



A new heating system based on coupled air source absorption heat pump for cold regions: Energy saving analysis



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ABSTRACT

Energy consumption for heating and domestic hot water is very high. The heating system based on an air source absorption heat pump (ASAHP) had been assessed to have great energy saving potential. However, the single-stage ASAHP exhibits poor performance when the outdoor air temperature is very low. A double-stage coupled ASAHP is proposed to improve the energy-saving potential of single-stage ASAHP in cold regions. The heating capacity and primary energy efficiency (PEE) of the proposed system operated in both coupled mode and single-stage mode are simulated under various working conditions. The building load and primary energy consumption of different heating systems applied in cold regions are analyzed comparatively to investigate the energy-saving potential of the coupled ASAHP. Results show that the coupled ASAHP exhibits stable PEE and provides high heating capacity in very cold conditions. The energy-saving rate of the coupled ASAHP in all the typical cities is above 20%. In addition, the energy-saving potential of the single-stage ASAHP in severely cold areas can be improved obviously by coupled ASAHP, with an improvement of 7.73% in Harbin.

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1. Introduction

1.1. Energy consumption and problems of traditional heat supply systems

Energy consumption for heating and domestic hot water is very high. In urban areas of north China, heating accounted for 23% of the total building energy consumption in 2008 and this was doubled from 72 million ton of standard coal equivalent (tce) in 1996 to 153 million tce in 2008 [1]. Regarding domestic hot water, the energy consumption in urban areas is about 28.1 million tce, accounting for up to 23.4% of the total building energy consumption in 2008 [1].

Traditionally, boiler is the most commonly used heating and domestic hot water system in cold regions [2]. In China, the coal boiler is still widely applied due to the coal-dominated energy structure [3]. However, the coal boiler is of low energy efficiency as well as high air pollution, which is regarded as one of the main sources of CO₂, SO₂, NO_x and particulate matters, such as PM_{2.5} and PM₁₀ [4–6].

1.2. Air source absorption heat pump (ASAHP) and its limitations

A heat supply system combining a conventional heating system with an air source absorption heat pump has been assessed to have

great potential in primary energy saving and emission reduction [7]. However, similar to the air source electrical heat pump (ASEHP) [8,9], the ASAHP exhibits poor performance or might not work when the outdoor air temperature is very low [10]. When the ASAHP cannot meet the heating demand, the boiler has to undertake the residual heating load. Consequently, the energy saving will be reduced in colder regions. Therefore, it is of great significance to improve the performance of ASAHP in cold and severely cold regions, just as is the case with ASEHP.

1.3. Research objectives on alternative heating systems

Regarding the ASAHP, there are few researches reported of its use for heating purposes, let alone its applicability to colder climates. In this work, a double-stage coupled ASAHP is proposed for heating purposes in cold regions. The coupled ASAHP can switch to a normal single-stage ASAHP when the ambient temperature rises to obtain higher efficiencies. In order to investigate the energy-saving potential of this novel heating system, the performance of the coupled ASAHP is simulated under various outdoor air temperatures. Then the energy-saving potential of the coupled ASAHP applied in typical cold cities is analyzed, taking the conventional coal boiler as a baseline heating system. In addition, the energy saving is compared with that of the single-stage ASAHP system, to ascertain the improvement contributed by the coupled ASAHP.

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Nomenclature

G	air volume flow rate, m ³ /s
h	specific enthalpy, kJ/kg
p	pressure, Pa
Q	heating load, kW
q	unit refrigeration capacity, kW/kg
V	fluid volume flow rate, m ³ /s
W	work consumption, kW

Abbreviations

AHP	absorption heat pump
ASAHP	air source absorption heat pump
COP	coefficient of performance
EHP	electrical heat pump
ESR	energy saving rate

LMTD	logarithmic mean temperature difference
PE	primary energy
PEE	primary energy efficiency
WSAHP	water source absorption heat pump

Subscripts

a	absorber
c	condenser
g	generator

Greeks

η	efficiency
ρ	density, kg/m ³
ε	refrigeration coefficient

2. Methodology

2.1. Description of double-stage coupled ASAHP

The double-stage coupled ASAHP is a hybrid system in which the condenser of the low temperature stage and the evaporator of the high temperature stage are connected through a middle water loop, as illustrated in Fig. 1. The ASAHP is located in the low temperature stage and a water source absorption heat pump (WSAHP) is placed in the high temperature stage.

