International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 0829

A COMPARATIVE EXPERIMENTAL STUDY ON THE PERFORMANCE OF ABSORPTION HEAT TRANSFORMER FOR PRODUCTION OF WATER AND STEAM

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ABSTRACT

This study presents an experimental rig of single-stage heat transformer (SSHT), to compare its performances in case of producing high-temperature water (HTW) or low-pressure steam (LPS). SSHT was built with four vertical falling film heat exchangers using a LiBr-water binary working fluid and is driven by low-grade hot water. Bilateral falling film vertical absorber is adopted for production of HTW or LPS. Following the principle of single variable, the effects of temperature and flowrate of heating water on the useful output heat, coefficient of performance (COP) and gross temperature lift (GTL) of the vertical SSHT were tested, respectively. The results show that bilateral falling film made it easier for the absorber to generate HTW and LPS directly. In case of producing water or steam, temperature at inlet and flowrate of heating water have similar effect on the useful output heat and COP. To some extent, we can improve the performance of SSHT by increasing the temperature.

Keywords: vertical single-stage heat transformer, low-pressure steam, bilateral falling film absorber, coefficient of performance, gross temperature lift

NONMENCLATURE

Abbreviations	
COP	Coefficient of performance
GTL	Gross temperature lift, °C
SSHT	Single-stage heat transformer
Symbols	
c	Specific heat capacity, kJ kg^{-1} K^{-1}
h	Enthalpy, kJ kg^{-1}
m	Mass flow rate, kg h^{-1}
Q	Component heat load, kW
t	Temperature, °C
V	Volume flowrate, m^3 h^{-1}
ρ	Density, kg m^{-3}
Subscripts	
ABS	Absorber
CON	Condenser
EVA	Evaporator
GEN	Generator
HDW	Heated water
HW	Heating water
HTW	High-temperature water
LPS	Low-pressure steam
SW	Saturated water

1. INTRODUCTION

Heat-driven absorption heat transformers are promising devices to recover and upgrade industrial waste heat to higher temperature levels for industrial applications, which consume negligible primary energy [1]. To date, technology and research are largely based on the single-stage heat transformer (SSHT) cycle, which uses the combination of water and lithium bromide as working fluid, which can generally upgrade the waste heat by approximately 50 °C and achieve a coefficient of performance (COP) of 0.5 [2, 3].

In terms of the type of heat exchanger in the SSHT system, the shell-and-tube type of heat exchangers is the most common type. Horizontal and vertical heat exchangers are the two most common arrangements. Rivera et al. [4] built an experimental SSHT, whose condenser and evaporator were heat exchangers made of double concentric coil-shaped tubes, whereas the generator and absorber were shell-and-tube heat exchangers. In another study, Rivera et al. [5] developed an SSHT with a vertical shell-and-coil heat exchanger as the absorber and condenser. Sekar et al. [6] developed an experimental SSHT with one vertical shell-and-tube heat exchanger as the absorber, and three other exchangers were horizontal. Genssle and Stephan [6] analysed another SSHT using a vertical shell and helical coil tube heat exchanger as the absorber, and the other ones were compact braze plate heat exchangers. Ma et al. [7] built an SSHT using the vertical falling-film type heat exchangers as the evaporator, generator, and absorber, where the fluid flowed inside the vertical spiral tube. Ibarra-Bahena et al. [8] studied a new type of SSHT with plate heat exchangers as the main components.

The vertical falling-film heat exchanger has some advantages, such as smaller pressure drop in the falling film, higher heat transfer coefficient, and leak proof. In view of the above benefits, four main components of the experimental SSHT in this study adopted vertical falling-film heat exchangers, of which the absorber had bilateral falling film. Previous work has been performed to study the energy and exergy performance of the SSHT under off-design conditions [9, 10] and experimental test for different-level steam [11]. This paper aims to evaluate the comparative performance of an experimental vertical SSHT for production of high temperature or low-pressure steam.

