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A Review of Recent Residential Heat Pump Systems and Applications in Cold Climates

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Abstract

The heat pump (HP) system is one of the environmentally friendly solutions to reduce the carbon footprint of buildings due to its high efficiency and low added initial cost from the cooling-only systems. This paper presents a literature review of the recent advances in HP systems applied in cold climate regions categorizing the systems into two major types depending on energy source types. The first type is the systems with an air source without additional energy sources, i.e., Air Source HP (ASHP) systems, which use various working fluids and configurations. However, several issues impede their widespread applications. When the systems are used for space or water heating in cold climates, ASHP systems suffer a high discharge temperature and pressure ratio at low ambient temperature, which leads to low efficiency and heating capacity. Furthermore, some researchers reported that the defrost penalty reduced the energy efficiency by up to 30%, leading to a degradation of heating capacity by 43%. The second type is the systems with additional energy sources, like solar-assisted HP systems, which can partly improve energy performance but have difficulties in coupling different sub-systems to achieve increased operational time and are limited to locations with enough solar radiation. This study identifies the future research directions as (1) developing multi-source heat pumps with efficient control; (2) utilizing waste heat for defrosting; and (3) optimizing HP configurations and minimizing refrigerant charge while achieving higher efficiency.

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Keywords: heat pump; cold climate; air source; multi-source; defrost

1. Introduction

A number of researchers have reported that the high energy consumption of the building sector is among the significant global challenges for sustainable human development [1]. Space and water heating take up more than half of residential energy consumption [2]. This ratio increases significantly in cold climate regions [3]. Over the last two decades, residential buildings have widely adopted Heat Pump (HP) systems due to their simple structure and low added initial cost [2]. Several different HP technologies exist. Air Source Heat Pump (ASHP) systems take low-grade heat from the air and produce high-temperature heat for domestic heating or other purposes [4]. Solar Assisted Heat Pump (SAHP) systems, which combine solar thermal panels with heat pumps, have been widely used to provide residential hot water owing to their simple structure, low cost, stable operation, and effective solar energy collection [5]. Ground Source Heat Pump (GSHP) and Water Source Heat Pump (WSHP) systems use heat energy naturally stored in either the ground or water, taking advantage of the

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relatively constant temperatures of the earth or waterbody throughout the seasons [6]. However, there are many challenges when people are using HP systems in cold climate regions. This paper groups the so-called cold climate heat pump (CCHP) systems into two major types depending on energy sources for clear discussion. The first type is the systems with an air source only without any additional energy sources, i.e., ASHP systems. The second type is the systems coupled with additional energy sources, like GSHP or SAHP systems. This study summarizes the challenge of different HP types to penetrate the cold climate region application.

2. Challenges of Heat Pump Application in Cold Climates

Challenges exist for almost all current CCHP systems. First, typical ASHP systems work under a high discharge temperature and pressure ratio at low ambient temperature, which leads to low efficiency and heating capacity [7]. For instance, with a decline in ambient temperature, a decreased heating capacity of the ASHP system may be insufficient for the building's heating load requirement, and the high compression ratio may lead to an extremely high discharge temperature and system shutdown. Furthermore, frost on the outdoor heat exchanger coil surface degrades thermal performance by reducing airflow area due to the blockage caused by the layer of frost [8]. Also, an insulating area is built up over the evaporator coils, thereby reducing their ability to absorb heat from the outdoor environment [8]. Defrost is a non-eligible problem in cold climate region. The heating COP would decrease by 30% if the heat exchanger was fully frost [9].

SAHP systems face challenges as well. The constant operation of the heat pump in the systems usually leads to a large carbon footprint, significant electrical energy use, and an energy inefficient operation [10]. However, owing to the fluctuation of solar radiation during the day time, the SAHP system may have a low efficiency without a proper control strategy or energy storage device [10]. As for the GSHP and WSHP systems, the installation region is restricted.

3. Air Source Heat Pump

Zhang et al. (2018) [2] reviewed the literature on vapor compression ASHP systems from 2005 to 2017 and classified the systems into single-stage, dual-stage, and multi-stage compression systems. They concluded that the quasi-two-stage compression system showed enormous potential for heating performance and initial cost. No similar study exists after Zhang's work summarizing new CCHP techniques based on the authors' knowledge. This section mainly focuses on reviewing the experimental studies conducted in the recent five years while comparing the new works with three old studies [11–13].

