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A FLEXIBLE SOLAR HEATING SYSTEM FOR SPACE HEATING IN WINTER AND PRODUCING LOW-PRESSURE STEAM IN NON-HEATING SEASONS

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ABSTRACT

Solar heating is a clean and promising way for space heating, however, the demand for low-temperature heat in non-heating seasons is very little, which also cause the extremely high cost of space heating. A flexible solar heating system is proposed in this paper, besides supplying heat in winter, it can upgrade low-temperature heat to process steam through a heat pump in non-heating seasons. The thermodynamic performance of the proposed system using in a textile mill is investigated. The system consists of a solar collector with an area of 120 m^2, a storage tank with a capacity of 50 kW and an ammonia compression-absorption heat pump with a capacity of 30 kW. The yearly natural gas saving and CO_2 emission reduction of the proposed system reaches 4957.64 m^3 and 5941.3 kg in total. The economic analysis turns out the investment would be recovered in 7.87 years, which is 54.13% less than that of the solar space heating system without an HP (14.17 years). Furthermore, the influences of the solar collector area, the capacity of the storage tank and heat pump on the proposed system are carried out.

Keywords: Solar energy, Space heating, Heat pump, Steam production

NONMENCLATURE

Abbreviations	
AESR	annual energy saving ratio, %
CER	CO_2 emission reduction
COP_h	heat coefficient of performance
HP	heat pump
NG	natural gas
SC	solar collector
SH	space heating
ST	storage tank
Symbols	
A	area, m^2
I_T	total radiation, kW/m^2
Q	Heat, kW
η	efficiency, %

1. INTRODUCTION

As reported by the international Energy Agency, China's original natural gas reserves are insufficient, and the import dependence reaches 30% of the total natural gas consumption. Using solar energy to replace natural gas for space heating and industry steam production is an important and promising way to ensure gas supply security and reduce CO_2 emission.

Usually the solar space heating systems only run during the winter, since the demand for low-temperature heat is little in non-heating seasons. This means that the running time of the solar space heating systems is very short, which leads to a poor economic performance. Seasonal storage for hot water is a way to overcome this problem, however, the energy storage capacity will be extremely large and there is still no seasonal storage for hot water available on market [1]. On the other hand the demands of low-pressure process steam is very large in industrial sectors such as textile mills and food mills. If the low-temperature heat generated by the solar space heating system can be upgraded to higher temperature heat, the running time can be extended significantly and the economic performance can be improved accordingly.

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A flexible solar heating system for space heating and steam production was proposed in this work. The model of the proposed system was constructed, and its thermodynamic performance was evaluated. The energy saving and CO_2 emission reduction in a year were also investigated.

2. SYSTEM DESCRIPTION

Fig. 1 shows the flow chart of the proposed system in this paper, which mainly contains four parts (the solar collectors, the storage tank, the heat pump and the auxiliary gas boiler). The heat pump is mainly consists of a rectifier, a compressor, a throttle valve, two pumps, three heat exchangers and an absorber, for more information can be seen in the previous work of authors [2]. The proposed system can be used to provide heat for space heating during the heating season and produce low-pressure steam for industry processes during the non-heating season. For space heating, the heating load first satisfied by the solar collector, then the storage tank, finally the auxiliary gas boiler. The surplus solar energy is stored in the storage tank. For steam production, the solar energy collected by the solar collector is first used to satisfy the heat pump for steam production, the surplus solar energy is stored in the storage tank, when the solar energy is insufficient, the solar energy sored in the storage tank as a supplement, then low down the heat pump load.

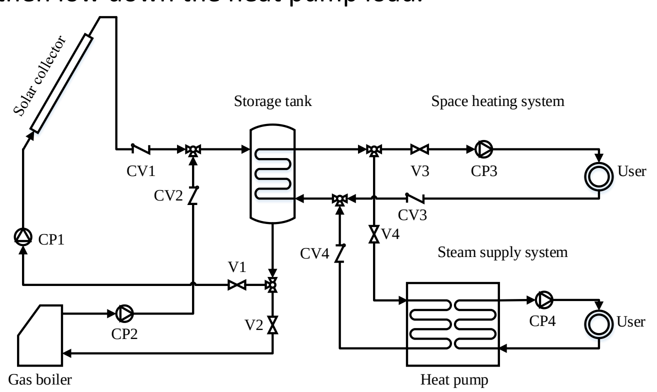

Fig. 1 Process diagram of the proposed multifunction system

3. MODEL AND SIMULATION

The solar energy collected by the solar collector can be calculated by:

$$Q_{SC} = I_T \cdot A_{SC} \cdot \eta_{SC} \tag{1}$$

where I_T, A_{SC} and η_{SC} refer to the total radiation, area and efficiency of the solar collector.

