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A BIPV/T System Design Based on Simulation and its Application in Integrated Heating System

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Abstract

In order to better master the internal airflow distribution characteristics of photovoltaic thermal (PV/T) collector on air source heat pump (ASHP) system heating performance, CFD software was applied in studying the building-integrated photovoltaic thermal (BIPV/T) sys-tem. A mathematical model of BIPV/T and ASHP integrated heating system was established. Numerical simulation of the system was conducted based on the typical meteorological data in Shenyang area. The influence of the inlet and outlet velocity, internal flow field distribution and temperature field distribution of the BIPV/T system were analyzed on the system thermal efficiency. The relationship between optimal COP and the inlet and outlet velocity of ASHP system was studied. The optimal inlet velocity of the BIPV/T – ASHP integrated system was determined to be 4 m/s, and the COP reached 4.6.

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Keywords: Photovoltaic-thermal technique; air-source heat pump; photovoltaic-thermal collector; cop

1. Introduction

Building-integrated photovoltaic is a new form of solar power applications. Photovoltaic module array is installed in the building envelop combining the enclosure structure and photo-voltaic module, which simultaneously provides electric energy to the building. There has been studies on the operation between BIPV/T and heat pump system [1,2]. However, PV/T collector with smaller area was applied in these kinds of system, which energy supply is restricted in the practical application. The Maintenance costs of PV/T collector when using air as the heat collecting medium is

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lower than using liquid in low temperatures. Overheating does not exist in energy transformation process. Freezing, boiling, corrosion and leakage problems are no need to be considered as well. Due to the air directly entering the environment after cooling photovoltaic module causes part of the heat waste [3], some researchers strengthened the recovery utilization on that part of heat and pro-posed BIPV/T system which realize the utilization of electricity and heat.

In this paper, BIPV/T-ASHP integrated heating system was established based on the energy efficiency characteristics of the BIPV/T system and the thermal performance characteristics of ASHP. This system was a subsystem of the passive demonstration building of Shenyang Jianzhu University. According to the meteorological data in typical Shenyang area, numerical simulation was conducted on the PV/T air collector. The influence of the inlet and outlet velocity, internal flow field distribution and temperature field distribution of the BIPV/T system were analyzed on the system thermal efficiency, and the optimal inlet and outlet velocity was determined, which provided theoretical support for practical application.

BIPV/T-ASHP integrated heating system was consist of BIPV/T subsystem, ASHP subsystem, phase change energy storage subsystem and end user (Figure 1). The BIPV/T subsystem, which made up of flat type PV/T module arrayed on the building envelope, was connected with ASHP subsystem by air duct closely (Figure 2). Electric air valve, fan and ASHP unit were controlled upon the internal temperature of the PV/T cavity. Working principle of the heating system is as followed. Low temperature air enters from the bottom of BIPV/T system and absorbs heat of thermal collecting plate. When the temperature of air rises, the air goes into the ASHP unit through the top air inlet driven by the fan conducting heat exchange. And the unit prepares hot water for buildings heating. Afterwards, low temperature air exhausts from the ASHP unit, then enters the BIPV/T system again, which constitutes the cyclic heat transfer procedure.

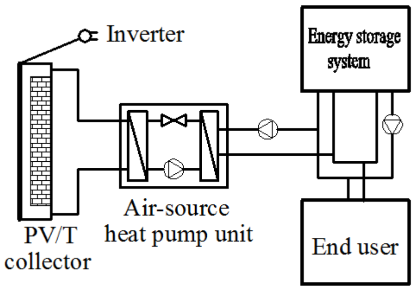


Fig. 1. Schematic diagram of BIPV/T-ASHP.

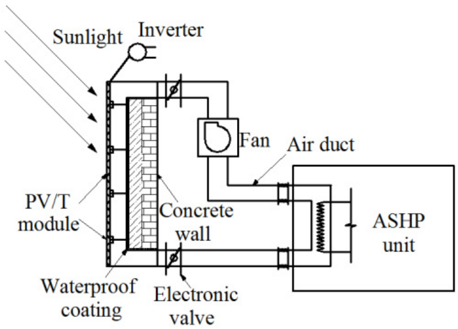


Fig. 2. System diagram of BIPV/T-ASHP.

