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# Solar-air hybrid source heat pump water heater: Performance characterization and comparison analysis

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**Abstract.** Heat pump water heater (HPWH) can yield great energy saving for commercial and residential appliance. To enable the HPWH maintain efficient operation under diverse circumstances, the solar-air hybrid source heat pump water heater has been proposed. The configurations of solar-air series type, air-solar series type and solar-air parallel type have been discussed and compared in this paper. The dynamic model has been developed to identify the impacts of solar irradiation and environmental temperature. The results show that the solar-air hybrid source heat pump water heater can guarantee efficient operation under the ambient temperature of 10°C and solar irradiation of 100W/m<sup>2</sup>, with the average COPs of 2.68 for solar-air series type HPWH, 2.71 for air-solar series type HPWH and 2.69 for solar-air parallel type HPWH. The rise of ambient temperature can improve the evaporating capacity and condensing capacity leading to the increase of power consumption and COP for each type of solar-air hybrid source heat pump water heater. With the rise of solar irradiation, the heat gain at evaporation side increases leading to the rise of condensing capacity and COP. The air-solar series type HPWH can achieve the highest COP under a range of working conditions and solar-air parallel type HPWH can provide the highest condensing capacity under lower solar irradiation.

**Keywords:** solar energy, hybrid source, air source, heat pump

## 1. Introduction

The power consumed by water heating takes over 30% of the overall energy consumption in building [1]. With the rising requirement for building energy saving, the efficiency improvement of domestic water heating has become increasingly significant. Heat pump water heater (HPWH) brings great energy conservation potential by recovering energy from low grade heat source [2].

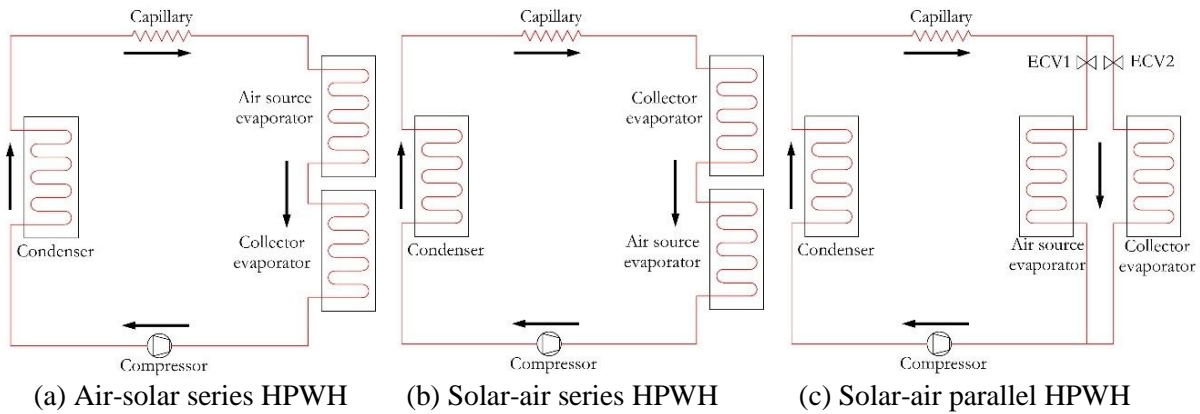
To raise the stability and efficiency of the HPWH system, hybrid source heat pump system with multi-source acting as the complementary has been developed. Chargui et al. developed a dual source heat pump applied in building with the air evaporator and water evaporator working alternately [3, 4]. Qu et al. analysed the behaviour of a dual source heat pump integrated with PV/T experimentally, and the results suggested that the air-water mode should be adopted under lower solar irradiation [5]. Wang et al. proposed a dual source heat pump system utilizing a three-medium composite evaporator modified from tube-fin heat exchanger, which can recover energy from the water and environment [6]. Han et al. reported a multi-source coupled heat pump system which was capable to operate efficiently and continuously in cold region [7]. On this basis, the seasonal thermal storage was applied in the above system to balance the output characteristics of system and the variation of building load [8]. Ahn et al. compared the heating and dehumidification performance of heat pump, air conditioner and dual evaporator heat pump for cabin, and the dual source configuration exhibited the optimal performance [9, 10]. Zou et al. designed a dual-parallel-evaporator heat pump with two evaporators connected in parallel for the thermal management of electric vehicle [11]. Besides, the similar configuration was used as for water heating with air source and solar energy acting as heat source [12, 13]. Liu et al.



tested the operation performance of a multi-functional heat pump, which has four different heat source combinations: water source, air source, water source and air source in series, and water source and air source in parallel [14]. It is proven that applying hybrid heat source in vapor compression heat pump system is an effective way to realize stable and economical operation. However, it may lead to complicated structure or complex control strategy, which brings limitation in practical application. In this paper, the performance of air-solar series type, solar-air series type and solar air parallel type hybrid source heat pump water heater is discussed and compared to identify the effect of ambient temperature and solar irradiation.

