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Techno-economic analysis of air source heat pump applied for space heating in northern China

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HIGHLIGHTS

- A techno-economic analysis model of different space heating modes was established.
- The energy performance of different heating modes was analyzed and compared.
- The pollution emissions of different heating modes were analyzed and compared.
- The economic applicability of different heating modes was analyzed and compared.
- LTASHP is applicable and suitable for space heating in northern China.

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ABSTRACT

To meet the demand of clean heating in cold regions of northern China, high efficiency and environment-friendly low temperature air source heat pump heating system has been proposed and applied. In this paper, the technical feasibility and economical applicability of low temperature air source heat pump heating mode were studied and compared with conventional heating systems. A mathematical model of technical and economic analysis of different heating modes was established. With the mathematical model, different heating systems were compared with their primary energy consumption, pollution emissions, initial investment and annual running cost. The results showed that the low temperature air source heat pump heating system can stably and reliably meet the demand of space heating in residential buildings when outdoor air temperature is −15 °C. In terms of energy efficiency, the primary energy consumption of low temperature air source heat pump heating mode is lower than coal-fired boiler, gas boiler, direct electric heating mode, but higher than combined heat and power generation. Comparing the pollution emissions, low temperature air source heat pump heating mode move the pollution source from residential areas to power plant, and has the relative low dioxide pollution emissions. Comparison results also show that the low temperature air source heat pump heating system is the most economical way among the candidates.

1. Introduction

As an energy efficient and environment friendly way, air source heat pump has been widely used for space heating in the regions along the middle and lower reaches of Yangtze River in southern China [1,2]. In these regions, air source heat pump runs smoothly and efficiently due to the relative high outdoor air temperature and low heating load in winter, which leads to good heating effect. However, when air source heat pump was applied in the northern regions of China where the heating load is larger and outdoor temperature is much lower than Yangtze River region, the heating capacity and the heating coefficient of performance (COP_h) will decrease significantly. Short service life and low energy efficiency caused by frosting over evaporator and large compression ratio greatly limit the application of air source heat pump in northern China. To improve the heating performance of air source heat pump under subzero climate, substantial researches have been conducted and a variety of feasible technical routes including new refrigerant substitution, phase change material combined with air source heat pump, new heat pump circulation system, defrost technology were proposed. Rao et al. [3] and Yu et al. [4] have reviewed the status

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Nomenclature

Q_h	the heat load per unit area in the heating season [kgce/m^2]
W_{hnet1}	the power consumption per unit area of primary network [kgce/m^2]
W_{hnet2}	the power consumption per unit area of secondary network [kgce/m^2]
COP_{zh}	the integrated heating coefficient of performance of low temperature air source heat pump in total heating season
η_{hnet1}	the thermal efficiency of primary network
η_{hnet2}	the thermal efficiency of secondary network
η_{CHP}	the heating efficiency of cogeneration units
η_e	the national average power generation efficiency
η_{enet}	the grid transmission efficiency
η_{cb}	the heating efficiency of coal-fired boiler
η_{gb}	the heating efficiency of wall hanging gas boiler
η_h	the electro-thermal conversion efficiency