2. THERMODYNAMIC CYCLE

A single-stage absorption heat transformer conventionally consists of an evaporator, a generator, an absorber, a condenser, an economizer, and some necessary pumps. A quantity of waste heat or low-grade heat Q_{GEN} was added to the generator at a relatively low temperature T_{GEN} to vaporize the working fluid from the weak salt solution. The vaporized working fluid flows into the condenser and delivers an amount of heat Q_{CON} at a reduced temperature T_{CON}. The liquid that leaves the condenser is pumped into the evaporator, where it is evaporated using a quantity of waste heat or grade heat Q_{EVA} at an intermediate temperature T_{GEN}. After the vapour flows into the absorber, it is absorbed by the strong salt solution at a relatively high temperature T_{ABS} and delivers an amount of heat Q_{ABS} to the heated water or another medium. Finally, the weak salt solution preheats the strong salt solution in the economizer before returning to the generator and starts another cycle.

3. EXPERIMENTAL SYSTEM

The vertical SSHT has a designed absorber heat capacity of 20 kW and is located in the Langfang R&D centre of the Institute of Engineering Thermophysics, Chinese Academy of Sciences. Fig 1 illustrates the diagram of the experimental vertical SSHT in this study. The absorption heat transformer is composed of four main vertical heat exchangers: vertical absorber, vertical generator, vertical evaporator and vertical condenser. When the heated water flows from the top and the falling film flows in the tube, it can perform double-sided falling film heat exchange with the solution outside the tube. Heat at higher temperature is produced by the vapour absorption into the strong solution and removed by the heated water from the heating source system. When the heated water flow rate is reduced to a certain extent, it can directly generate steam after being absorbed by the absorber. Fig 2 shows the distribution of liquid film of bilateral falling film absorber in case of producing high-temperature water and low-pressure steam.

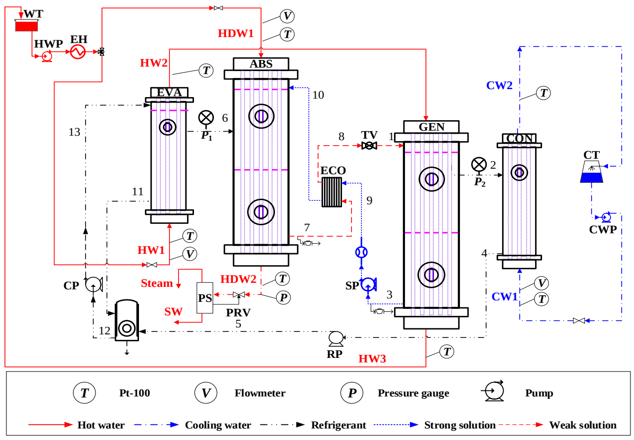
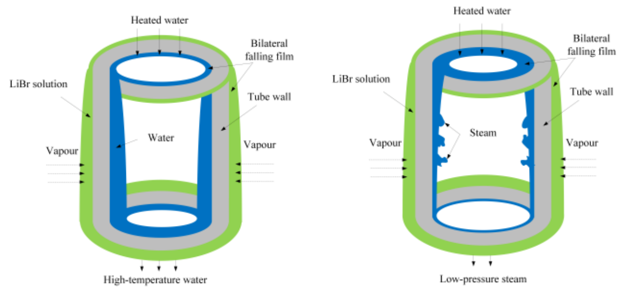


Fig 1 Diagram of the experimental SSHT in this study



(a) (b)

Fig 2 Distribution of liquid film of bilateral falling film absorber (a) HTW production (b) steam production

4. DATA REDUCTION

The external heats delivered to the evaporator and generator are

$$Q_{EVA} = \rho_{HW} V_{HW} c_{HW} (t_{HW1} - t_{HW2})/3600 \quad (1)$$

$$Q_{GEN} = \rho_{HW} V_{HW} c_{HW} (t_{HW2} - t_{HW3})/3600 \quad (2)$$

The external heat delivered from the condenser is

$$Q_{CON} = \rho_{CW} V_{CW} c_{CW} (t_{CW2} - t_{CW1})/3600 \quad (3)$$

Absorber is the place where high-temperature water or low-pressure steam is produced. The external heat delivered from the absorber, i.e., the useful output heat,

