustainable and renewable energy systems.

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GSHPs are regarded as a green and renewable energy solution, using the ground as a heat source in winter and a heat sink in summer to supply heating and cooling. They are becoming increasingly popular as a sustainable method for managing building temperatures due to their lower energy consumption compared to air source heat pumps and electric heating. This mechanism operates by circulating a liquid, typically water or an antifreeze agent, via a subterranean conduit known as a ground loop, which is connected to an internal heat pump in the structure. Employing a cooling system, the heat pump extracts warmth from the earth for heating in winter and discharges it into the soil for cooling in summer, thus maintaining effective temperature control[12].

Although GSHPs offer significant benefits in terms of energy efficiency and environmental sustainability, several barriers must be addressed to expand their use. One major hurdle is the high upfront costs associated with the specialized tools and technical knowledge needed for drilling boreholes and setting up the system[13]. Moreover, compared to traditional boiler systems, the installation process is more complex and requires a larger installation space. In cities, limited space often restricts the ability to drill boreholes. Additionally, in colder regions, heating demands typically exceed cooling needs, leading to more heat being extracted from the ground annually than is replenished. This imbalance can result in a gradual drop in soil temperature, potentially reducing system efficiency and eventually causing it to fail[14]. To address the aforementioned issues, seasonal thermal energy storage methods can be employed. This involves storing excess heat energy (such as solar energy or industrial waste heat) underground during the summer using solar collectors or waste heat recovery systems, and extracting it for use in the winter. This approach helps balance the soil's annual heat budget, resolves soil thermal imbalance problems, and improves the system's COP (Coefficient of Performance). Moreover, ground source heat pumps can be integrated with other systems, like air source heat pumps or cooling towers, to distribute the load more effectively. During winter, ground source heat pumps can be prioritized, while air source heat pumps can be activated as auxiliary support during extreme cold conditions. In summer,heat can be dispersed using cooling towers, reducing the amount of heat injected into the soil and lessening reliance on soil thermal properties.

3.2.2. Applicable regions

Ground Source Heat Pump (GSHP) systems have gained widespread global adoption due to their high energy efficiency and environmental benefits. However, their applicability is significantly influenced by geographical location and climatic conditions. Generally, GSHP systems perform best in regions with distinct seasons and moderate temperature fluctuations. In such areas, the soil temperature remains relatively stable, providing sufficient thermal energy for heating in winter and cooling in summer. GSHP systems are highly suitable for cold climate zones (such as Nordic countries: Sweden, Norway, etc.), temperate climate zones (such as central and southern European countries: Germany, France, as well as Asian countries like China, South Korea, and Japan). Research in South Korea has shown that the COP (Coefficient of Performance) of various GSHP systems ranges from 3.45 to 4.80, with an average COP of 4.18[15] .

Additionally, GSHP systems have greater advantages in areas with high groundwater levels, stable geological structures, and good soil thermal conductivity, as these conditions facilitate efficient heat transfer and storage. However, in extreme climates, such as very cold or hot regions, the performance of GSHP systems may be affected, necessitating additional measures to balance the soil's thermal budget, such as seasonal thermal energy storage or integration with other heat pump technologies, as mentioned earlier. Therefore, when deciding whether to adopt a GSHP system, it is essential to comprehensively consider local geographical, climatic, and economic factors.

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3.3. Water-Source Heat Pump (WSHP)

3.3.1. Technical characteristics

As global energy consumption continues to increase, the need for heating and cooling in buildings is expected to grow by 50% by 2050 [16]. In this context, enhancing energy efficiency in buildings has become a global priority for sustainable development, with water-based thermal energy systems being increasingly recognized as an effective method for generating heating and cooling energy in recent years [17]. Water Source Heat Pump (WSHP) systems use surface water (like lakes or rivers) or groundwater as a heat source, transferring heat through a heat pump cycle to provide heating and cooling for spaces. These systems harness thermal energy from water sources to deliver heating, cooling, and hot water. They function by exchanging heat with the geothermal energy in water, enabling efficient energy conversion and utilization[18].

