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Heating Performance of Solar Heat Pump Heating System With Aluminum Tube Collector

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ABSTRACT A solar heat pump heating system with an aluminum tubular collector is proposed in this paper. Mathematical models are established for solar energy absorption and air energy absorption of the aluminum tubular collector, as well as the heat-absorption coefficient of the working substance. The electronic expansion valve is controlled via the fuzzy PID method to adjust the working substance flow rate, as well as to control the evaporator overheating and set the indoor heating temperature. TRNSYS is used to analyze the effects of the wind speed, solar radiation amount, environment temperature, and working substance flow rate on the heat transfer performance of the aluminum tubular collector. The results indicate that the heat transfer performance of the aluminum tubular collector is significantly affected not only by the solar radiation but also the wind speed. For wind speed > 2 m/s, the absorbed power of the collector increases rapidly with an increase in the wind speed; when the working-medium flow rate reaches 4 m/s, the collector absorption power tends to be saturated. Subsequently, an experimental heating system with a heating area of 170 m^2 is constructed. Experiments revealed that the maximum coefficient of performance (COP) of the heating system is 4.46, and the average COP value is 3.95, indicating good heating effect.

INDEX TERMS Aluminum tube collector, coefficient of performance, heating system, heating transfer property, solar heat pump.

I. INTRODUCTION

Under the dual pressure of energy transition and environmental pollution,comprehensive utilization of renewable energy is the direction for the development of a diversified clean energy system [1], [2].As the main of renewable energy,solar energy has been widely used in light-electricity, light-heat, photochemical and so on. In recent years, the use of solar heat pumps for heating has become a popular research topic in the field of solar thermal utilization. Solar energy heat pump heating technology uses solar energy as the low temperature heat source of heat pump system to realize building heating [3]–[5].

JODAN *et al.* proposed the idea of combining solar energy and a heat pump for heating and verified the feasibility of solar heat pump operation through experimental research, laying a research foundation for the development of solar heat pump heating [6]. Subsequently, numerous solar heat pump projects were initiated in the United States, Japan, Europe and other countries, ranging from small-scale hot water supply to large-scale seasonal heating for residents, which further promoted the development of solar heat pump technology [7]–[9].

As the main energy source of solar heat pump system, collector is one of the core devices of solar heat pump system. Its heat collection performance will have a huge impact on COP (coefficient of performance), so many scholars have done a lot of research on solar heat pump collector, especially flat plate collector.

ARINZE *et al.* used dynamic numerical model to study the heat transfer performance of flat plate collector with glass cover [10]. FIJITAF *et al.* studied the performance of the heat pump system with cover plate collector / evaporator by experiments [11]. Bare flat plate collector has been widely studied because it can absorb solar energy and air energy at the same time. ZHU *et al.* compared the heat pump system with cover

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plate collector and bare flat plate collector, and concluded that the performance of bare flat plate collector is better [12]. ITO *et al.* carried out experimental research on the relationship between evaporation temperature and system performance of bare flat plate collector [13]. CHATA *et al.* studied the effect of refrigerant on the performance of bare flat plate collector heat pump system [14]. HAWLADER *et al.* used experiments to analyze the impact of bare plate collector area on system performance [15]. KONG *et al.* analyzed the annual operating characteristics of the bare flat plate collector heat pump system by establishing a dynamic numerical model, and analyzed the influence of different environmental parameters on the performance of the bare flat plate collector [16].

In addition, the development of solar collectors with better performance is also a hot topic in recent years. SAHU *et al.* carried out numerical simulation on a solar collector / evaporator with inclined fins [17]. SUN *et al.* measured the thermal performance of T-type and honeycomb type bare flat plate collector / evaporator heat pumps based on channel optimization [18]. JI *et al.* carried out numerical modeling and analysis for the proposed PV / T collector, and verified the effectiveness of the model through experiments [19]. ZHOU *et al.* proposed a new type of heat pump system based on the micro-channel PV/T collector and analyzed its performance through experiments [20]. Although these new collectors improve the collector performance to some extent, they generally have the disadvantages of complex structure and difficult operation and maintenance, and their service life is not guaranteed because of the lack of long term operation data. Based on the above reasons, this paper proposes an aluminum tube collector, which retains the advantages of bare flat plate collector that can absorb solar energy and air energy at the same time, and has the characteristics of simple structure and convenient operation and maintenance. It is a type of collector that can be used on a large scale at present.

In this paper, the collector module of transient simulation software TRNSYS is used to analyze the influence of environmental factors on the collector performance. At the same time, through building the experimental system of building heating heat pump, the operation characteristics of the system are studied by using the fuzzy PID control method, and the feasibility and effectiveness of the system are verified.

II. EQUIPMENT AND METHODS DESCRIPTION

A. ALUMINUM TUBE COLLECTOR

As shown, different from the traditional flat plate collector, it without light transmission and thermal insulation materials, and is directly exposed to the atmosphere, which is the energy input of solar heat pump for heating. The solar energy and air energy can be absorbed simultaneously through the absorption coating on the surface of the collector and the temperature difference between the working medium in the tube and the environment. The aluminum tubular collector analyzed here is composed of several single pipes having an inner diameter 21mm and has an outer diameter of 25mm, a fin thickness of 1 mm, and a fin length of 150 mm. A pipe and a fin form a single pipe having a total width of 325mm.Two single pipes are connected by an elbow of the same material, forming a U-pipe.