The hourly gas consumption of the auxiliary gas boiler can be determined by energy balance as follow:

$$Q_H = Q_{SH} - Q_{SC} - Q_{ST} \tag{2}$$

where Q_H, Q_{SH} and Q_{ST} refer to the heat load of auxiliary gas boiler, the heat demand for space heating and the heat stored in the storage tank, respectively.

The heat output of the proposed system during the non-heating season can be calculated by:

$$\begin{aligned}
&\text{if } (Q_{SC} + Q_{ST}) \cdot COP_h \ge Q_{HP,max} \\
&\qquad Q_{HP} = Q_{HP,max} \\
&\text{else} \\
&\qquad Q_{HP} = (Q_{SC} + Q_{ST}) \cdot COP_h \\
&\text{end}
\end{aligned} \tag{3}$$

where $Q_{HP,max}$ refers to the heat pump capacity, kW.

The heat sored in the storage tank can be calculated by:

$$\begin{aligned}
&\text{if } Q_{Req,i} \in (Q_{SC,i} + Q_{ST,i}, +\infty) \\
&\qquad Q_{ST,i+1} = 0 \\
&\text{else if } Q_{Req,i} \in (Q_{SC,i}, Q_{SC,i} + Q_{ST,i}) \\
&\qquad Q_{ST,i+1} = Q_{ST,i} - (Q_{Req,i} - Q_{SC,i}) \\
&\text{else if } Q_{Req,i} \in (Q_{ST,i} + Q_{SC,i} - Q_{ST,max}, Q_{SC,i}) \\
&\qquad Q_{ST,i+1} = Q_{ST,i} + Q_{SC,i} - Q_{Req,i} \\
&\text{else if } Q_{Req,i} \in (-\infty, Q_{ST,i} + Q_{SC,i} - Q_{ST,max}) \\
&\qquad Q_{ST,i+1} = Q_{ST,max} \\
&\text{end}
\end{aligned} \tag{4}$$

where $Q_{ST,max}$ refers to the storage tank capacity, kW. $Q_{Req,i}$ represents the space heating demand during the heating season or the heat pump rated heat demand during the non-heating season, kW.

The annual energy saving ratio (AESR) and the CO_2 emission reduction (CER) are considered to evaluate the thermodynamic performance of the proposed system. The former is defined as the ratio of the energy consumption of the proposed system decrease to the energy consumption of conventional individual systems for the same amount of products output:

$$\text{AESR} = \frac{F_{sp} - m_{NG} \cdot H_u}{F_{sp}} \tag{5}$$

where F_{sp} is the energy consumed by the conventional individual systems. m_{NG} and H_u are the natural gas mass flow and low calorific value, respectively.

The CER is calculated by:

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$$\mathrm{CER} = \Delta m_{\mathrm{NG}} \cdot f_{\mathrm{CO_2}} \quad (6)$$

where Δm_{NG} and $f_{\mathrm{CO_2}}$ are the natural gas consumption reduction and CO_2 emission factor, respectively.

The thermodynamic performance of the proposed system with a collector area of 120 m^2, storage tank capacity of 50 kW and heat pump capacity of 30 kW are carried out based on the weather data of Jinan, China. The proposed system is adopted to provide heat for space heating of an office building during the heating season, while for steam (130 °C) production for industry process during the non-heating season. The steady-state simulation of the system is performed by EES [3].

4. RESULTS AND DISCUSSION

4.1 Base case of the proposed system

In typical days (space heating for an office building in winter, while steam production for industry process in spring, summer and autumn), the heat output and the CER of the proposed system is presented in Fig. 2. The results show the heat output and CER of the proposed system have a big difference among the four seasons, this is mainly due to the variation of the ambient temperature and solar radiation throughout a year. The heat output during the winter typical day is lower than that during the summer typical day, however, the CER during the winter typical day is more than that during the summer typical day. This is because of the power consumption of the heat pump in the proposed system increased the CO_2 emission during the summer, which is not operated during the space heating mode.