2. Method

In order to take an intensive research to the BIPV/T- ASHP integrated heating system, CFD technology was used in this study.

2.1. Theoretical model

BIPV/T subsystem was constitute of flat-plate solar air collector. For the convenience of analysis and reducing unnecessary computation, the heat transfer model was simplified rationally [4]. The three-dimensional model is showed in Figure 3 and Figure 4. Simplified conditions are as follows: 1) The BIPV/T system in the quasi steady state; 2) The solar air collector plate as a constant heat source; 3) Radiation heat transfer between heat plate and glass cover plate is ignored; 4) As the internal radiation heat transfer intensity of collector is low, it is negligible; 5) Internal cavity flow heat exchanger is set as hydraulically smooth condition; 6) Collector plate and the frames are of good insulation properties, they are set to adiabatic wall which ignoring the heat loss; 7) Airtight performance of the collector is fine, so the leakage problem is not considered.

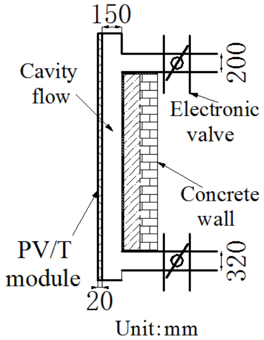


Fig. 3. Profile of PV/T thermal system.

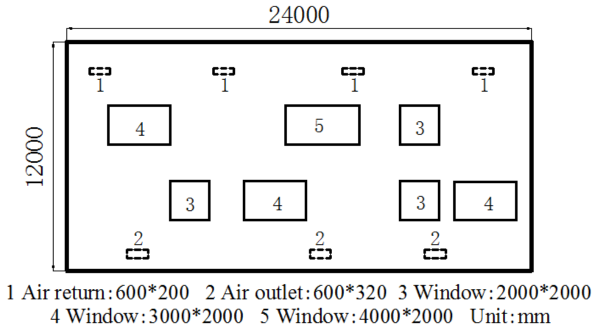


Fig. 4. System diagram of PV/T thermal system.

In the three-dimensional space rectangular coordinate system, continuity equation (1), energy equation (2) and momentum equations (3, 4,5) are as followed:

- $$\frac{\partial u_x}{\partial x}+\frac{\partial u_y}{\partial y}+\frac{\partial u_z}{\partial z}=0 \tag{1}$$
- $$u_x\frac{\partial T}{\partial x}+u_y\frac{\partial T}{\partial y}+u_z\frac{\partial T}{\partial z}=\frac{\lambda}{\rho C_p}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \tag{2}$$
- $$u_x\frac{\partial u_x}{\partial x}+u_y\frac{\partial u_y}{\partial y}+u_z\frac{\partial u_z}{\partial z}=\upsilon\left(\frac{\partial^2 u_x}{\partial x^2}+\frac{\partial^2 u_y}{\partial y^2}+\frac{\partial^2 u_z}{\partial z^2}\right)-\frac{1}{\rho}\frac{\partial P}{\partial x} \tag{3}$$
- $$u_x\frac{\partial u_x}{\partial x}+u_y\frac{\partial u_y}{\partial y}+u_z\frac{\partial u_z}{\partial z}=\upsilon\left(\frac{\partial^2 u_x}{\partial x^2}+\frac{\partial^2 u_y}{\partial y^2}+\frac{\partial^2 u_z}{\partial z^2}\right)-\frac{1}{\rho}\frac{\partial P}{\partial y} \tag{4}$$
- $$u_x\frac{\partial u_x}{\partial x}+u_y\frac{\partial u_y}{\partial y}+u_z\frac{\partial u_z}{\partial z}=\upsilon\left(\frac{\partial^2 u_x}{\partial x^2}+\frac{\partial^2 u_y}{\partial y^2}+\frac{\partial^2 u_z}{\partial z^2}\right)-\frac{1}{\rho}\frac{\partial P}{\partial z}-g \tag{5}$$

Where u_x is velocity of x direction, u_y is velocity of y direction, u_z is velocity of z direction, T is the temperature of air. ρ is air density, υ is coefficient of kinematic viscosity, Cp is the specific heat of air, λ is thermal conductivity, g is acceleration of gravity.