and development of air source heat pump in recent years. Hakkaki-Fard et al. [5] assessed the potential benefits of implementing zeotropic refrigerant mixtures in residential air-source heat pumps for cold climates to increase their seasonal performance. Hu et al. [6] have made a study on air-source transcritical CO_2 heat pump water heater system, and presented an ESC based self-optimizing control scheme for maximizing the COP of air-source CO_2 heat pump water heater system. Other attempts including air-supplying enthalpy-adding, two-stage compression, quasi-two-stage compression, single and double stage coupled heat pump system and cascade heat pump system combined with defrosting technology were proposed by researchers, and positive results have been got in these researches. Li and Wang [7] have simulated the system of a single-stage air source heat pump and a supplementing-compressing air source heat pump. In their study, a calculation of heat pump with a refilling process was presented and the most appropriate pressures in different evaporation temperatures were obtained [7]. Jiang et al. [8] studied optimum compressor cylinder volume ratio for two-stage compression air source heat pump systems. Li and Yu [9] presented an optimum system configuration analysis for a flash tank cycle based two-stage compression air source heat pump system using a developed theoretical model with lumped parameter. The analysis results indicated that the heating coefficient of performance (COP) of the heat pump system could be maximized by optimally allocating the thermal conductance inventory [9]. Pang and Ma [10] designed a quasi two-stage compression heat pump system coupled with ejector, in which the ejector replaced the throttling element in conventional heat pump with economizer. The testing results showed that the coupled heat pump system with the ejector could obtain excellent performances in a wide range of operating conditions, and its heating COP could be 10% higher than the system without the ejector. Xu and Ma [11] have made an exergy analysis for quasi two-stage compression heat pump system coupled with ejector. Zhang et al. [12] made an experiment on the application of air source heat pump in Harbin, the coldest provincial capital of China, and the results showed that ASHPs could be used for heating applications in cold regions. However, the difference between indoor and outdoor air temperatures should be controlled within 41 °C to achieve an acceptable COP. Poppi et al. [13] analyzed a system improve method which combined solar thermal with air source heat pump, the results showed that variations in electricity price affected the additional investment limit far more than the other economic parameters. Li et al. [14,15] discussed the feasibility of air source heat pump floor radiant heating in energy saving buildings of north cold regions by theoretical calculation and field measurement. Dongellini et al. [16] conducted numerical analysis of the energy performance of HVAC systems for heating and cooling, based on a reversible electrical air-source heat pump. The results evidenced that downsizing/oversizing degree of the considered heat pump with respect to the thermal loads of the building was a crucial parameter that influenced the energy performance of the HVAC system.

Studies on frost accumulation and defrosting technologies have been carried out by researchers as well since frost has significant influence on the operation of low temperature air source heat pump in winter. Wang et al. [17] tested the performance of low temperature air source heat pump, and proposed some suggestions to modify the current defrosting control strategy, which were helpful to avoid the mad-frost problem. Kwak and Bai [18] tested the performance of heat pump using electric heater under the frosting condition to enhance the heating capacity and increase COP of small capacity air-to-air heat pump under the frosting condition during heating operation. The results showed that when the outdoor temperature is 2 °C/1 °C (DB/WB), the heat pump turned on the electric heater in outdoor unit. The heating capacity increases 38% and COP increases 57% in comparison with those of conventional heat pump. When the outdoor temperature is 4 °C/2 °C (DB/WB), the electric heater is in ON/OFF mode according to the temperature of the evaporator. The heating capacity increases of 9.1% and COP increases of 71.1% in comparison with those of conventional heat pump. Zhang et al. [19] proposed a novel defrosting method using heat energy dissipated by the compressor of air source heat pump, and developed a novel ASHP unit to test the defrosting method. The results showed that the increase in the system COP is 1.4%. Wang et al. [20] proposed an air source heat pump with novel photoelectric sensors and tested the characteristics of air source heat pump combing with the novel photoelectric sensors during periodic frost-defrost cycles, the results demonstrated that tube encircled photoelectric sensor (TEPS) could substantially prolong defrost intervals from 28.8 min to 52 min under the experimental conditions, and the number of defrost cycles can be reduced from 9 to 5. The performance improvement was found to be 6% of heating efficiency, and 5% of the COP [20]. Wang et al. [21] have analyzed and studied the novel frost-free air-source heat pump water heater (ASHPWH) system, which coupled with an extra heat exchanger coated by a solid desiccant with an energy storage device, the results showed that COP of the frost-free ASHPWH are 17.9% and 3.4% higher than reverse-cycle defrosting at the ambient temperature of −3 °C and 3 °C respectively. There are other defrosting technology researches, such as changing the outdoor machine structure, the use of solar energy and phase change energy storage technology [22,23].

With the new technologies and development of air source heat pump technologies, ASHP has been gradually applied in northern regions of China for space heating. The application of low temperature air source heat pump normally uses floor radiant heating, air convective heating and radiator heating. One schematic diagram of the low temperature air source heat pump combined with radiator is shown in Fig. 1.

In the rural areas not reached by district heating, air source heat pump has been designated to be promoted technology by the government. However, before large-scale promotion and application, researches on the energy saving effect, environment influence and economical applicability of low temperature air source heat

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