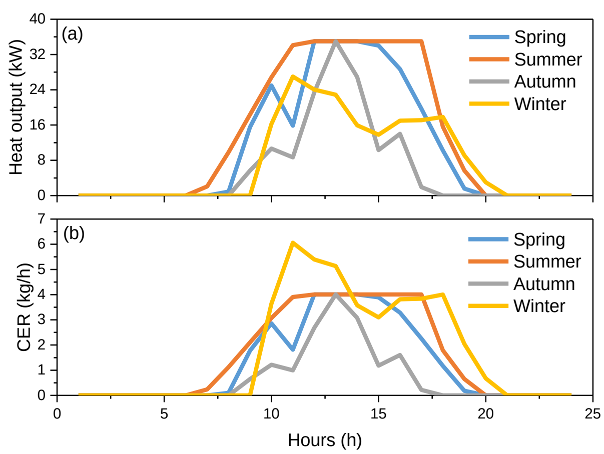

Fig. 2 Heat output and CO_2 emission reduction in typical days

During the heating season (15th November to next year 15th March), the heat demand for space heating is 13000 kWh, in which more than 50% is provided by solar collector. Meanwhile, the CER reaches 1521.3 kg. During the non-heating season, the heat output in the form of saturated steam at a temperature of 130 °C is 38609 kWh and the CER reaches 4420 kg. As a consequence, the yearly natural gas saving, the AESR and the CER of the proposed multifunction system reaches 4957.64 m^3, 51.29% and 5941.3 kg. Furthermore, the economic analysis is performed by the evaluation of the simple payback relating the extra investment required by proposed system with the economic savings offered by it. It turns out the investment would be recovered in 7.87 years, which is 54.13% less than that of the solar space heating system without an HP (14.17 years). Moreover, as the investment cost of the HP and the solar collectors are expected to decrease in the near future, the solution has potential for being even more profitable.

4.2 Parameters analysis

Several parameters (the A_{SC}, the $Q_{ST,max}$ and the $Q_{HP,max}$) which have a great influence on the yearly performance of the proposed system are discussed in this section.

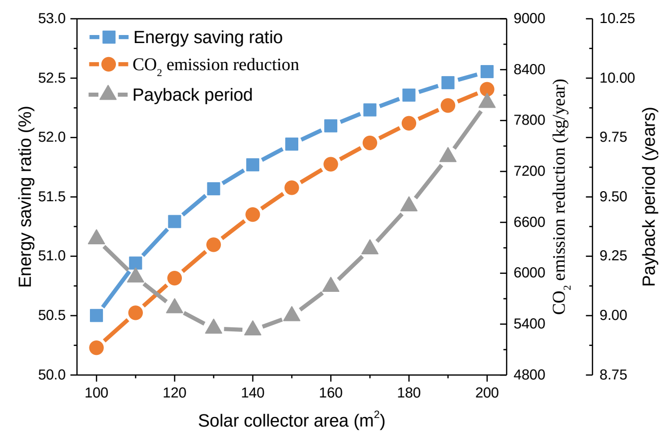

Fig. 3 The effect of the solar collector area

The influence of the A_{SC} on the AESR, the CER and the payback period (PBP) of the proposed system is presented in Fig. 3. Both the AESR and the CER increase with the increasing of the A_{SC}. This is because the larger the A_{SC} is, the less natural gas will be consumed during the heating season and the more steam will be produced during the non-heating season. However, the increasing speed decline with the A_{SC} further increases. This result comes from the limitation of the fixed capacity of the storage tank and heat pump, the effect of the A_{SC} on the AESR and the CER of the proposed system will gradually decrease till disappear. The PBP first decreases with the increasing of the A_{SC}, then increases. A shortest PBP of 8.94 years is obtained when the A_{SC} equals to 140 m^2.