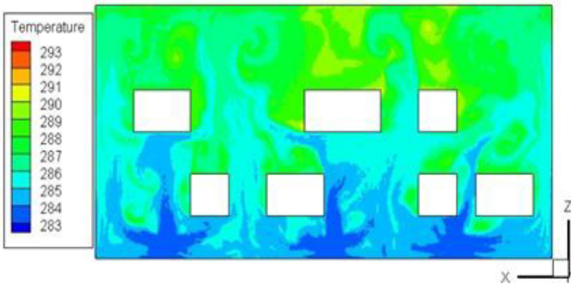
2.2. Simulation process

RNG k-ε turbulence model originates from statistical data strictly, and it is very similar to standard k-ε turbulence model. However, it adds an extra condition in the ε equation and provides analytic formulas on low Reynolds number viscous flow, which takes into account the effect of the turbulent eddies and improve the accuracy effectively. According to the simplified heat transfer model, the inlets and outlets of the BIPV/T system emerge large air disturbance, which produces turbulent vortex phenomenon. Therefore, in this paper, the steady state RNG k-ε turbulence model was applied in CFD numerical simulation for the BIPV/T system.

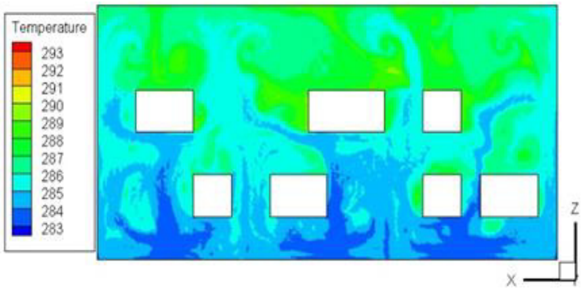
Gambit was used to establish three-dimensional model and mesh tetrahedral grid of computational area. The total grid number was 1107 thousands. In the FLUENT solver, RNG k-ε turbulence model was selected in the Viscous Model, and Enhanced Thermal Treatment was active in near-wall treatment. Environmental atmospheric pressure was defined as standard atmospheric pressure and ambient temperature was set to be 268.15 K. The thermal collecting plate was set to the constant inner heat source equals to 400 W/m2 solar radiation. The inlet temperature was set to 283.15 K, turbulent intensity was 5%. Outlet was provided to be free flow. The heat transfer surface between the air and the thermal collecting plate was coupled. SIMPLE algorithm was used in pressure-velocity coupling equation. Second Order Upwind was selected in momentum and energy equations. The whole computational domain was initialized, and the initial temperature was patched 283.15 K.

3. Result

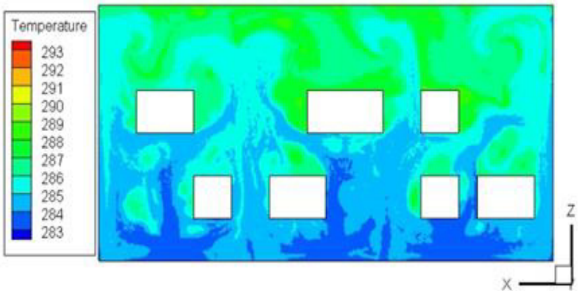
In this paper, inlet and outlet velocity was mainly studied on affecting the efficiency of the BIPV/T system. Therefore, only inlet and outlet velocity was changed in the simulation process, other conditions remain the same. Inlet velocity was respectively set to 2m/s, 3m/s, 4m/s, 5m/s and 6m/s. Temperature contour away from the thermal collecting plate 5cm section are showed in Figure 5.