In case of producing high-temperature water,

$$Q_{ABS} = \rho_{HDW} V_{HDW} c_{HDW} (t_{HDW2} - t_{HDW1})/3600 \quad (4)$$

In case of producing low-pressure steam,

$$Q_{ABS} = \frac{m_{SW}(h_{SW} - h_{HDW1})}{3600} + \frac{m_{LPS}(h_{LPS} - h_{HDW1})}{3600} \quad (5)$$

Coefficient of performance (COP) represents the efficiency of an absorption heat transformer and is defined as follows:

$$COP = Q_{ABS}/(Q_{EVA} + Q_{GEN}) \quad (6)$$

Gross temperature life (GTL) reflects the ability of SSHT to upgrade the temperature of waste heat and is defined as

$$GTL = t_{HDW2} - t_{HW1} \quad (7)$$

5. RESULTS AND DISCUSSION

As source of the heating water, the low-grade waste heat from the process engineering or renewable energy is always inevitably instable. In this comparative experimental study, temperature at inlet and volume flowrate of heating water are chosen as two active variables.

5.1 Variable temperature of heating water at inlet

Figs 3 to 5 present the performances of SSHT when the heating water temperature at inlet changes. The initial and boundary conditions of experiments are listed in Table 1.

Table 1 Initial & boundary conditions of experiments

	Heating water		Cooling water		Heated water	
	t_{HW1}	V_{HW}	t_{CW1}	V_{CW}	t_{HDW1}	V_{HDW}
	°C	m^3/h	°C	m^3/h	°C	m^3/h
HTW	~	3.44	19.2	3.26	84.0	0.85
Steam	~	4.06	16.2	3.01	85.4	~

As can be seen in Figs 3 and 4, with the increase of the heating water temperature at inlet from 74.3 °C to 93.3 °C, the useful output heat increases from 1.23 kW@74.3 °C to 10.0 kW@91.0°C, together with COP from 0.12 to 0.32.

This is because the rising heating water temperature responds to a higher evaporator temperature. Higher evaporator temperature means larger pressure difference and stronger absorption capacity, which leads to higher useful output heat and higher COP.

By improving the heating water temperature, the system performance of the SSHT is improved. When the heating water temperature is increased to a certain extent (around 91.0 °C), the system performance is no longer enhanced, however.

In Fig 5, we can also see that the gross temperature lift decreases with the rise of the heating water temperature at inlet. On the condition of constant heated water flowrate and constant temperature at inlet, the increase rate of heated water at outlet is lower than that of heating water at inlet, thus making the temperature difference between them get smaller and smaller. In case of producing high-temperature water, after the heating temperature at inlet is over 93.3 °C, the GTL is close to 0, which means that the SSHT nearly loses the ability of lifting temperature. On the condition that the temperature of the heating water is much higher than that of the heated water, it is a better choice to use a heat exchanger rather than an SSHT system.

When the SSHT produces high-temperature water or low-pressure steam, the heat transfer coefficient of the absorber changes with variation of the heating water temperature at inlet. The decrease of the heated water flowrate in a certain range reduces the amount of heat exchange in the absorber. When the flowrate of the heated water decreases to a certain extent, the flow of heated water through in the tube of absorber is converted from convective heat transfer to falling film heat transfer.