B. PERFORMANCE ANALYSIS METHOD FOR COLLECTOR

TRNSYS is a flexible modular transient system simulation software. The main application areas include: building energy saving optimization, building energy supply system, air conditioning system and optimization, etc. The collector module is developed by TRNSYS software for various types of collectors. The performance simulation of the collector can be realized by selecting the structure and setting the parameters. TRNSYS software is used to analyze the performance of the aluminum tube collector, and the total heat collection is:

$$Q = Qs + Qa \tag{1}$$

where Q represents the total heat of the collector (in W); Q_s represents the solar energy absorption of the collector(in W); Q_a represents the air energy absorption of the collector(in W).

If the system operates in steady state, the total heat collected by the collector can be expressed as:

$$Q = cm(Tin\text{-}Tout) \tag{2}$$

where c represents the specific heat capacity of the working medium of the heat pump cycle(in J/(kg·K)); m represents the flow rate of the working medium of the heat pump(in kg/h); Tin and Tout represent the inlet and outlet temperatures of the working medium of the collector(in K).

C. SOLAR ENERGY ABSORPTION

The solar energy absorption of the collector is mainly determined by two factors: the collector absorbs the direct radiation and dissipates the heat radiation. Under steady state conditions, the corresponding mathematical model is expressed as follows::

$$Q_s = Q_b + Q_d \tag{3}$$

where Q_s represents the solar energy absorption of collector(in W); Q_b represents the direct radiation absorbed by collector(in W).Q_d represents the scattered radiation absorbed by collector(in W).

As reported by KONDRATYEV, Q_s can be expressed as follows [21], [22]:

$$Q_s = I_b R_b + I_d R_d (1 - \cos\beta)/2 + \rho I_g (1 - \cos\beta)/2 \tag{4}$$

where I_b, I_d and I_g represent the normal direct radiation intensity, scattered radiation intensity and total radiation intensity of horizontal plane(in W/m^2); ρ represents the reflection coefficient of the collector installed on the ground; R_b represents the ratio of the direct radiation of the inclined plane and the horizontal plane in unit time;R_d represents the ratio of the scattered radiation on the inclined plane to that on the horizontal plane in unit time;β represents the collector tilt angle(in °C);

R_b, R_d can be calculated by the following formula:

$$R_b = \cos\theta / \cos\theta z \tag{5}$$

$$R_d = (2 + \cos\beta)/3 \tag{6}$$

where θ represents the angle of incidence;θz represents the zenith angle.

D. AIR ENERGY ABSORPTION

The air absorption capacity of an aluminum exhaust collector is mainly carried out by the convective heat transfer at the top and bottom, as follows:

$$Q_a = Q_{conv,t} + Q_{conv,b} \tag{7}$$

where Q_a represents the air absorption capacity (in kJ/hr); $Q_{conv,t}$ represents the convective heat transfer at the top of the collector (in kJ/hr), and $Q_{conv,b}$, represents the convective heat transfer at the bottom of the collector (in kJ/hr).

The convective heat transfer between the top and bottom of the collector is calculated as follows:

$$\begin{cases} Q_{conv,t} = A_a h_{t,conv}(T_e - T_{fpc}) \\ Q_{conv,b} = A_a h_{b,conv}(T_e - T_{fpc}) \end{cases} \tag{8}$$

where $h_{t,conv}$ is the convection heat-transfer coefficient at the top (in kJ/(hr·m^2·K));$h_{b,conv}$ is the convection heat transfer coefficient at the bottom (in kJ/(hr·m^2·K)); T_{fpc} represents the surface average temperature of the collector (in K), and T_e represents the temperature of the environment (in K).

In actual operation,the convective heat transfer between the collector surface and the environment includes both natural convection and forced convection, which belongs to mixed convection.If the aluminum tube collector is simplified as a flat plate collector, the convective heat transfer coefficient h can be obtained according to the research results of KENZON[23]:

At $GrRe^{2.5} > 1$, the Nusselt number of the collector surface is calculated by the following formula:

$$Nu = 0.518(Ra)^{1/5} \tag{9}$$

At $GrRe^{2.5} < 1$, the Nusselt number of the collector surface is close to the calculation result of the following formula:

$$Nu = 0.458(Re)^{1/2} Pr^{1/3} \tag{10}$$

where Gr, Re, Nu and Ra represent Grashof number, Reynolds number, Nusselt number and Rayleigh number of the heat transfer process between the ambient air and the collector.

E. HEAT PUMP EXPERIMENTAL SYSTEM

The proposed solar heating system with the aluminum tubular collector is presented in Fig. 2. It mainly includes aluminum tube collector, compressor, electronic expansion valve, heat exchanger, control module, etc. Its working principle is as follows: firstly, the heat of solar energy absorbed by the aluminum tube collector is transferred to the working medium flowing through the collector to make it evaporate; secondly, the working medium in the steam state becomes high temperature and high pressure steam after being pressurized by the compressor; thirdly, the working medium in the high temperature and high pressure flows through the heat exchanger to transfer the heat to the indoor circulating thermal medium (air or water), and condenses itself to the liquid state; finally, the working medium in the steam state becomes high temperature and high pressure steam after being pressurized by the compressor. The working medium in liquid state flows through the electronic expansion valve, throttles to the low pressure state, and then reenters the collector to complete a cycle.

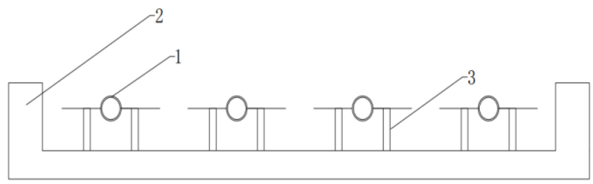

FIGURE 1. Schematic diagram of aluminum tube collector 1 Aluminum tube; 2 Fixing frame; 3 Bracket.