## 2. System description

The configurations of solar-air hybrid source heat pump water heater discussed in this paper include air-solar series type, solar-air series type and solar-air parallel type, as shown in Fig. 1. The main components of solar-air hybrid source heat pump include collector evaporator, air source evaporator, compressor, capillary and condenser. In series type, the refrigerant gets vaporized in air source/collector evaporator and collector/air source evaporator in sequence. The electric control valve(ECV) is utilized to adjust the flow distribution in the evaporators of the parallel type. The solar collector (with total area of 4.20 m<sup>2</sup>) without any glazing or back insulation was used as evaporator for the refrigerant. The water tank with immersed condensing coil acts as the condenser. The air source evaporator is a finned tube heat exchanger.



**Fig 1.** The schematic of solar-air hybrid source heat pump water heater

## 3. Modelling and evaluation

### 3.1 Mathematical modelling

For collector evaporator

The energy balance equation for the refrigerant pipeline is:

$$\rho_p c_p \frac{\partial T_p}{\partial t} = k_p \frac{\partial^2 T_p}{\partial z^2} + \frac{1}{A_p} \left[ \pi D_{p,i} \alpha_{ref,p} (T_{ref} - T_p) + W \alpha_{a,p} (T_a - T_p) + \beta G W \right] \quad (1)$$

$\rho_p$ ,  $c_p$ ,  $k_p$ ,  $T_p$ ,  $A_p$  and  $D_{p,i}$  are the density, specific heat, heat conductivity, temperature, cross section area and inner diameter of the refrigerant pipe respectively,  $W$  is the tube pitch of collector evaporator,  $G$  is the solar irradiation,  $\alpha_{ref,p}$  is the convective heat transfer coefficient between the refrigerant and pipeline,  $\alpha_{a,p}$  is the convective heat transfer coefficient between the air and pipeline,  $T_a$  and  $T_{ref}$  are the temperatures of the ambient and refrigerant respectively,  $\beta$  is the absorptivity of collector evaporator.

For air source evaporator

The energy balance equation for the refrigerant pipeline is:

$$\rho_p c_p \frac{\partial T_p}{\partial t} = k_p \frac{\partial^2 T_p}{\partial z^2} + \frac{1}{A_p} \left[ \pi D_{p,i} \alpha_{ref,p} (T_{ref} - T_p) + \pi D_{p,o} \alpha_{a,p} (T_a - T_p) \right] \quad (2)$$

$D_{p,o}$  is the outer diameter of the refrigerant pipe.

For compressor

The mass flow rate of refrigerant can be concluded as:

$$\dot{m}_{ref,com} = \eta_v \frac{nV_{com}}{v_{suc}} \quad (3)$$

$V_{com}$ ,  $n$  and  $\eta_v$  are the displacement, rotating speed and the volumetric efficiency of compressor respectively,  $v_{suc}$  is the specific volume of refrigerant at the suction of compressor.

The power consumed by compressor is given as [33]:

$$P_{com} = n \frac{p_{suc} V_{com}}{\eta_{com}} \frac{\gamma}{\gamma-1} \left[ \left( \frac{p_{dis}}{p_{suc}} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \quad (4)$$

$\eta_{com}$  is the total operation efficiency of compressor,  $\gamma$  is the polytropic index,  $p_{suc}$  and  $p_{dis}$  are the suction and discharge pressures respectively.

In compressor, the refrigerant is compressed into the vapor with high temperature and pressure, which causes the temperature rise of the compressor cylinder and the heat loss to environment. Therefore, the energy balance equation of compressor is:

$$M_{com} c_{com} \frac{\partial T_{com}}{\partial t} = P_{com} - \dot{m}_{ref,com} (h_{com,out} - h_{com,in}) - U_{com} A_{com} (T_{com} - T_a) \quad (5)$$

$M_{com}$ ,  $c_{com}$ ,  $T_{com}$  and  $A_{com}$  are the mass, specific heat, temperature, and external surface area of compressor respectively,  $U_{com}$  is the total heat transfer coefficient between the compressor and the environment.