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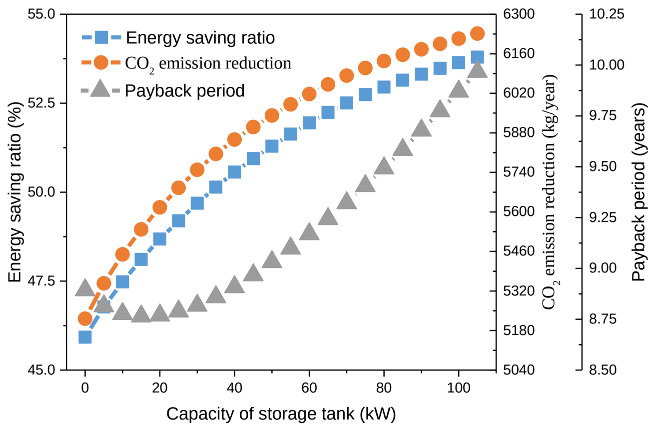

Fig. 4 The effect of the capacity of storage tank

The influence of the $Q_{ST,max}$ on the AESR, the CER and the PBP is presented in Fig. 4. Similar to the A_{SC}, the increasing of the $Q_{ST,max}$ lead to both the AESR and CER increase. This is because more solar energy will be stored in the storage tank when the solar energy is surplus, and less natural gas will be consumed for space heating and more steam will be produced when the solar energy is insufficient. The influence of the $Q_{ST,max}$ decrease with the increasing of the capacity. This is due to the A_{SC} and Q_{Req} are fixed, the peaking demand gradually decreases. The PBP first decreases with the increasing of the $Q_{ST,max}$, then increases. A shortest PBP of 8.76 years is obtained when the $Q_{ST,max}$ equals to 15 kW.

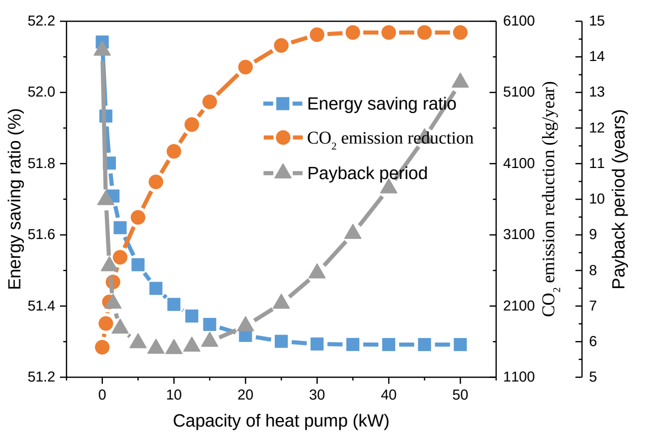

Fig. 5 The effect of the capacity of heat pump

The influence of the $Q_{HP,max}$ on the AESR, the CER and the PBP is presented in Fig. 5. The CER increases with the increasing of the $Q_{HP,max}$, however, the AESR decreases. As the $Q_{HP,max}$ increases, the steam produced during the non-heating season increases, so the CER increases. The AESR contains two parts, the ESR during the heating season and the ESR during the non-heating season. The former is larger than the latter, thus as with the increasing of the $Q_{HP,max}$, the AESR decreases. As the A_{SC} and $Q_{ST,max}$ are fixed, the existing energy cannot support the increased $Q_{HP,max}$ to produce more steam, the AESR and the CER of the proposed system will no longer change. The influence of the $Q_{HP,max}$ on the PBP is similar to that of the A_{SC} and the $Q_{ST,max}$, but is stronger.

5. CONCLUSIONS

A new solar energy based flexible system is developed in this paper, which mainly contains four parts (the solar collectors with an area of 120 m^2, the storage tank with a capacity of 50 kW, the heat pump with a capacity of 30 kW and the auxiliary gas boiler with a capacity of 40 kW). It can stably provide heat for space heating during in the heating season and saturated steam production during in the non-heating season. The thermodynamics performances of the proposed system is carried out through numerical simulations.

During the heating season, the heat output in the form of space heating is 13000 kWh, in which more than 50% is provided by solar collector. Meanwhile, the CER reaches 1521.3 kg. During the non-heating season, the heat output in the form of saturated steam at a temperature of 130 °C is 38609 kWh and the CER reaches 4420 kg. In total, the AESR and the CER of the proposed multifunction system reaches 51.29% and 5941.3 kg. The increase of the HP leads to a PBP reduction about 54.13% of the solar space heating system without an HP.

Furthermore, the influences of the solar collector area, the capacity of the storage tank and heat pump on the proposed system are carried out. The CER increases with all the increasing of the three parameters. The AESR increases with the former two, decreases with the last one. The cost of the proposed system is carried out based on the simple payback analysis, the PBP first increase then decrease with all studied factors.

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