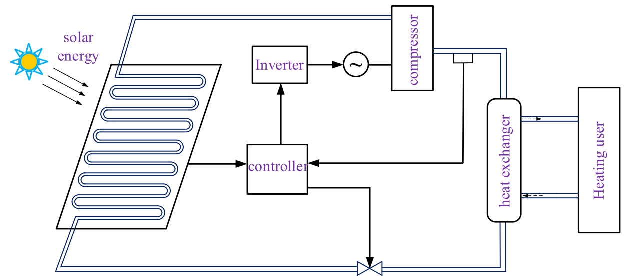

FIGURE 2. Solar heat pump heating system with the aluminum tubular collector.

F. CONTROL METHOD OF HEAT PUMP

In the working process of the heat pump, the control of the degree of superheat is a crucial link and the key to determining the heating efficiency. For improving the reliability of the system, the use of the difference between the inlet and outlet temperatures of the evaporator to control the overheating of the working fluid is proposed. A control flowchart is shown in Fig.3.

By controlling the opening degree of the electronic expansion valve, the flow rate of the working fluid can be controlled to adjust the flow rate of the fluid. According to the control effect, the mathematical model of the valve opening and the flow rate is expressed as follows(11)-(13):

$$\dot{m} = C_D A \sqrt{2\rho\,(p_1 - p_2)} \tag{11}$$

$$C_D = 0.02\sqrt{\rho} + 0.634v \tag{12}$$

$$A = \pi d \sin\frac{\theta}{2} h - \pi \sin^2\frac{\theta}{2}\cos\frac{\theta}{2} h^2 \tag{13}$$

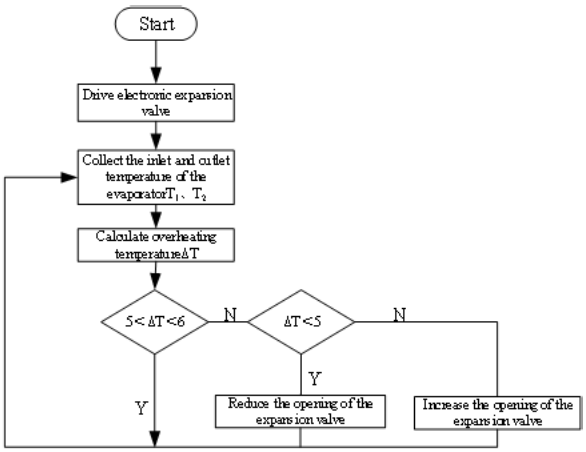

FIGURE 3. Overheating control flowchart.

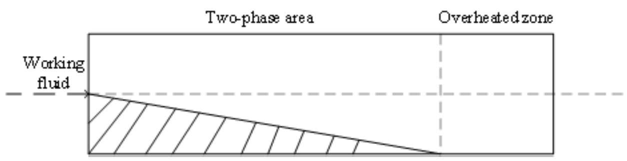

FIGURE 4. Evaporator physical model.

where $\dot{m}$ represents the mass flow rate (in kg/h); C_D is the flow coefficient; A represents the flow area (in m^2);ρ represents the refrigerant density (in kg/m^3);P_1 and P_2 represent the inlet and outlet pressures, respectively (in Pa);v represents the specific volume at the refrigerant outlet (in m^3/kg); d represents the diameter of the valve needle hole (in m); θ represents the cone angle of the valve needle (in degrees); and h represents the valve opening.

The working fluid is discharged through the expansion valve and is mostly in a two-phase state when it first enters the evaporator. In the evaporator overheating control analysis, modeling with the state of the two-phase area is more practical. The operating process of the working fluid in the evaporator is described using the physical model in Fig. 4.

The main modeling methods for evaporators are the moving boundary method and the energy conservation method. The modeling method of the moving boundary method is more complex, and the analysis needs to be simplified and linearized, which is not easy. This paper proposes the use of the energy-conservation method for modeling analysis.

$$Q = \left[A_b I_s + \dot{m}\, c_p \left(T_a - T_{fp}\right)\right]\eta \tag{14}$$

$$Q = \dot{m}\, c_p \left(T_{out} - T_{in}\right) \tag{15}$$

$$T_{fp} = \frac{T_{out} + T_{in}}{2} \tag{16}$$

where, Q represents the heat absorption of the evaporator (in J); A_b represents the heat exchange area of the evaporator (in m^2); I_s represents the total solar irradiance on the evaporator (in W); $\dot{m}$ represents the mass flow of the working fluid (in kg/h); c_p represents the constant pressure specific volume; T_a represents the ambient temperature; T_{fp} represents the average temperature of the evaporator; T_{out} represents the evaporator outlet temperature; T_{in} represents the evaporator inlet temperature; and η represents the heat transfer coefficient.

For the control of the overheating, the fuzzy PID control method was used in this study. The control block diagram is shown in Fig. 5.

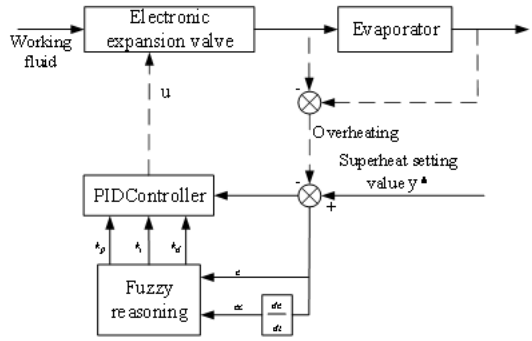

FIGURE 5. Fuzzy PID control block diagram.