The working principle of WSHP (Water Source Heat Pump) systems is similar to that of GSHP (Ground Source Heat Pump) systems, as both utilize low-temperature heat sources for heat transfer. The key difference lies in the fact that WSHP systems use water as the heat source instead of soil. In a WSHP system, the circulating medium (typically water or a glycol solution) cycles between the heat pump unit and the water source. Through a heat exchanger, thermal energy is either absorbed from or discharged into the water source, and the heat pump unit adjusts the temperature accordingly to fulfill the building's heating or cooling requirements. Water source heat pumps offer advantages such as high efficiency, energy savings, and environmental friendliness. Since water temperatures are relatively stable and generally higher than air temperatures, WSHP systems have a higher energy efficiency ratio compared to air source heat pumps. Additionally, WSHP systems do not require the combustion of fossil fuels during operation, producing no exhaust gases or pollutants, which aligns with environmental protection requirements. Moreover, WSHP systems occupy relatively small spaces and have minimal impact on the building's appearance and surrounding environment.

However, the application of WSHP systems is subject to certain limitations. Their suitability depends on local water source conditions and geological structures. In many provinces in China, such as Beijing, Shandong, Jiangsu, Zhejiang, Liaoning, Hebei, Shanghai, Hubei, Henan, Heilongjiang, Jilin, and Tibet, WSHP systems have demonstrated good performance due to abundant water resources, good water quality, and stable geological structures in these regions. Conversely, in areas with scarce water resources, poor water quality, or unstable geological conditions, the application of WSHP systems may be limited, as these factors directly affect the system's operational efficiency and stability.

Nevertheless, with the increasing awareness of environmental protection and the continuous development of renewable energy technologies, the application prospects for water source heat pumps (WSHP) remain broad. Particularly in regions with abundant water resources and high environmental protection requirements, WSHP systems are poised to become a significant method for heating and cooling. Additionally, as technology continues to advance and costs decrease, the scope of WSHP applications is expected to expand further.

3.3.2. Applicable regions

Water Source Heat Pump (WSHP) systems are primarily suitable for regions with abundant water resources and stable geological structures. These systems are typically well-suited for coastal cities, areas around lakes, riverbanks, and inland regions with plentiful groundwater. In such areas, WSHP systems can effectively utilize the abundant water resources to extract or release heat through the heat pump cycle, providing stable heating and cooling services for buildings.

Schibuola and Scarpa, in their 2016 research, assessed the annual cooling effectiveness and energy consumption of a surface water source heat pump system in contrast to a simulated air source heat pump system. The study focused on a system for heating surface water sources in the Venetian Lagoon. Results indicated a notable increase in the system's Energy Efficiency Ratio (EER) and Seasonal Energy Efficiency Ratio (SEER) throughout the winter, underscoring its enhanced energy efficiency[19].

Hailing Fu utilized Tianjin's meteorological data and examined buildings along the Haihe River to perform a dynamic simulation of a water source heat pump system using the TRNSYS software. The research showed a strong link between the heat pump's COP (Coefficient of Performance) and the Haihe River's water temperature. The COP peaked when the water temperature was between 12°C and 13°C. The system achieved an energy efficiency ratio (EER) of 3.26 in the cooling season and 3.08 in the heating season, demonstrating its suitability for Tianjin's climate[20].

4. Conclusions and foresight

Through the analysis of the three main heat pump technologies, it is evident that heat pumps, as an efficient and environmentally friendly energy utilization method, are increasingly gaining attention in modern building applications. Each type of heat pump possesses unique technical characteristics and suitable regions. Therefore, in practical applications, the appropriate heat pump system should be selected based on local geographical, climatic, and economic factors to achieve optimal energy utilization. This approach can significantly reduce building energy consumption and carbon emissions, driving the development of green buildings and low-carbon cities. By improving energy efficiency, heat pumps also promote the widespread use of renewable energy.

In the context of global climate change and energy crises, the promotion and application of heat pump technology are particularly important. By efficiently utilizing low-temperature heat sources, heat pump technology not only reduces reliance on traditional energy but also effectively lowers greenhouse gas emissions, aligning with the global trend of energy transition and sustainable development. Therefore, governments worldwide should increase policy support and financial investment in heat pump technology, encourage enterprises to enhance research and development efforts, improve the performance and efficiency of heat pump systems, reduce production costs, and promote the widespread adoption and application of heat pump technology. Simultaneously, research institutions should strengthen both fundamental and applied research on heat pump technology, exploring more innovative heat pump systems and technologies to provide a stronger scientific foundation and technical support for the advancement of heat pump technology.

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