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Techno-economic analysis of air source absorption heat pump: Improving economy from a design perspective

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ABSTRACT

The heat supply system combining a conventional boiler with an air source absorption heat pump (ASAHP) has been evaluated as having great potential in energy saving and emission reduction. However, an economic analysis needs to be performed before its wide applications. To improve the economy of ASAHP from a design perspective, a year-round simulation and techno-economic analysis are conducted. Results show that the energy saving rate (ESR) does not decrease much when the relative design capacity of ASAHP is within 50–100%. At a relative design capacity of 75% in Harbin, 35% in Shenyang, 50% in Beijing, and 50% in Zhengzhou, ESR can reach 21.6%, 24.3%, 26.2% and 26.3%. Given an ASAHP price of 1.5 CNY/W and a gas price of 4.0 CNY/Nm^3, the payback period is 6.8, 6.6, 4.1 and 4.6 years in these four cities, at a 50% relative design capacity. There is a conflict between ESR and the payback period, but a small sacrifice (1.5–6.0%) in ESR can contribute a great reduction (38–48%) in the payback period. The heating period and energy price in the local area, as well as the expected ESR and acceptable payback period should be comprehensively considered for a better energy efficiency and economy.

1. Introduction

1.1. Necessity for economy improving on ASAHP

Energy consumption for space heating and domestic hot water is very high [1]. Traditionally, boilers are the most commonly used system to meet the heat demand in cold regions, which turn out to be of low energy efficiency and produce serious air pollution [2–4]. A novel heat supply system combining a conventional heating system with an air source absorption heat pump (ASAHP) has been proposed in the previous work to solve this problem [5]. The proposed ASAHP is driven by the conventional boiler or district heating network, and can extract low-grade heat from the ambient, which can obviously increase the heating capacity of the conventional systems. The proposed ASAHP has been evaluated as having great potential in primary energy saving and emission reduction [5–7].

However, the investment of the proposed ASAHP is estimated to be higher than the conventional systems, so the payback period is predicted to be longer. To solve this problem, the economy has to be improved based on the characteristics of ASAHP. The previous work is mainly focused on the energy respect, without any economic analysis or economy improving, which may be a great concern before being scaled up to wide applications.

1.2. Problems of conventional design and analysis method

Much economic analysis on absorption systems has been conducted. Abdullah and Hieng [8] demonstrated a techno-economic comparison on the H_2O–NH_3–H_2 absorption cooling system driven by three different energy sources. Taking electricity as a baseline, LPG (liquefied petroleum gas) requires 6.2 years to achieve payback, while a photovoltaic heater needs a period of 23.1 years. Tsoutsos et al. [9] presented a performance and economic evaluation of a solar cooling system in a Greek hospital. The payback period without funding subsidies is 11.5 years, while with a funding of 40% it is 6.9 years. Mammoli et al. [10] conducted an energy, economic and environmental analysis of a solar-thermal-assisted HVAC system based on the absorption chiller. The economics of building-scale solar thermal systems are strongly dependent on the cost of energy, and the economics are favorable where electricity costs are high. Calise [11] simulated a solar heating and

Abbreviations: COP, coefficient of performance; ASAHP, air source absorption heat pump; ASEHP, air source electrical heat pump; ESR, energy saving rate; LMTD, logarithmic mean temperature difference; LPG, liquefied petroleum gas; PHX, plate heat exchanger.

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Nomenclature

$C_{Initial}$	initial cost, CNY
$C_{Operation}$	operation cost, CNY
$C_{Operation,boiler}$	operation cost of boiler system, CNY
$C_{Operation,new}$	operation cost of the new system, CNY
E	year-round heat consumption of a heating system, kWh
E_{ASAHP}	year-round heat consumption of the ASAHP mode, kWh
E_{Boiler}	year-round heat consumption of boiler system, kWh
E_{New}	year-round heat consumption of the new system, kWh
E_{PHX}	year-round heat consumption of the PHX mode, kWh
$e_{Boiler,i}$	hourly heat consumption of boiler system at the ith hour, kWh
$e_{New,i}$	hourly heat consumption of the new system at the ith hour, kWh
FR_{ASAHP}	ratio of heat supplied by ASAHP to heat supplied by the entire system
H_{gas}	lower heat value of natural gas, MJ/Nm^3
h_{in}	inlet specific enthalpy, kJ/kg
h_{out}	outlet specific enthalpy, kJ/kg
m_{in}	inlet mass flow rate, kg/s
m_{out}	outlet mass flow rate, kg/s
P_{ASAHP}	unit price of the ASAHP, CNY/W
P_{gas}	local price of natural gas, CNY/Nm^3
PP	payback period, year
Q	heating capacity of heat exchanger, kW
Q_d	design heating capacity of the ASAHP, kW
Q_h	heating capacity of the ASAHP, kW
Q_i	hourly heating load at the ith hour, kW
q_d	design index of building heating load, W/m^2
S	total building heating area, m^2
T	temperature, °C
T_{air}	ambient air temperature, °C
$T_{air,d}$	design outdoor air temperature, °C
$T_{air,i}$	ambient air temperature at the ith hour, °C
T_{in}	design indoor air temperature, °C
t_e	ending hour of the heating season, h
t_s	starting hour of the heating season, h
UA	product of heat transfer coefficient and heat transfer area, kW/K
V_{gas}	gas volume under nominal condition, Nm^3
x_{in}	inlet solution concentration, kg/kg
x_{out}	outlet solution concentration, kg/kg
η_{boiler}	boiler efficiency
$\Delta C_{Operation}$	operation cost saved by the ASAHP, CNY