Table 1 summarizes the authors and some features of the target studies. In the "cycle type" column, "cascade" refers to two-stage systems using two separate compressors [14,15], while "VI" refers to the systems using the Vapor Injection (VI) technique. "-" in this column refers to single-stage systems. In the "discharge temperature" column, "-" means the information is not given in the related studies. Among the studies, Zhang et al. (2017) and Fan et al. (2022) [16,17] highlighted the need to reduce defrosting process power consumption in cold climates. Zhang et al. (2019) developed and investigated a novel thermal storage refrigerant-heated radiator coupled with an ASHP heating system. Zhang et al. (2017), Wei et al. (2020), and Wu et al. (2022) [16,19,20] examined the long-term performance of the ASHP system in the field test.

Fig. 1 plots these studies using the ambient temperature as the x-axis and COP as the y-axis. All points were tested under the same indoor condition (21 °C). The linear regression line of the data points shows that most of the ASHP systems can reach 1.5 COP under extreme conditions. One outstanding piece of research was carried out by Bertsch and Groll (2008) [11,12]. They applied a special low-pressure stage compressor with an oil tap in the VI system and mentioned that this compressor with a suction volume of approximately 90 cm^3/rev was not commercially available, which might explain the impressive performance.

First, the data suggest that VI using R410A is the primary trend technique applied for cold climate ASHP system. However, the discharge temperature of the upper stage cycle typically exceeds 90 °C. Except for some limited studies, the COP limitation exists under the extreme ambient conditions of -20 °C to -30 °C. Second, frost-caused performance degradation is non-negligible [9]. Supplying an auxiliary heat source, e.g., an electric heater, seems necessary for cold-climate ASHP systems.

In summary, from the existing studies, the maximum COP of the advanced system under low ambient temperature conditions based on the published literature is still low from the viewpoint of the primary energy ratio. Secondly, its heating capacity deserves to be further enhanced to satisfy building heating loads, especially under extreme conditions. Finally, more research on the technology about system start-up at low ambient temperature and year-round control strategy is required to ensure the reliability of the advanced system.

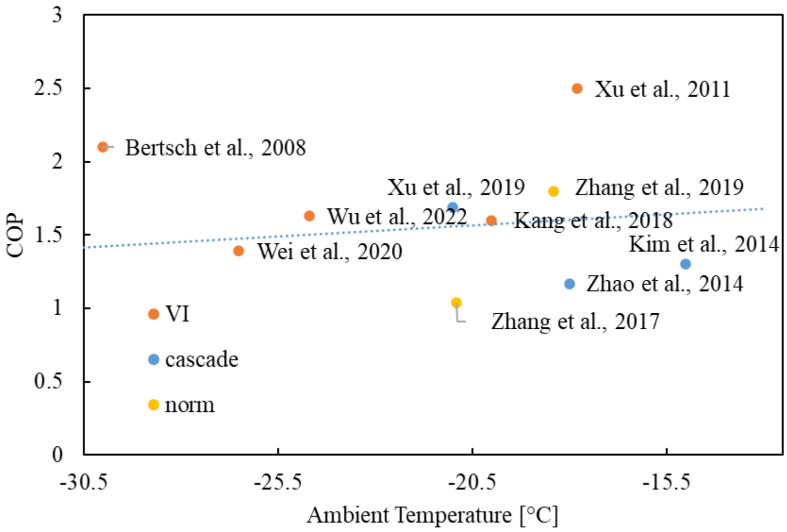

Fig. 1. Comparison of existing studies under extremely cold conditions

Table 1. Existing ASHP performance under extreme conditions

Authors, year	COP	Ambient Temp. [°C]	Cycle Type	Refrigerant	Discharge Temp. [°C]
Bertsch and Groll, 2008 [11]	2.1	-30.0	VI	R410A	93.0~102.0
Xu et al., 2011 [12]	2.5	-17.8	VI	R410A	-
Kim and Kim, 2014 [13]	1.3	-15.0	cascade	R410A/R134a	80.0~90.0
Zhang et al., 2017 [16]	1.1	-20.9	-	R22	-
Kang et al., 2018 [21]	1.6	-20.0	VI	R410A	97.3~101.2
Xu et al., 2019 [22]	1.7	-21.0	cascade	R404A/R134a	93.9~91.4
Zhang et al., 2019 [18]	1.8	-18.4	-	R410A	-
Wei et al., 2020 [19]	1.4	-26.5	VI	R410A	90.6
Wu et al., 2022 [20]	1.6	-24.7	VI	R410A	-