G. EXPERIMENTAL SYSTEM AND PROCESS DESCRIPTION

As shown in Figure 6,the solar energy heat pump heating experimental system using aluminum tubes for heat collection was constructed. The system was employed for heating an ordinary residential building with a heating area of 170 m^2. The system used STM32F103 as the intelligent controller, and the fuzzy PID control method proposed was used to control the overheating of the evaporator in real time, to improve the comprehensive energy efficiency of the heating system.The block diagram of fuzzy control is shown in Fig 7.

The design of superheat controller is mainly based on fuzzy rules of fuzzy control. In order to achieve better control effect, the parameters kp, ki and k_d in PID control are adjusted by fuzzy reasoning.

In the fuzzy control, e the difference between the superheat measured value and the set value is taken as input 1, and

FIGURE 6. Experimental heating system.

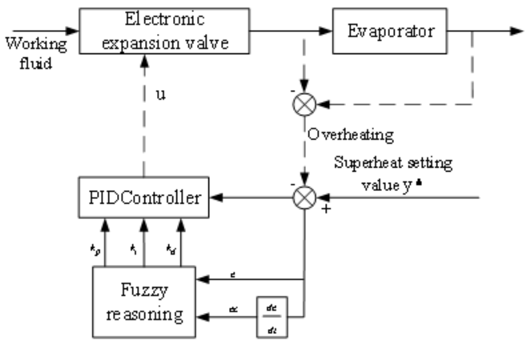

FIGURE 7. Fuzzy PID control block diagram.

the difference change rate between the superheat measured value and the set value is taken as input 2.The incremental values $k_{p,}$ k_i and k_d of Δkp, Δki *and* Δkd are taken as the output of fuzzy control. The membership functions of e, e_c, Δkp, Δki *and* Δkd are used to fuzzy and defuzzify, and the corresponding control quantity is output. The domain of e and e_c is [− 3,3], Δkp is [− 0.3,0.3], Δki is [− 0.6,0.6] and Δkd is the same as that of e. The domain of input and output is composed of seven subsets. According to the actual operation and parameter setting principle of solar heat pump heating system, the fuzzy rules of fuzzy controller are shown in Tables 1-3.

The initial parameters of Δkp, Δki and Δkd of fuzzy PID controller are 8, 0.03 and 12 respectively. The detailed parameters and models of the solar heat pump heating system using aluminum tubes are presented in Table4:

According to the experimental system of solar heat pump heating, the heat pump experiment is carried out from 8:00 on November 10 to 8:00 on November 11, 2020.

TABLE 1. Fuzzy rule of output Δkp.

e \ ec	NB	NM	NS	Z	PS	PM	PB
NB	PS	PM	PB	PM	PS	0	0
NM	PM	PS	PM	PB	PS	0	0
NS	PB	PN	PB	PB	0	NS	NS
Z	PN	PB	PM	0	NM	NB	NM
PS	PM	PM	0	NM	NB	NB	NS
PM	PB	PM	NM	NM	NM	NB	NM
PB	0	NS	NM	NM	NB	NB	0

TABLE 2. Fuzzy rule of output Δ *ki*.

e \ ec	NB	NM	NS	Z	PS	PM	PB
NB	NM	NN	NS	NS	NM	0	0
NM	NM	NS	NS	NS	NS	PS	PS
NS	NM	NS	NN	0	0	PB	PM
Z	NS	NM	0	0	PM	PM	PB
PS	NS	0	PS	PM	PB	PB	PM
PM	NS	0	0	PM	PM	PB	PM
PB	0	PS	PS	PS	PM	PM	0

TABLE 3. Fuzzy rule of output Δkd.

e \ ec	NB	NM	NS	Z	PS	PM	PB
NB	PM	0	NM	NS	0	NS	PS
NM	PM	0	NM	NS	NS	0	PS
NS	PS	NS	NS	NM	0	NS	0
Z	0	NS	0	0	NM	NM	0
PS	NS	0	0	0	0	NS	NS
PM	PS	NM	0	PM	PS	0	PM
PB	PS	PS	PS	PS	PM	PM	PS

TABLE 4. Heating system parameters and models.

Name	Parameter /mode	Name	Parameter/ mode
Heating area (m^2)	170	Collector area(m^2)	16.45
Outer diameter of collector tube(mm)	25	Inner diameter of collector tube(mm)	21
Flow rate (kg/s)	1.25-2.5	Collector inclination (°)	55
Working substance	R134a	Compressor	ZR61KCE
Circulating pump	TL-180	Electronic expansion valve	DPF(T01)

The main process of the experiment is: turn on the power at 8:00 a.m. on the 10th, and put the system into automatic operation. Stable and optimized operation of the solar heat pump heating system was realized through variable frequency control of the compressor and intelligent adjustment of the opening of the electronic expansion valve. The starting condition of the solar heating system was that when the indoor temperature was < 19°Catha STM32F103 intelligent controller frequency conversion control compressor and intelligent adjust the opening of the electronic expansion valve to ensure stable operation of the indoor temperature and the overheating of the collector. Taking into account the operating cost of the heating system, when the indoor temperature reached 25°C, the system was automatically shut down. Additionally, considering the reliability of the system operation, the system was prevented from starting frequently. When the indoor temperature reached 23°C, the frequency conversion will controlled the compressor to reduce the working substance flow rate, realizing adaptive and flexible control of the indoor heating temperature. At the same time, the temperature of indoor and outdoor environment, the outlet temperature of working medium in the heat exchanger and the power consumption of compressor and circulating pump during the operation of the system are recorded. The output thermal power and comprehensive energy efficiency data of the heating system can be obtained through further analysis.