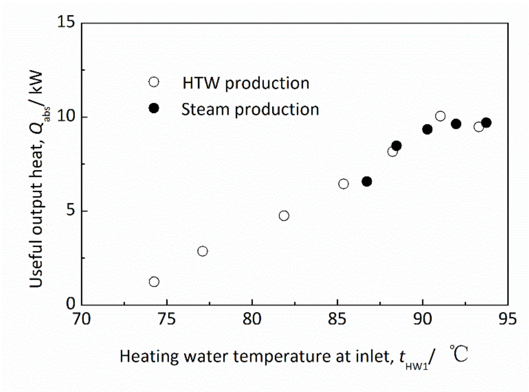


Fig 3 Useful output heat versus heating water temperature for production of HTW and steam

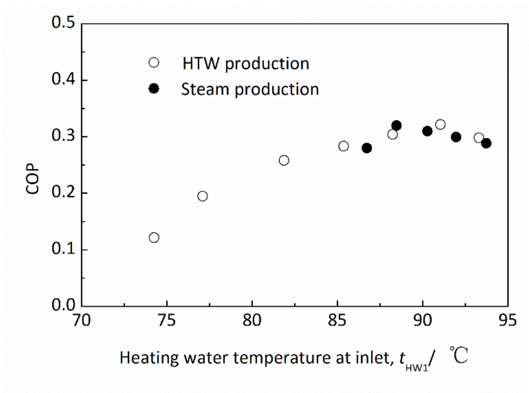


Fig 4 COP versus heating water temperature for production of HTW and steam

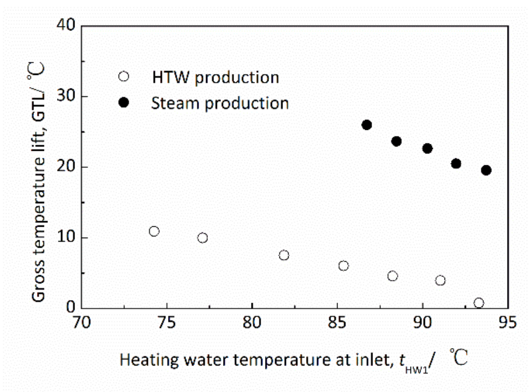


Fig 5 Gross temperature lift versus heating water temperature for production of HTW and steam

In addition, for the given initial condition, when the heating water temperature is lower than 86.7 °C, it is difficult for the SSHT to generate low-pressure steam. So, the generation of steam has certain requirements on the temperature of the heating water, and the temperature is too low to be detrimental to the production of low-pressure steam. Comprehensive consideration of system performance improvement and waste heat recovery should be taken when we increase the heating water temperature.

5.2 Variable volume flowrate of heating water at inlet

Figs 6 to 8 present the performances of SSHT when the heating water volume flowrate changes. The initial and boundary conditions of experiments are listed in Table 2.

Table 2 Initial & boundary conditions of experiments

	Heating water		Cooling water		Heated water	
	t_{HW1}	V_{HW}	t_{CW1}	V_{CW}	t_{HDW1}	V_{HDW}
	°C	m^3/h	°C	m^3/h	°C	m^3/h
HTW	87.7	~	16.0	3.33	86.5	0.88
Steam	91.8	~	16.2	3.04	88.9	~

As can be seen in Figs 6 to 7, with the heating water volume flowrate increasing from 1.5 m^3/h to 6.2 m^3/h, useful output heat increases from 7.5 kW to 14.8 kW, together with the COP from 0.37 to 0.45. Like the situation in 5.1, growing heating water volume flowrate means the increase of the evaporator temperature and higher maximum system pressure, which leads to a higher absorber temperature and heated water temperature at outlet, together with the absorber heat load. Meanwhile, in terms of the increase rate of heat capacity, the absorber is higher than the sum of the evaporator and the generator, thus increasing the COP of the system.

In Fig 8, we can see that the gross temperature lift decreases with the rise of the heating water volume flowrate in case of producing high-temperature water. As analyzed above, a rising heating water volume flowrate results in a higher heated water temperature at outlet, which enlarges the temperature difference between the heating water and heated water. In case of higher temperature needed, we can realize it by improving the heating water volume flowrate.