4. Systems with additional energy sources

4.1. Solar Assisted Heat Pump

Some researchers identified the merits of SAHP systems as flexibility, efficiency, and stability in cold regions [23]. Others argued that cold regions in winter usually lack solar energy [7]. Many studies exist to improve the thermal performance of SAHP systems. Ji et al. (2008) and Fu et al. (2012) [24,25] optimized the structure of the solar thermal panels and evaporator; Zhang et al. (2014) [26] studied the optimal geometrical sizes and capacity; Gorozabel Chata et al. (2005) and Kong et al. (2017) [27,28] concentrated on the refrigerant type; Chaturvedi et al. (1998) and Kong et al. (2018) [29,30] focused on the control strategy for compressor and electronic expansion valve, and Chaturvedi et al. (2009) [31] combined the cascade structure with Thermal-SAHP water heater to reach higher supply temperature. Nevertheless, none of the research mentioned how their proposed system could match the requirements under low ambient temperature or radiation conditions. Qiu et al. (2018) [32] investigated a low-temperature heat-collecting system and got a simulation COP result of only 1.6 at -25 °C ambient temperature and 200 W/m^2 solar radiation intensity. Only limited scholars studied combined photovoltaic-thermal (PV/T) SAHP (air-source). Li et al. (2015) [33] developed a mathematical model of a PV/T-SAHP system and optimized the flow distribution and velocity to reach the COP as high as 4.6 at 10 °C ambient conditions. However, this result was given with 400 W/m^2 radiation, and the authors also mentioned that the performance could reduce to 21% when the outdoor air temperature was -5 °C. Cao et al. (2016) [34] simulated a PV/T-SAHP performance using Computational Fluid Dynamics (CFD). The COP could reach 3.5 when the ambient temperature was around 0 °C. However, they did not study the performance under further lower temperature conditions.

A comparative study of different seasonal Thermal Energy Storage (TES) systems using HPs with solar collectors identified the heat pump's COP and the solar fraction as the main factors that influenced the efficiency of the system, with both factors being a function of the collector area and storage volume [35]. Pensini et al. (2014) [36] undertook an economic analysis of using excess renewable energy for heating purposes, and reported that HPs with centralized thermal storage met heat demand at lower costs than conventional systems even if there was a charge for producing excess renewable energy. Kapsalis and Karamanis (2016) [37] considered solar TES and heat pumps with Phase Change Materials (PCMs) and concluded that further investigation and experimental work were necessary to determine the combined effect PCMs in building components and HP operation within different climates.

This section discussed the merits and limitations of SAHP systems in cold regions. Several studies have been conducted to improve the thermal performance of SAHP systems. SAHP could improve the COP in cold regions with high solar radiation, but the benefit is limited in low solar radiation regions.

4.2. Ground Source Heat Pump

It was reported that Ground Source Heat Pump (GSHP) systems have relatively stable performance throughout a year but can only be installed at specific locations [38]. One study shows that such systems are 40% more energy efficient than ASHPs [39]. Huang et al. (2019) [40] reported that the GSHP system had higher installation costs but higher energy efficiency and 10% lower costs across 10 years. Direct expansion GSHPs, a variant of the common GSHP that uses a buried copper piping network through which refrigerant is circulated, can deliver superior performance relative to GSHPs and ASHPs in Canadian and Chinese locations [41,42]. Mattinen et al. (2015) [43] compared carbon emissions across direct electric heating, ASHP, and GSHP systems and found that GSHPs perform better in colder climates due to higher COP at lower outdoor temperatures. Carbon emissions in ASHP systems were 40% lower than direct electric heating and 70% lower in the GSHP system. From an emissions perspective, this makes GSHP systems the best option; however, reducing emissions is only possible if the heat pumps are integrated with low-carbon power systems. Otherwise, deploying large quantities of heat pumps in a power system where there is a low level of decarbonization of electricity generation merely results in shifting emissions from one sector to another. Wu compared ASHPs with GSHPs and concluded that GSHPs have the advantages of higher efficiency; lower life cycle cost; lower impact on environment; and better reliability [44]. Safa et al. got a result that for cooling mode, the COP of ASHP ranged from 4.7 to 5.7 at an outdoor temperature of 33 °C and 16 °C respectively, while the COP of GSHP ranged from 4.9 (at an ELT of 8.5 °C and EST of 19.2 °C) to 5.6 (at an ELT of 12.4 °C and EST of 17.8 °C) [45]. Garber et al.'s results of the analysis show that potential savings from a full-size GSHP system largely depend on projected HVAC system efficiencies and gas and electricity prices [46].

This section summarizes that GSHP systems can be more efficient than ASHP systems. However, their emissions benefits are only realized if they are integrated with low-carbon power systems.