III. RESULTS AND ANALYSIS

A. ANALYSIS OF HEAT TRANSFER PERFORMANCE OF ALUMINUM TUBE COLLECTOR

Tansy's was used to analyze the heat transfer performance of the aluminum tubular collector. The inlet working substance enters the solution pump at a constant flow rate and temperature from an infinite space and then enters the collector in the same manner through the solution pump. The exit working substance of the collector enters the infinite space is to analyze the effects of the wind speed, direct radiation, environment temperature, and outlet temperature on the heat collection performance. The simulation time was 24hr, and the initial parameters are presented in Table 5.

TABLE 5. Initial parameters.

Name	Parameter	Name	Parameter
Inner diameter of collector tube (mm)	21	Lighting area (m^2)	16
Outside diameter of collector tube(mm)	25	Wind speed/(m/s)	0
Temperature in(°C)	-25	Radiation (kJ/(hr·m^2))	500
Flow rate (kg/s)	1.35	Environment temperature	0
Surface absorption of collector	0.9	Surface emissivity of collector	0.1
Working substance	R22	Collector dip angle(°C)	45

B. EFFECT OF WIND SPEED ON HEAT TRANSFER PERFORMANCE

According to the previous analysis, the convective heat transfer coefficient is closely related to the wind speed in the process of absorbing air energy on the collector surface. In order to further explore the influence of wind speed, only change the wind speed through the collector, and other parameters remained unchanged. TRNSYS software is used to simulate the heat collection of the collector, and the results are presented Figs. 8-10.

As shown, with an increase in the wind speed, the total absorbed energy and collector power increased significantly, among with the air energy absorption. This is mainly because the convection heat transfer coefficient increased with the wind speed, which increased the amounts of convection heat transfer energy at the top and the bottom. The surface temperature of the collector increased because of the amount of internal energy absorbed by the collector increased and the outlet temperature increased when the coefficient of thermal conductivity was kept constant.

C. EFFECT OF DIRECT RADIATION INTESITY ON HEAT TRANSFER PERFORMANCE

Solar energy is one of the main energy sources of the aluminum tube collector, in which the direct radiation intensity is the main part of the total solar radiation intensity. In order to further study the influence of solar irradiance on the heat collection performance of the collector, the direct radiation parameter of the collector's lighting surface was changed, and the other parameters remained unchanged (at the initial values). The calculation results are presented in Figs. 11-13.

As shown in Figs. 11-13, the increase in the direct radiation amount did not significantly affect the air energy absorption, whereas the collector power, total absorption amount, and

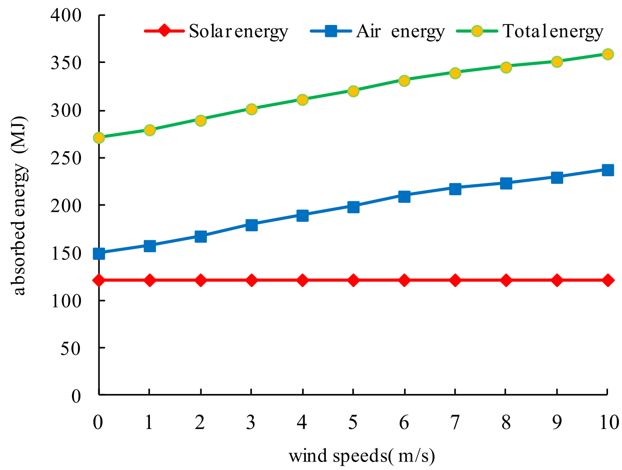

FIGURE 8. Heat absorption of the collector at different wind speeds.

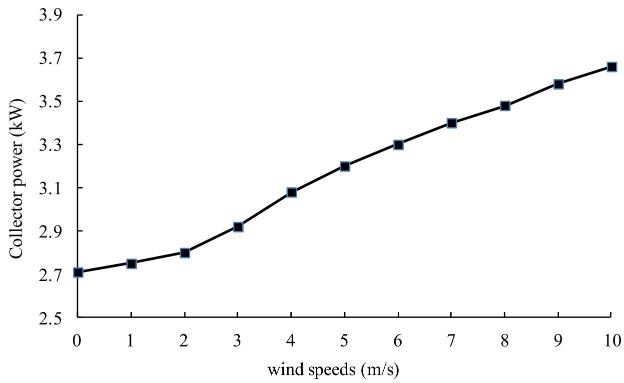

FIGURE 9. Power of the collector at different wind speeds.

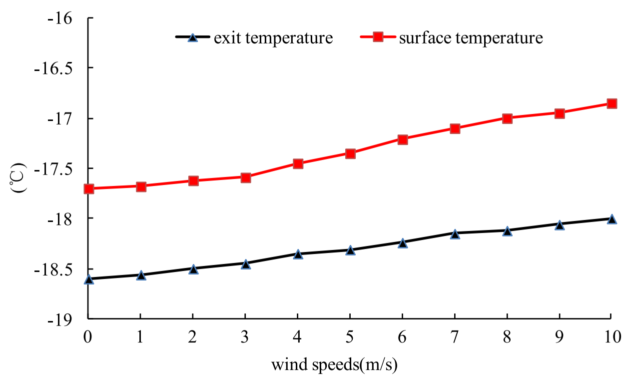

FIGURE 10. Outlet temperature and surface temperature of the collector at different wind speed.

