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Air source absorption heat pump in district heating: Applicability analysis and improvement options

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ABSTRACT

The low-temperature district heating system based on the air source absorption heat pump (ASAHP) was assessed to have great energy saving potential. However, this system may require smaller temperature drop leading to higher pump consumption for long-distance distribution. Therefore, the applicability of ASAHP-based district heating system is analyzed for different primary return temperatures, pipeline distances, pipeline resistances, supplied water temperatures, application regions, and working fluids. The energy saving rate (ESR) under different conditions are calculated, considering both the ASAHP efficiency and the distribution consumption. Results show that ASAHP system is more suitable for short-distance district heating, while for longer-distance heating, lower supplied hot water temperature is preferred. In addition, the advantages of NH_3/H_2O are inferior to those of $NH_3/LiNO_3$, and the advantages for warmer regions and lower pipeline resistance are more obvious. The primary return temperatures are optimized to obtain maximum ESRs, after which the suitable distances under different acceptable ESRs are summarized. To improve the applicability of ASAHP, the integration of cascaded heat exchanger (CHX) and compression-assisted ASAHP (CASAHP) are proposed, which can reduce the primary return temperature. The integration of CHX can effectively improve the applicability of ASAHP under higher supplied water temperatures. As for the utilization of CASAHP, higher compression ratio (CR) is better in longer distance, while lower CR is more advantageous in shorter distance. For a distance of 50 km, the maximum ESR is improved from 13.6% to 20.4–25.6% under different CRs.

1. Introduction

1.1. Progress of absorption heat pump (AHP) in district heating

Energy consumption for heating and domestic hot water is very high and is predicted to increase continuously due to the improvement in living standards [1]. In China, district heating is very widely used in cold and severely cold regions, with coal boilers and coal-based combined heating and power (CHP) being the main heat sources [2]. Low energy efficiency and high air pollution make coal-based heating a thorny problem in energy conservation as well as environment protection [3]. Though some governments or researchers suggested replacing them with cleaner heating systems, such as gas boiler or electrical heat pump (EHP) [4–6], China's coal-dominated energy structure determines that it is very difficult to abandon coal-based heating completely. Moreover, massive application of gas boiler or EHP heating will lead to serious insufficiency of gas and electricity supply, not to mention the bad applicability of EHP in cold and severely cold regions [7]. Even as regards gas heating, the primary energy efficiency (PEE) of a conventional configuration is also far from satisfactory [8]. Under these circumstances, it is more practically reasonable to improve the energy efficiency and reduce the pollutant emission of the present district heating systems rather than replace them with other heating systems attached with new problems.

The AHP has been widely used to improve the energy efficiency of district heating systems in two main considerations: waste heat recovery and distribution temperature drop lifting. In terms of heat recovery, Li et al. [9] proposed a distributed AHP system to recover low-grade renewable energy, which was assessed to save energy by 23–46% compared with the conventional district heating

Abbreviations: AHE, absorption heat exchange; AHP, absorption heat pump; ASAHP, air source absorption heat pump; ATT, absorption temperature transformer; CASAHP, compression-assisted air source absorption heat pump; CHP, combined heating and power; COP, coefficient of performance; CR, compression ratio; EHP, electrical heat pump; ESR, energy saving rate; CHX, cascaded heat exchanger; LMTD, logarithmic mean temperature difference; LTD, low-temperature driven; PEE, primary energy efficiency.

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Nomenclature

c_p	specific heat, kJ/(kg °C)
d	pipe inner diameter, m
E_c	electricity consumption of the conventional system, kW h
E_p	electricity consumption of the proposed system, kW h
F_A	ratio of heating load supplied by ASAHP
G	air flow rate of fan, m^3/s
G_t	water flow rate inside the pipeline, m^3/h
H	pumping head (total resistance), kPa
H_0	resistance of generator or heat exchanger, kPa
h_{in}	inlet specific enthalpy, kJ/kg
h_{out}	outlet specific enthalpy, kJ/kg
K	equivalent absolute roughness of tube wall, m
L	distance between the heat source and the heat substation, km
m_f	water or air mass flow rate, kg/s
m_{in}	inlet mass flow rate, kg/s
m_{out}	outlet mass flow rate, kg/s
m_r	refrigerant mass flow rate, kg/s
Q	heat exchange rate, kW
Q_a	absorber heat exchange rate, kW
Q_c	condenser heat exchange rate, kW
Q_g	generator heat exchange rate, kW
R_l	specific frictional resistance of pipeline, Pa/m
S	heat supplied to the users, kW h
T_{in}	inlet temperature, °C
T_{out}	outlet temperature, °C
UA	product of heat transfer coefficient and heat transfer area, kW/K
W_{comp}	electricity consumption of compressor, kW
W_{fan}	electricity consumption of fan, kW
W_{pump}	electricity consumption of distribution pump, kW
W_{sp}	electricity consumption of solution pump, kW
x_{in}	inlet solution concentration, kg/kg
x_{out}	outlet solution concentration, kg/kg
η_{boiler}	boiler efficiency, %
η_{comp}	compressor efficiency, %
η_{power}	power generation efficiency, %
η_{pump}	pump efficiency, %
ρ	density, kg/m^3
α	ratio of local resistance to fractional resistance