In the operational mode of the coupled ASAHP, pump 1, valve 1 and valve 5 are open, while valves 2, 3 and 4 are closed. The heat production in the condenser of the low temperature stage (C1) becomes the heat source of the evaporator of the high temperature stage (E2). In this way, the condensation temperature of the low temperature stage is low and the evaporation temperature of the high temperature stage is high. Both the ASAHP in the low temperature stage and the WSAHP in the high temperature stage can operate efficiently, even when the air temperature is very low. The returned hot water is heated sequentially in the condenser (C2) and absorber (A2) of the high temperature stage and the absorber (A1) of the low temperature stage. When the air temperature increases, the heating performance of the single-stage ASAHP improves and can meet the building heating demand. Then, the double-stage coupled ASAHP can be switched to a single-stage ASAHP by opening valves 2, 3 and 4, while at the same time closing pump 1, valves 1 and 5. In this mode, the returned hot water is heated sequentially in the condenser (C1) and absorber (A1) of the low temperature stage.

In a coupled ASAHP heating system, both the heating safety in lower ambient temperatures and energy efficiency in higher ambient temperatures can be guaranteed by the mode switching.

2.2. Modeling and design of coupled ASAHP

In order to investigate the performance of the proposed heating system and to compare it with a conventional boiler system, mathematical models of the coupled ASAHP are developed. Based on these models, the heating capacity and energy efficiency of both the coupled ASAHP and the single-stage ASAHP under various air temperatures can be simulated.

2.2.1. Modeling of absorption heat pump

To simplify the model of the absorption heat pump (AHP), some reasonable assumptions should be made [11,12]:

- (1) the system is in steady flow and heat balance;
- (2) the refrigerant leaving the evaporator and condenser is saturated vapor and liquid, respectively;
- (3) the solutions leaving the generator and absorber are both saturated;
- (4) the flow resistance, pressure losses and heat losses in pipes and components are all ignored;
- (5) the throttling in the expansion valves are isenthalpic processes; and
- (6) the electricity consumption of water pumps is not included.

Based on these simplifications, the mathematical models of the ASAHP system can be built based on the mass and energy balance of each component [13,14], validated in previous work [7]:

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

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

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

$$Q = UA \cdot \text{LMTD} \quad (4)$$

where UA is the product of the heat transfer coefficient and the heat transfer area of each heat exchanger, and LMTD is the logarithmic mean temperature difference.

$\text{NH}_3\text{-LiNO}_3$ is used as the working fluid for both stages of the coupled ASAHP, owing to its advantages of low freezing point and lack of need of a rectifier [15,16]. The thermodynamic properties of the fluids are obtained from [17,18]. Coefficient of performance (COP) for heating is defined as the useful heat loads of the absorber and condenser divided by the required heat load of the generator. For the proposed system operated in coupled ASAHP mode:

$$\text{COP}_{\text{coupled ASAHP}} = \frac{Q_{c2} + Q_{a2} + Q_{a1}}{Q_{g1} + Q_{g2}} \quad (5)$$

For the proposed system operated in single-stage ASAHP mode:

$$\text{COP}_{\text{ASAHP}} = \frac{Q_{c1} + Q_{a1}}{Q_{g1}} \quad (6)$$

where Q_{a1} , Q_{c1} and Q_{g1} are the heat loads of the absorber, condenser and generator in the low temperature stage, and Q_{a2} , Q_{c2} and Q_{g2} are the heat loads of the absorber, condenser and generator in the high temperature stage.

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