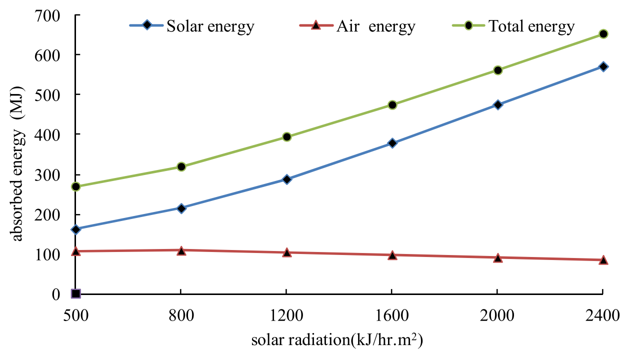

FIGURE 11. Effect of the direct radiation dose on the heat absorption.

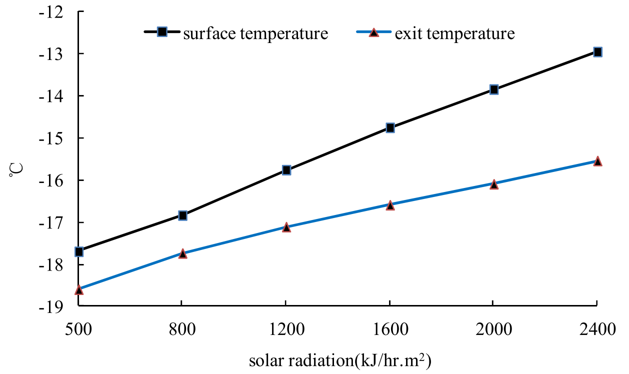

FIGURE 12. Effect of the direct radiation amount on the collector temperature.

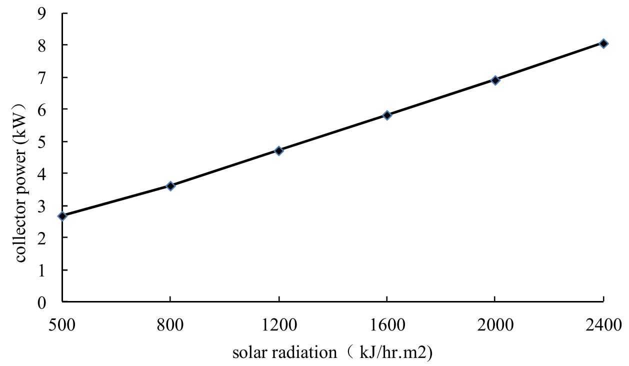

FIGURE 13. Effect of the direct radiation amount on the collector power.

surface temperature increased with the radiation amount. This is mainly because the solar energy absorbed by the collector surface increased rapidly after the increase in the direct radiation amount. This means that increasing the intensity of direct solar radiation is an important means to increase the heat collection of the aluminum tube collector.

D. EFFECT OF ENVIRONMENT TEMPERATURE ON HEAT TRANSFER PERFORMANCE

The environmental temperature is another important factor that affects the heat collection performance of aluminum tube collector. In order to study the effect of environment, only the environmental parameters temperature were changed, and the other parameters were kept unchanged (at the initial values).The analysis results for the effect of the environment temperature on the heat collection performance of the collector are presented in Figs. 14-16.

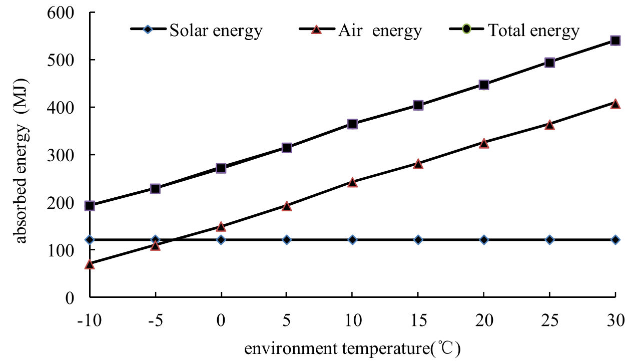

FIGURE 14. Effect of the environment temperature on the heat absorption.

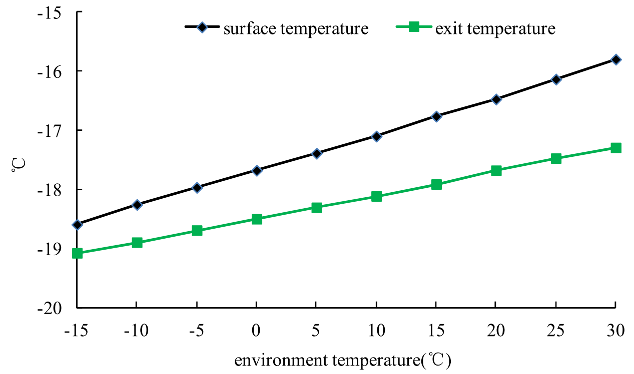

FIGURE 15. Effect of the environment temperature on the collector temperature.

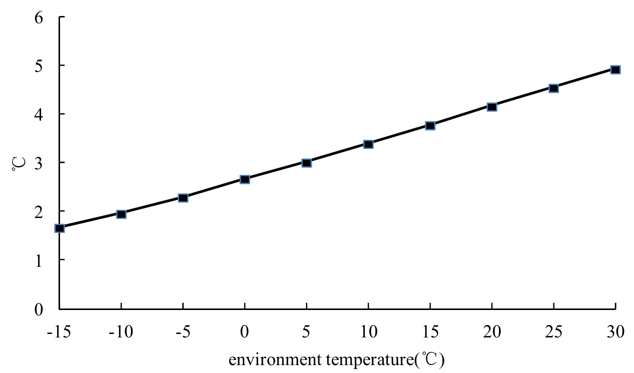

FIGURE 16. Effect of the environment temperature on the collector power.