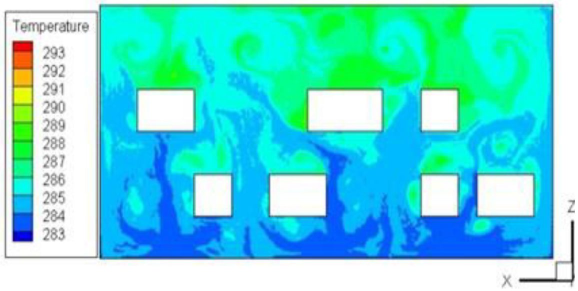
a v=2m/s



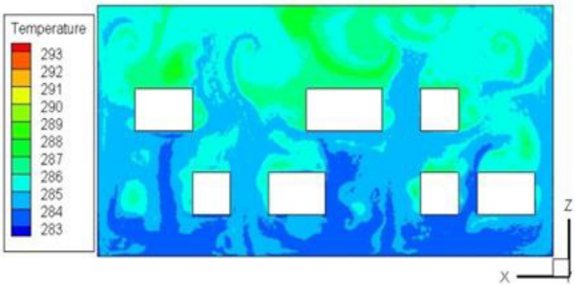
b v=3m/s



c v=4m/s



d v=5m/s



e v=6m/s

Fig. 5. Temperature contour in different inlet velocity.

Simulation results show that when the inlet velocity was low, there was a large temperature gradient in vertical direction, which would increases the outlet temperature. The air stagnated upper portion of the window, forming a vortex region which caused heat exchange blocked. After high intensity solar radiation shining in a long time, PV/T collector would form local high temperature zone. When the inlet velocity was increased, internal temperature gradient decreased and the temperature field distribution was more uniform. Vortex area reduced in PV/T collector, which was conducive to heat exchange. While the outlet temperature decreased, which caused temperature difference between inlet and outlet decreases.

The heat extracts from the BIPV/T system can be calculated as follow:

- $$Q_{air}=C_pM\left(T_{out}\text{-}T_{in}\right) \tag{6}$$

Where Cp is the specific heat of air, M is air mass flow, T_{out} is outlet temperature of the BIPV/T system, T_{in} is inlet temperature of the system.

The thermal efficiency of air collector η and the transient thermal efficiency of the system η_i can be calculated as followed:

- $$\eta=\frac{Q_{air}}{AG} \tag{7}$$

- $$\eta_i=\frac{Q_{air}}{AG+P_i} \tag{8}$$

Where A is the collector area of BIPV/T system, $A=240m^2$, G is the heat flux of the collector and P_i is the fan power under different wind speed in the corresponding.

Table 1 shows the working state parameter of BIPV/T system under different inlet velocity of air collector. Figure 6 shows the collector efficiency and system transient thermal efficiency with the change of inlet velocity. With the BIPV/T system inlet velocity increases, the outlet temperature reduces, Δt reduces from 6.93K to 4.55K, which leads to heat exchange limited and thermal efficiency growths flattened, eventually reached about 21%. If the inlet velocity increases continually, circulating air of the system will be improved, fan power consumption will increase, and the total energy consumption proportion accounted for the system will also increase, which causes the difference between transient thermal efficiency and thermal efficiency increases and will eventually lead to the decline of the transient thermal efficiency of the system.

Table 1. Air collector working condition under different inlet velocity.

Veloity m/s	Mass Flow kg/s	Δt K	C_p J/K·kg	Heat flux W	Fan capacity W	Thermal efficiency %	Transient thermal efficiency %
2	1.41	6.93	1005	9820.2	900	10.67	10.13
3	2.12	6.45	1005	13742.3	1100	14.94	14.15
4	2.82	5.98	1005	16947.9	2350	18.42	17.23
5	3.53	5.25	1005	18625.2	3700	20.24	18.68
6	4.23	4.55	1005	19342.7	5100	21.02	19.13

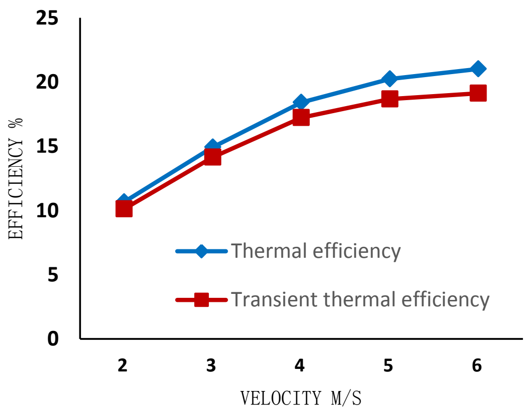


Fig. 6. Efficiency comparison.