system. Fu et al. [10] proposed an exhaust heat recovery system based on AHP technique in the gas boiler district heating, where the exhaust flue flowed through the AHP evaporator, and whose temperature was low enough to condense the vapor in the flue. This AHP integrated system was evaluated to have a 5% higher efficiency over the existing condensing recovery methods. Minea and Chiriac [11] presented the configurations, the main thermodynamic and hydraulic parameters, and some design guidelines and operating experiences of a medium-temperature, NH_3/H_2O hybrid AHP heat recovery system for district domestic hot water production. Fang et al. [12] proposed a holistic approach to the integrated and efficient utilization of low-grade industrial waste heat. It was found that applying AHPs in substations is more cost-efficient than applying heat exchangers in substations. Zhu et al. [13] combined the AHP and the direct-contact heat exchanger, removing heat from the flue gas below the dew point so as to realize the total heat recovery for the gas boiler. Field test and experimental analysis of an actual case in a district heating system operating at various system loads was carried out. Qu et al. [14] introduced three configurations to improve boiler thermal efficiency by integrating AHP with natural gas boilers. For conceptual proof and validation, an existing hot water-driven absorption chiller was operated as a heat pump at operating conditions similar to one of the devised configurations. An overall system performance and economic analysis were provided for decision-making and as evidence of the potential benefits.

The absorption heat exchange (AHE) technology based on AHP has been proven to be a promising approach to increase the temperature difference between supply and return water to reduce the pump energy consumption or to increase the distribution capacity of district heating network. Li et al. [15] designed a district heating system based on an AHE to improve both the heating capacity and the cogeneration efficiency. The return water temperature of the primary network could be reduced to 25 °C through the AHE units in the substation, which increased the circuit temperature drop so that the delivery capacity of the heating network increased dramatically. Sun et al. [16] proposed a waste heat district heating system based on the AHE to increase the CHP heating capacity and to enhance the heat transmission capacity of the heating network. Compared with the conventional CHP, the proposed one increased the heating capacity by 31%, and the heat transmission capacity by 75%. Sun et al. [17] investigated a waste CHP system integrated with ejector heat exchangers and AHP to recover waste heat of exhausted steam from a steam turbine, as well as increase the heat transmission capacity of the primary heating network by decreasing the return water temperature to 30 °C. The proposed system was analyzed to decrease consumption of steam extracted from a steam turbine by 41.4% and to increase heat transmission capacity of heating network by 66.7%. Wang et al. [18] developed a new absorption temperature transformer (ATT), which has the similar function to the AHE in increasing the temperature drop of primary network. The condensation or evaporation pressure was separated into several levels in order to enhance the heat transfer processes based on entransy dissipation analysis [19]. Optimization showed that the total UA (product of heat transfer coefficient and heat transfer area) reduction becomes not obvious when the stage number is over 3, while the total UA reduction of a 4-stage ATT reached 28.9% compared with a 1-stage AHE.

1.2. Advantages and problems of ASAHP in district heating

The above progress indicates that AHP is promising in terms of waste heat recovery and temperature drop lifting. However, from the standpoint of system energy balance, no extra energy is extracted from the ambient, which means that the PEE of existing fuel-based district heating can be improved but can never be higher than 100%. To enhance further the PEE, a low-temperature heating system combining a boiler/heat network with an air source absorption heat pump (ASAHP) was proposed [20]. The conventional and the proposed heating systems are shown in Fig. 1. In the proposed system, the conventional boiler/network acts as the driving source of the ASAHP rather than supplying heat directly or through an intermediate heat exchanger. The air-source evaporator extracts low-grade heat from the ambient air to produce an increased capacity of hot water. The heat exchanger in the conventional heating system is in parallel with the ASAHP to provide direct heating when the ASAHP produces insufficient capacity or stops working. In this manner, the required fuel can be greatly reduced to meet the same heating demand, and thus the pollutants caused by burning fuel could also be lessened.