In the previous analysis, it can be concluded that with the inlet parameters of the collector unchanged, increasing the ambient temperature can increase the temperature difference between the two, so as to improve the air energy absorption. As shown, the increase in the environment temperature had a larger effect on the absorption of ambient energy than on the air energy, mainly because the increase in the environment temperature had a strong effect on the growth of the radiation heat transfer coefficient. The surface temperature, outlet temperature, and collector power increased with the collector surface absorption. The amount of solar energy absorbed did not change with an increase in the ambient temperature.

E. EFFECT OF WORKING SUBSTANCE FLOW RATE ON HEAT TRANSFER PERFORMANCE

During the operation of the heat pump system, the change of working fluid flow can be realized by changing the opening of the expansion valve, which has an impact on the heat collection of the collector. Therefore, it is necessary to carry out the research on the impact of working fluid flow on the performance of the collector. The working substance flow rate was changed, and the other parameters remained unchanged (at the initial values). The performance analysis results of the collector are presented in Figs 17-19.

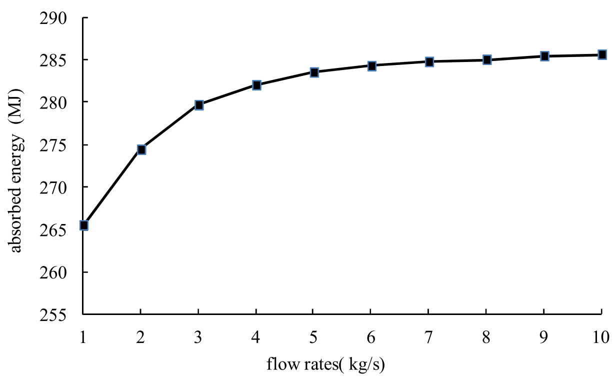

FIGURE 17. Effect of the flow rate on the heat absorption.

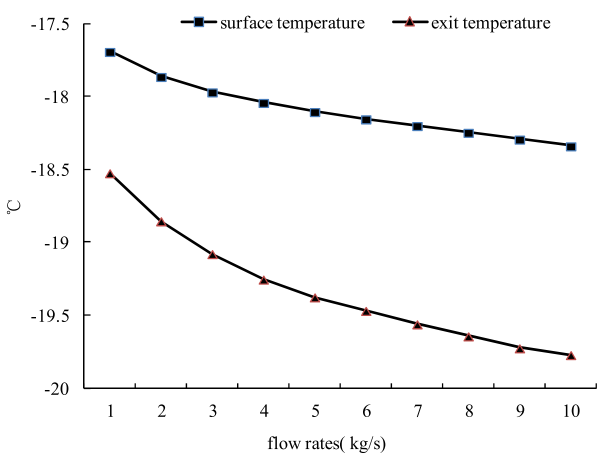

FIGURE 18. Effect of the working substance flow rate on the collector temperature.

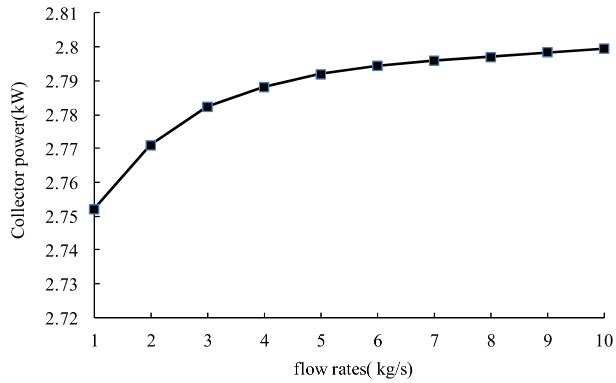

FIGURE 19. Effect of the flow rate on the collector power.

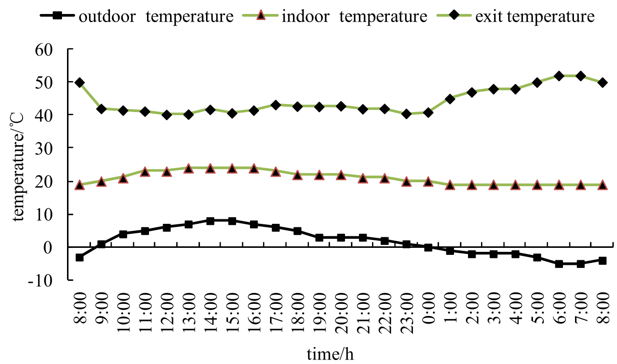

FIGURE 20. Indoor, outdoor and outlet temperature during heating system operation.

As shown, with an increase in the working substance flow rate, the surface and outlet temperatures decreased, the capacities of air absorption increased, the total absorption capacity increased, but the increment was relatively small, and with the continuous growth of the inlet flow, the increase trend is gradually slowed. This was mainly owing to the influence of working substance flow rate on the heat transfer coefficient of the working substance flow in the tube. The growth of each parameter gradually became stable.

F. SYSTEM PERFORMANCE EXPERIMENT AND RESULT ANALYSIS

After one day's operation, the outdoor environment temperature, indoor temperature and the indoor outlet temperature of the heat exchanger are recorded, as shown in Fig 20.