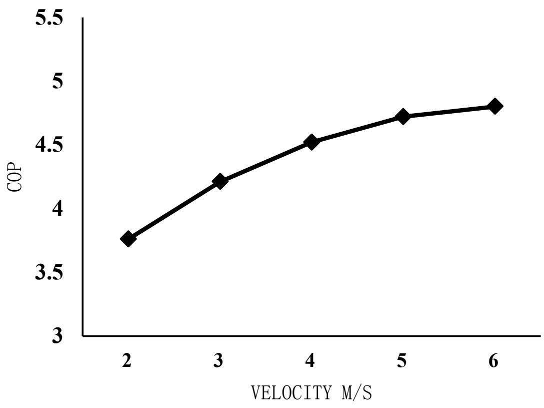


Fig. 7. Relation between flow velocity and COP.

As the inlet velocity increases, even if the outlet air temperature drops, heat gains of the sys-tem still continues to increase, and the COP of ASHP unit still show a growing trend in a certain range (Figure 7). When the inlet flow rate at 2 ~4m/s, COP of the unit of grows rapidly, increased from 3.72 to 4.6. When the inlet velocity is larger than 4m/s, in this period of operation range, the thermal efficiency of the system and the transient thermal efficiency decreased growth, COP of the unit will eventually reach 4.79. Therefore, based on the characteristic of COP curve and the thermal efficiency of the system, inlet velocity of the BIPV/T- ASHP integrated heating system is selected 4m/s. Under this work condition, it is conducive to the improvement of the transient thermal efficiency of the system, which ensure the ASHP system operating at higher energy efficiency condition and reduce the energy consumption of the system.

4. Discussion

Through the study, we know that the thermal efficiency still reaches 21% when the outdoor temperature is -5℃, which is relatively high in low temperature. It will be an effective way of using solar energy for heating, especially in cold area in our country. However, the BIPV/T – ASHP integrated heating system is theoretically operating in steady-state, and the amount of heat collection of solar energy is unstable practically. Therefore, the system may not reach the ideal heat collecting when operating. The inlets and outlets, confined by the building structure, are determined by empirical calculation. Further research should be taken to find out the optimal arrangement of inlets and outlets.

5. Conclusion

In this study, CFD simulation software was applied in exploring how the inlet and outlet velocity, internal airflow distribution and temperature distribution affect the thermal efficiency of the PV/T collector and the COP of the BIPV/T–ASHP integrated heating system. Through the simulation study, we conducted that when the outdoor air temperature of Shenyang was -5℃, the thermal efficiency of BIPV/T system could reach 21%, which provided heat to the ASHP system effectively. When the system operated in the optimal inlet velocity, COP of heat pump unit reached 4.6. Research proved that thermal efficiency of BIPV/T-ASHP integrated heating system was relatively high in low temperature environment and heating effect was good, which could directly provide building heating. When plate-type air collector was installed on large area BIPV/T system, characteristics of architectural shapes and enclosure structure should be considered, and reduced barrier of BIPV/T system. In practical engineering application, heat pump unit should be adapted to the system, and inlet velocity should be chosen appropriately for avoiding generating vortex region in the collector. In the context of energy-saving, promoting the use of renewable energy alternative to traditional fossil fuels is one of the main measures to solve the problem of energy and environment. BIPV/T and ASHP technology have a lot of advantages, such as low environmental pollution, energy saving, high efficiency energy saving potential, we should vigorously popularize them in our country.

Acknowledgements

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