We can also see that the gross temperature lift is nearly independent of the variation of the heating water flowrate in case of generating low-pressure steam. Since the pressure regulating valve at outlet of the absorber is set to a fixed value, the corresponding temperature of low-pressure steam is also relatively fixed, resulting in the temperature difference, i.e., gross temperature lift, remaining unchanged. The increased useful output heat is transferred to the outside by increasing the amount of low-pressure steam.

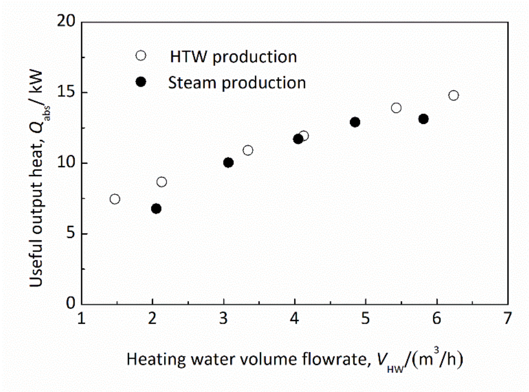


Fig 6 Useful output heat versus heating water volume flowrate for production of HTW and steam

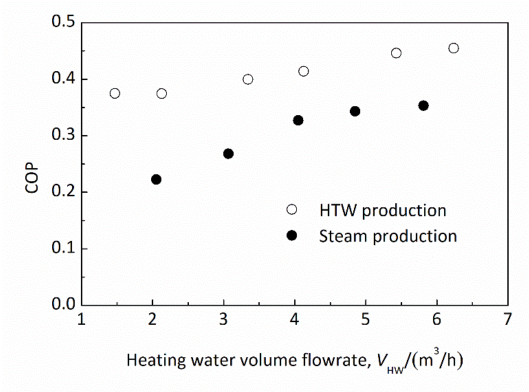


Fig 7 COP versus heating water volume flowrate for production of HTW and steam

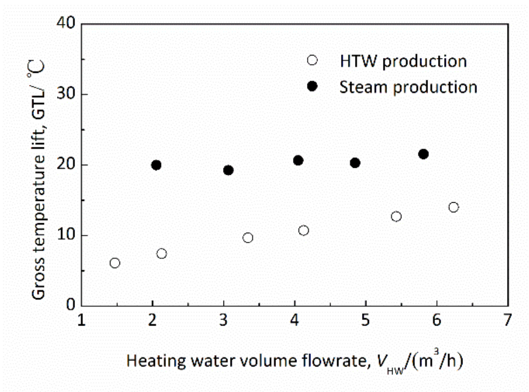


Fig 8 Gross temperature lift versus heating water volume flowrate for production of HTW and steam

We can improve the system performance by increasing the heating water flowrate within a certain range, but excessive flowrate may cause erosion corrosion of the heat exchange tube and thus shorten the lifespan of the system.

6. CONCLUSIONS

This study aims to present an experimental vertical SSHT system to compare its performances in case of producing high-temperature water or low-pressure steam. A series of experiments were carried out to study the influence of temperature and flowrate of the heating water on the useful output heat, COP, and gross temperature lift. Based on the experimental results, we can conclude that:

(1) Both of the temperature and flowrate of the heating water have similar effect on the useful output heat and COP of the SSHT. The useful output heat loads in case of producing low-pressure steam and high-temperature water are almost equal under the same initial boundary conditions, so are the COPs.

(2) We can improve the system performance by increasing the heating water temperature or flowrate within a certain range. Excessive low or high temperature and flowrate influence the performance improvement. Comprehensive consideration of system performance improvement and waste heat recovery should be taken when we increase the heating water temperature or flowrate.

(3) Vertical bilateral falling film absorber makes it easier to produce low-pressure steam under small flowrate of heated water. We can adjust the product flexibly according to actual needs.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the support by the National Key R&D Program of China (No. 2018YFB0905101), the National Natural Science Foundation of China (No. 51806213) and Guangdong Provincial Key Laboratory of Distributed Energy Systems (No. 2017DES05).

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