For capillary

In the capillary, the throttling process is taken as isenthalpic, and the mass flow rate of refrigerant is determined by the length ( $L_{cap}$ ) and inner diameter ( $D_{cap,i}$ ) of the capillary, the subcooled temperature ( $\Delta T_{cap,in}$ ) and the condensing temperature ( $T_{con}$ ), given as [18]:

$$\dot{m}_r = C_1 D_{cap,i}^{C_2} L_{cap}^{C_3} T_{con}^{C_4} 10^{C_5 \times \Delta T_{cap,in}} \quad (6)$$

$C_1 \sim C_5$  are the empirical constant.

In condenser, the energy balance equation of condensing coil is:

$$\rho_p c_p \frac{\partial T_p}{\partial t} = k_p \frac{\partial^2 T_p}{\partial z^2} + \frac{1}{A_p} \left[ \pi D_{p,i} \alpha_{ref,p} (T_{ref} - T_p) + \pi D_{p,o} \alpha_{w,p} (T_w - T_p) \right] \quad (7)$$

$T_w$  is the temperature of the condensing water,  $\alpha_{w,p}$  is the convectively heat transfer coefficient between the condensing coil and condensing water.

For the condensing water, the energy balance equation is:

$$M_w c_w \frac{\partial T_w}{\partial t} = A_{con} U_{con} (T_a - T_w) + A_{p,o} \alpha_{w,p} (T_p - T_w) \quad (8)$$

$M_w$  and  $c_w$  are the mass and specific heat of condensing water respectively,  $A_{con}$  is the external surface area of the water tank,  $U_{con}$  is the total heat transfer coefficient between the water tank and ambient.

### 3.2 Performance evaluation

The evaporating capacity in collector evaporator is:

$$Q_{eva, coll} = \dot{m}_{ref, coll} (h_{coll, out} - h_{coll, in}) \quad (9)$$

$h_{coll, out}$  and  $h_{coll, in}$  are the specific enthalpies at the outlet and inlet of the collector evaporator respectively.

The evaporating capacity in air source evaporator is:

$$Q_{eva, air} = \dot{m}_{ref, air} (h_{air, out} - h_{air, in}) \quad (10)$$

$h_{air, out}$  and  $h_{air, in}$  are the specific enthalpies at the outlet and inlet of the air source evaporator respectively.

The condensing capacity can be calculated by:

$$Q_{con} = \dot{m}_{ref, con} (h_{con, in} - h_{con, out}) \quad (11)$$

$h_{con,out}$  and  $h_{con,in}$  are the specific enthalpies at the outlet and inlet of the condenser respectively.

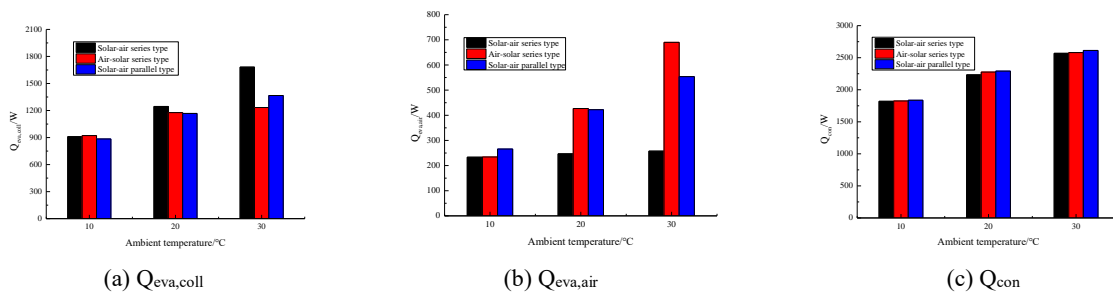
For the SA-HPWH system, the performance of coefficients (COP) is:

$$COP = \frac{Q_{con}}{P_{com}} \quad (12)$$

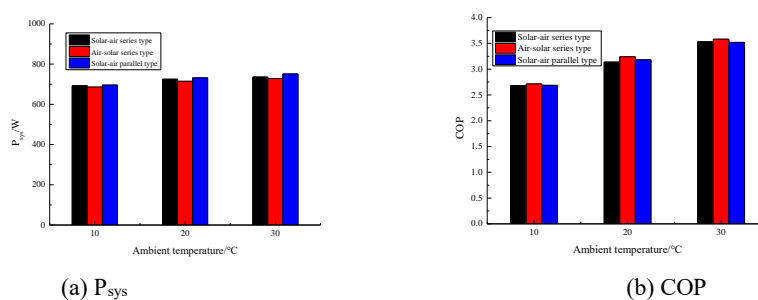
## 4. Results and discussions

### 4.1. Impact of ambient temperature

The performance of solar-air series type, air-solar series type and solar-air parallel type HPWH has been compared at the ambient temperature of 10°C, 20°C and 30°C with the solar irradiation of 100W/m<sup>2</sup>, as shown in Fig. 2~3. It can be observed that the evaporating capacities in air source evaporator and collector evaporator increase with the rise of ambient temperature. The evaporating capacity of collector evaporator is the highest in solar-air series type HPWH, and the evaporating capacity of air source evaporator is the highest in air-solar series HPWH. Similarly, the condensing capacity increases with the rise of ambient temperature. With the ambient temperature rising from 10°C to 30, the average condensing capacity increases from 1819.97W to 2568.14W for solar-air series type HPWH, rises from 1825.42W to 2579.33W for air-solar series type HPWH, and increases from 1836.65W to 2613.45W for solar-air parallel type HPWH. It can be concluded that the solar-air parallel type HPWH can obtain the highest condensing capacity at the solar irradiation of 100W/m<sup>2</sup>.



**Fig 2.** The comparison of evaporating capacity and condensing capacity at specified ambient temperature



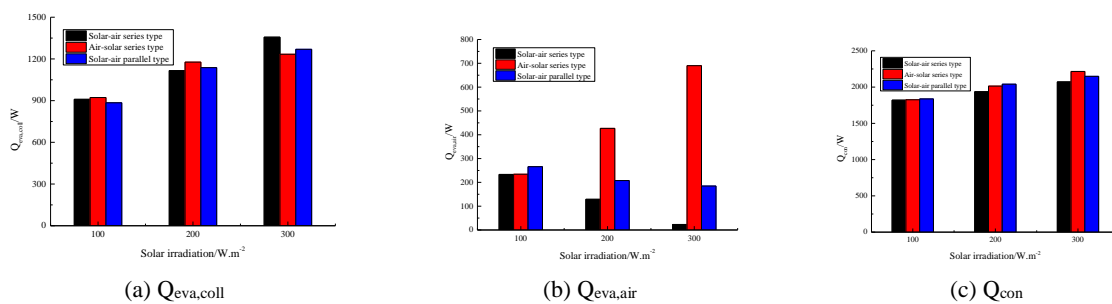
**Fig 3.** The comparison of power consumption and COP at specified ambient temperature

The power consumption in each type of HPWH is approximative and increases with the rise of ambient temperature. With the ambient temperature rising from 10°C to 30°C, the average power consumption increases from 691.92W to 735.50W for solar-air series type HPWH, increases from 685.91W to 728.36W for air-solar series type HPWH, and increases from 695.62W to 750.88W for solar-air parallel type HPWH. Due to the rise of pressure ratio caused by the increase of ambient temperature, the COP in each type of HPWH increases with the rise of ambient temperature. With the ambient temperature rising from 10°C to 30, the average COP increases from 2.68 to 3.53 for solar-air series type HPWH, increases from 2.71 to 3.58 for air-solar series type HPWH, and increases from 2.69 to 3.52 for solar-air parallel type HPWH. It can be concluded that the air-solar series type HPWH can obtain the highest COP at the solar irradiation of 100W/m<sup>2</sup>.