It can be seen from fig. 19, as the outdoor temperature changed, the outlet temperature of the solar heat pump heating system was constantly adjusted to ensure that the indoor temperature essentially remained constant and the temperature range was 19-24°C. The indoor temperature was 24 °C in the time range of [13:00-16:00]. At this time, the outdoor temperature was relatively high, resulting in the indoor temperature reaching 24 °C. Owing to the higher outdoor temperature and larger amount of solar radiation, the COP

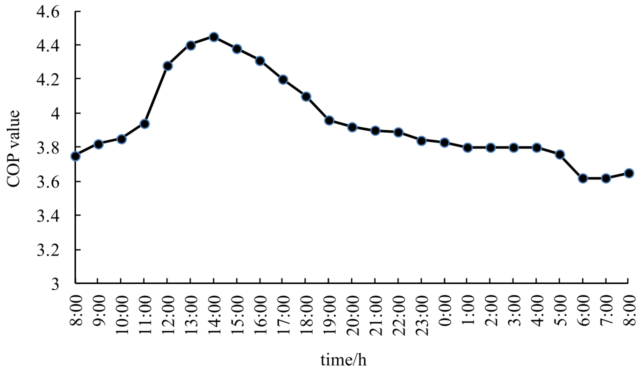

FIGURE 21. COP value during heating system operation.

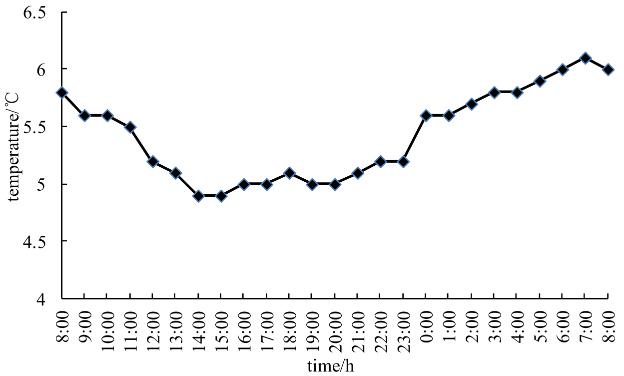

FIGURE 22. Overheating temperature during heating system operation.

of the heat pump at this time was greater. The results are presented in Fig. 20.

As shown, the COP of the heating system was maximized (4.35) at 14:00.This is mainly because the amount of solar radiation was still large at 14:00, and the ambient temperature was the highest at this time. Under the combined action of the two factors, the heat absorption capacity of the aluminum tube collector was maximized. At the same time, the indoor temperature affected by the external environment at 14:00 was also higher, which led to the maximum COP. The results confirm that the solar heat pump heating system with aluminum tube collectors has a higher comprehensive energy efficiency.

In the solar heat pump heating system based on aluminum tube collectors, the collector which provides the energy input for the entire system, plays a vital role, but the control of the evaporator overheating is also an important factor determining the heating effect of the system. The real-time adjustment control of the electronic expansion valve keeps the overheating on the collector within a certain temperature range as soon as possible. When the system is stable, the overheating is essentially maintained within 6 °C, and the fluctuation range is within the allowable range. During the operation of the heating system, there was no frost on the surface of the collector, as expected. The evaporator overheating temperature can be controlled as shown in Fig.22.

The electric energy consumed by the heating system is shown in Fig.22. There was a large difference in the hourly electric power consumption, which was in the range of 1.94-3.64kwh. It was mainly affected by the outdoor environment temperature. When the outdoor temperature was low and the energy absorbed by the aluminum tube collector was insufficient, the electric power consumption value is large. In particular when the temperature was low at night, the solar energy absorbed heat was 0. Reducing the wind speed increased the electric power consumption. As shown in Fig. 23, the electric power consumption was maximized at 7:00 am on November 11, 2020, mainly because of the low outdoor environment temperature and low ambient wind speed.

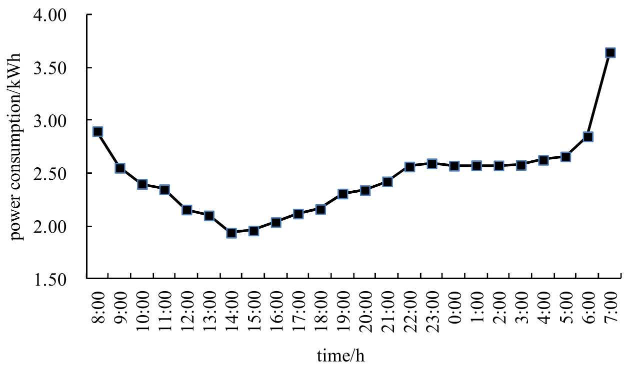

FIGURE 23. Electric power consumption value during heating system operation.

IV. CONCLUSION

In this paper, we provide a solar collector using aluminum tube. Through TRNSYS software, we study the influence of wind speed, solar direct radiation intensity, ambient temperature and working medium flow rate on the collector's performance. At the same time, the experimental system is built to analyze the heat transfer performance and heating effect of the solar heat pump heating system with aluminum tube collector. The main conclusions are as follows:

(1)The wind speed, environment temperature, and working-medium flow rate do not affect the solar absorption. However, the amount of direct solar radiation significantly affects the amount of solar absorption.

(2)The air energy absorption of the collector increases with the increase of wind speed, ambient temperature and inlet flow, and the change of wind speed has the most obvious effect on the air energy absorption.

(3)With increases in the working substance flow rate and environment temperature, the environmental energy absorption capacity of the collector increases. However, a continuous increase in the working substance flow rate limits the increase in the environmental energy absorption.

(4)The experimental data indicated the following: the designed solar heat pump heating system can achieve a good heating effect, the constant temperature and overheating problems are solved, the average COP of the system is 3.95, and the energy saving and environmental protection effects are remarkable.

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