cooling system based on the coupling of parabolic trough collectors with a double-stage LiBr–H_2O absorption chiller. Economic analysis showed that the payback period is in the range of 12.0–27.0 years under most conditions. Borge-Diez et al. [12] studied a triple-state LiCl–H_2O absorption system with a power of 10 kW that was fully driven by solar thermal energy in Spain. The economic analysis showed that the internal rate of return reaches 12.45% while achieving a 68% reduction in greenhouse gasses emissions. Mateus and Oliveira [13] presented an economic analysis of an integrated solar absorption cooling and heating system in different building types and climates and found that total cost is actually high, even when extending the operation period as much as possible. To make solar cooling more competitive, it is necessary that the initial costs for absorption chillers and solar collectors are further reduced [14].

In the above economic analysis, the heating capacity is determined by the peak heating load of a building. However, the peak value usually occurs at a very low ambient temperature, and the performance of an ASAHP used in cold regions will deteriorate greatly as the ambient temperature decreases [15]. If the conventional design method is still used, the ASAHP has to be large enough to satisfy the heating demand in very cold conditions [16]. What is more, the price of ASAHP is expected to be much higher than that of the conventional electrical heat pump. Both these two factors will certainly lead to a high initial cost and an economic barrier to the application of this potential technology.

1.3. Objectives of this work

It is worth noticing that low ambient temperatures and high heating loads are actually of a low percentage during the entire heating season, which means that the ASAHP is oversized most of the time. A large percentage of the heating capacity of an ASAHP is designed simply to meet high heating loads over a very short time. Consequently, the payback period of this proposed heating system compared with conventional boilers may be too long. If the capacity of ASAHP is designed less than the maximum heating load, the initial cost may be decreased greatly, but the heating amount provided by ASAHP may be decreased only a little. Therefore, we can improve the economy of the proposed system by a better design of ASAHP capacity.

There is little research on the economic analysis of the heating systems based on an ASAHP, let alone on improving the economy of an ASAHP from the design perspective. This work is to present a techno-economic analysis of an ASAHP and to improve its economic feasibility from the design perspective. A year-round simulation of an ASAHP will be conducted to investigate the influence of design capacity on the energy saving rate (ESR) and payback period of an ASAHP, taking a gas boiler as the baseline heating system.

2. Methodology

2.1. The ASAHP heating system and the capacity design method

The studied heat supply system (as shown in Fig. 1) integrates the conventional boiler or district heating system with an ASAHP, with the conventional system acting as the driving source of the ASAHP, which then extracts low-grade heat from the ambient air to produce an increased capacity of demanded hot water [5]. The plate heat exchanger (PHX) in the conventional heating system is kept in this proposed system, installed in parallel with the ASAHP to provide direct heating (called PHX heating mode in this work) when the capacity of the ASAHP is insufficient or the ASAHP stops working.

It is assumed for simplification that: the system is in steady state; the refrigerant leaving the evaporator and condenser is saturated; the solutions at the outlet of the generator and absorber are both in equilibrium; the flow resistance, pressure losses and heat losses are all ignored; the throttling process is isenthalpic [17,18]. The mathematical models of the ASAHP can be built based on the mass and energy balance of each component [19,20]:

$$\sum m_{out} = \sum m_{in} \quad (1)$$

$$\sum m_{out}x_{out} = \sum m_{in}x_{in} \quad (2)$$

$$Q + \sum m_{out}h_{out} = \sum m_{in}h_{in} \quad (3)$$

$$Q = UA \cdot LMTD \quad (4)$$