4.3. Water Source Heat pump

Water source heat pumps (WSHPs) use lakes, ponds, rivers, groundwater, and other water sources, as a source of heat. They convert low-grade heat from the water source to a higher grade. The temperature of the waterbody fluctuates less than that of air; thus, the performance of WSHP is relatively stable. Bach et al. (2016) [47] from Denmark found the seasonal variation of COP had little or no impact on the transmission and distribution networks of the district heating system, as COPs of WSHPs did not vary much throughout the year. Thus, such systems can work well in cold weather. However, WSHP applications are limited due to the requirement of large water bodies or storage tanks near dwellings. Moreover, the need to adhere to specific environmental regulations may further result in a low uptake rate of WSHPs.

5. Discussion

5.1. Existing studies

First, based on existing literature for ASHP systems, the two-stage compression system shows tremendous potential for performance and cost [2]. Furthermore, Table 1 suggests that VI systems using R410A are the main trend technique. However, the discharge temperature of the upper stage cycle was usually high. In addition, the COP of all the systems is still a bit small from the viewpoint of the primary energy ratio. The defrost power consumption, low-temperature start-up technology, and year-round control strategy are significant but are seldom mentioned in current published literature.

Some studies concluded that SAHP and GSHP systems are better options than ASHP systems in colder regions [4]. However, the type of heat pump to be installed is location and application specific. This is due to the concern that ASHPs may not be able to meet the thermal comfort and energy efficiency requirements when ambient temperatures are immensely low. The requirement of solar radiation, ground thermal sources, and other environmental concerns limit SAHP, WSHP, and GSHP systems' overall uptake rate.

5.2. Current Barriers

Several issues that impede the widespread of above applications still exist: 1) the lack of clear decarbonization pathways, technology acceptance, and funding are the primary sources of barriers to cold climate heat pump uptake [48]; 2) public acceptance and awareness issues, i.e., emanate from unwarranted fear, misperception, misinformation, and previous experiences on the reliability, also pose significant challenges in adopting the new technology [49]; 3) existing market structures combined with public perception can also hinder the penetration of cold climate heat pumps [50]; 4) barriers related to lack of standards and mandatory policies can also considerably constrain some special HP systems deployments, like GSHP and WSHP [51]; 5) an essential barrier to widespread adoption of heat pumps in cold climate is the limitation of the electrical network, which may be further increased at peak periods and in turn may require additional electricity grid infrastructure investment to satisfy the demand [52]; and 6) proper sizing and installation of a heat pump is essential in order to achieve the desired design objectives and overcome the barriers to widespread adoption.

5.3. Future work

The future research directions were identified: (1) multi-source heat pumps, for example, the systems using both solar energy and ground source energy, could be proposed; for these systems, an efficient control to coordinate each part is necessary; (2) waste heat or low-grade heat shall be used for heat pump defrosting in cold climate regions; identification of more heat source other than the ground source or water source could be investigated; (3) people may also study advanced heat storage technology and heat exchanger design strategies; and (4) researcher may continue to optimize the configuration and refrigerant usage to achieve low discharge temperature in cold climate heat pumps.

6. Conclusions

Due to the great efficiency and minimal added initial cost compared to cooling-only systems, HP systems are one of the ecologically sustainable ways to lower the carbon footprint of buildings. In this research, the HP systems are divided into two main categories depending on supplementary energy sources, and current HP system developments for cold climate regions are thoroughly assessed. Following is a list of the conclusions:

The two-stage compression system shows tremendous potential for performance and cost, and VI systems using R410A are the primary trend technique for ASHP systems. However, the discharge temperature of the upper stage cycle was usually high. In addition, the COPs of all the systems are still a bit low from the primary energy ratio viewpoint.

Some researchers reported that the defrost penalty reduced energy efficiency by up to 30%, leading to further degradation of heating capacity by 43%. Thus, defrost is a non-negligible factor for CCHP application.

Low-temperature start-up technology and year-round control strategy are significant but are seldom mentioned in published literature.

Some studies concluded that SAHP and GSHP systems are better options than ASHP systems in colder regions. However, the type of heat pump installed is location and application specific. This is due to the concern that ASHPs may not be able to meet the thermal comfort and energy efficiency requirements when the ambient temperature is immensely low. The requirement of solar radiation, ground thermal sources, and other environmental concerns limit SAHP, WSHP, and GSHP systems' overall uptake rate.

Current barriers to CCHP systems include policy limitation, public acceptance, economic reasons, a lack of standards and funding, and insufficient studies on an electronic network.

Future research should focus on the following topics: (1) multi-source heat pump with effective control; (2) heat pump defrosting capability utilizing waste heat; (3) advanced Heat Storage and Heat Exchange Unit technology; and (4) optimized structure and refrigerant usage to obtain low discharge temperature.

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