#### 4.2. Impact of solar irradiation

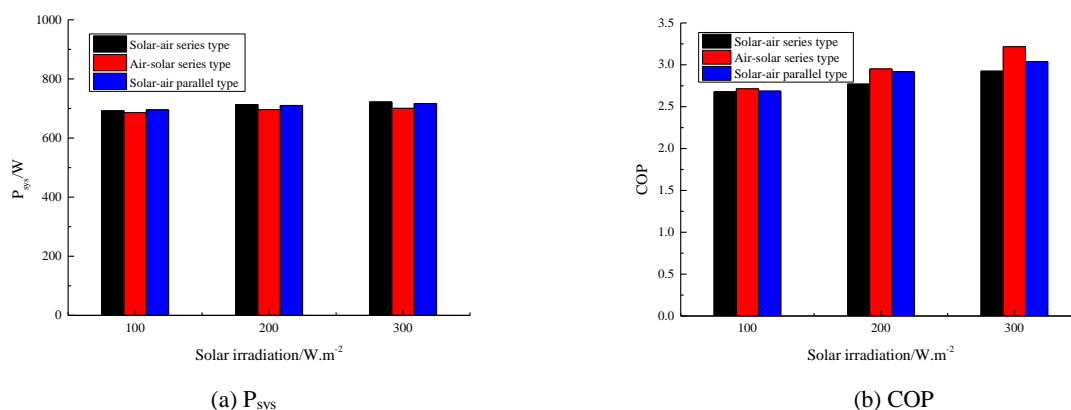
The performance of solar-air series type, air-solar series type and solar-air parallel type HPWH has been compared at the solar irradiation of  $100\text{W/m}^2$ ,  $200\text{W/m}^2$  and  $300\text{W/m}^2$  with the ambient temperature of  $10^\circ\text{C}$ , as shown in Fig. 4~5.

It can be observed that the evaporating capacity in collector evaporator and the condensing capacity increase with the rise of solar irradiation. In air-solar series type HPWH, higher solar irradiation can improve the evaporating capacity in air source evaporator, while it plays the opposite role for solar-air series type HPWH and solar-air parallel type HPWH. With the solar irradiation rising from  $100\text{W/m}^2$  to  $300\text{W/m}^2$ , the average condensing capacity increases from  $1819.97\text{W}$  to  $2071.46\text{W}$  for solar-air series type HPWH, the average condensing capacity increases from  $1825.42\text{W}$  to  $2215.45\text{W}$  for air-solar series type HPWH, and the average condensing capacity increases from  $1836.65\text{W}$  to  $2147.98\text{W}$  for solar-air parallel type HPWH. It can be concluded that the air-solar series type HPWH can obtain the highest condensing capacity at the ambient temperature of  $10^\circ\text{C}$ .



**Fig 4.** The comparison of evaporating capacity and condensing capacity at specified solar irradiation

The power consumption increases with the rise of solar irradiation, and air-solar series type HPWH consumes the least power. With the solar irradiation rising from  $100\text{W/m}^2$  to  $300\text{W/m}^2$ , the average power consumption increases from  $691.92\text{W}$  to  $722.12\text{W}$  for solar-air series type HPWH, increases from  $685.91\text{W}$  to  $700.62\text{W}$  for air-solar series type HPWH, and increases from  $695.62\text{W}$  to  $716.50\text{W}$  for solar-air parallel type HPWH. The COP in each type of HPWH increases with the rise of solar irradiation. With the solar irradiation rising from  $100\text{W/m}^2$  to  $300\text{W/m}^2$ , the average COP increases from 2.68 to 2.92 for solar-air series type HPWH, increases from 2.71 to 3.32 for air-solar series type HPWH, and increases from 2.69 to 3.04 for solar-air parallel type HPWH. It can be concluded that the air-solar series type HPWH can obtain the highest COP at the ambient temperature of  $10^\circ\text{C}$ .



**Fig 5.** The comparison of power consumption and COP at specified solar irradiation

#### 5. Conclusion

In this paper, the solar-air hybrid source heat pump water heater with solar-air series, air-solar series and solar-air parallel configurations has been discussed and compared. The dynamic model has been

developed to identify the impacts of solar irradiation and environmental temperature. The conclusion has been summarised as follows:

- Solar-air hybrid source heat pump water heater can guarantee efficient operation under the ambient temperature of 10°C and solar irradiation of 100W/m<sup>2</sup>, with the average COPs of 2.68 for solar-air series type HPWH, 2.71 for air-solar series type HPWH and 2.69 for solar-air parallel type HPWH.
- The ambient temperature can improve the evaporating capacities of air source evaporator and collector evaporator leading to the rise of condensing capacity. The pressure ratio increases with the rise of ambient temperature leading to the increase of power consumption and COP for each type of solar-air hybrid source heat pump water heater.
- In air-solar series type HPWH, higher solar irradiation can improve the evaporating capacity in air source evaporator, while it plays the opposite role for solar-air series type HPWH and solar-air parallel type HPWH. As the overall heat gain at the evaporating side increases with the rise of solar irradiation, the COP of each type of HPWH increases with the rise of solar irradiation.
- It can be concluded that the air-solar series type HPWH can achieve the highest COP under a range of working conditions and solar-air parallel type HPWH can provide the highest condensing capacity under lower solar irradiation.

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