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Parameter Evaluation and Optimum Design of Building-Integrated Photovoltaic-Thermal Modules

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Abstract

In recent years, the application of the building-integrated photovoltaic-thermal (BIPVT) technology has developed rapidly around the world. The BIPVT module can generate electricity and hot water simultaneously. These features can effectively reduce the fossil fuel energy consumption in the building sector. In this paper, a dynamitic simulation model is developed to evaluate the energy performance of the single-glazed flat-plate-tube BIPVT module. The impact of configuration parameters of the BIPVT module has been analysed. Based on the investigations, the optimum design of the BIPVT module is obtained. For the optimum design of the BIPVT module, the average electrical efficiency and average thermal efficiency is respectively 12.9% and 46.9%, increasing by 4.0% and 9.6%, compared with the initial design.

Keywords-BIPVT module; parameter evaluation; optimum design; energy performance

1. Introduction

Public awareness of the need to reduce greenhouse gas emission and the drastic increases in oil prices has encouraged many policy makers and developers to promote renewable energy applications for reducing electricity consumption in buildings. The application of the Building-Integrated Photovoltaic-Thermal (BIPVT) technology has become more widespread in the world. In Hong Kong, the BIPVT technology utilizing solar energy is also regarded as one of the possible potential technologies of renewable energy. In fact, in a densely populated city like Hong Kong, integrating PVT modules into buildings will be advantageous since no additional land is required for installation, and better sunshine can be received on the facades of high-rise buildings. In addition, PVT modules can also generate hot water for dwellers in the building and an amount of electrical power for heating water has been cut down. In order to efficiently use solar energy on the BIPVT module, a lot of studies [1-8] have been carried out for maximum energy benefits.

This paper aims to develop a dynamic simulation model of the BIPVT module and to estimate its energy performance, including electrical power generation and thermal heat for hot water. Several main configuration parameters, including the thickness of the cover glass, the thickness of the air gap, the thickness and material of the thermal absorber, the internal diameter and spacing of the water tube and the thickness of the thermal insulation material, are optimized to achieve the most desirable energy benefits including electrical power generation and electrical power reduction due to hot water generation. Thus the maximum energy benefits and electrical efficiency of the BIPVT module can be found.

2. Dynamic Thermal model

2.1 Cover Glass

As there is solar radiation passing through the cover glass, in addition to conduction, the solar radiation absorbed by the cover glass should be included. The heat transfer balance equation of cover glass is

$$\rho_{cg}C_{cg}l_{cg}\frac{\partial T_{cg}}{\partial t}=G_{cg}+h_o\left(T_{ao}-T_{cg}\right)+h_{cg-s}\left(T_s-T_{cg}\right)+\frac{T_{pv}-T_{cg}}{\frac{1}{h_{r,pv-cg}}+\frac{1}{h_{c,pv-cg}}} \qquad (1)$$

where ρ_{cg}, C_{cg} and l_{cg} are the density, thermal capacity and thickness of cover glass, respectively. G_{cg} is the solar radiation absorbed by the cover glass. T_{ao}, T_s and T_{pv} are the temperature of the outdoor air, sky and PV cell, respectively. h_o is the convective heat transfer coefficient of the outside surface of the cover glass. h_{cg-s} is the long wave radiant heat transfer coefficient between the cover glass and the sky. $h_{c,pv-cg}$ and $h_{r,pv-cg}$ are the convective and longwave radiant heat transfer coefficient between the cover glass and the PV cell, respectively.

2.2 PV Cell

The heat transfer of PV cell is expressed by two dimensional dynamic heat transfer equation as follows

$$\rho_{pv}C_{pv}l_{pv}\frac{\partial T_{pv}}{\partial t}=\lambda_{pv}\frac{\partial^2 T_{pv}}{\partial x^2}dx+\lambda_{pv}\frac{\partial^2 T_{pv}}{\partial y^2}dy+\left(1-\eta\right)G_{pv}+\frac{T_{cg}-T_{pv}}{\frac{1}{h_{c,pv-cg}}+\frac{1}{h_{r,pv-cg}}}+\frac{T_c-T_{pv}}{R_{si}} \qquad (2)$$

where ρ_{pv}, C_{pv}, l_{pv} and λ_{pv} are the density, thermal capacity, thickness and thermal conductivity of the PV cell, respectively. η is the electrical efficiency of the PV cell. G_{pv} is the solar radiation absorbed by the PV cell. R_{si} is the thermal conductive resistance of the silicon gel.

2.3 Thermal Absorber

For different heat transfer phenomenon, the thermal absorber is divided into two parts: thermal absorber without water tube and thermal absorber with water tube. The temperature of the thermal absorber without water tube is calculated as

$$\rho_c C_c l_c \frac{\partial T_c}{\partial t} = \lambda_c \frac{\partial^2 T_c}{\partial x^2} dx + \lambda_c \frac{\partial^2 T_c}{\partial y^2} dy + \frac{T_{pv} - T_c}{R_{si}} + \frac{T_{ao} - T_c}{R_{in}} \quad (3)$$

The heat transfer equation of the thermal absorber with water tube is expressed as

$$\rho_c C_c l_c \frac{\partial T_c}{\partial t} = \lambda_c \frac{\partial^2 T_c}{\partial x^2} dx + \lambda_c \frac{\partial^2 T_c}{\partial y^2} dy + \frac{T_{pv} - T_c}{R_{si}} + \frac{T_f - T_c}{\dfrac{dy}{h_f \pi d_i} + R_{bond}} \quad (4)$$

where ρ_c, C_c, l_c and λ_c are the density, thermal capacity, thickness and thermal conductivity of the thermal absorber, respectively. d_i is the internal diameter of the water tube. R_{in} and R_{bond} are the thermal conductive resistance of the thermal insulation material and the bond, respectively.

2.4 Water in Water Tube

If water tubes are connected in parallel, the mass flow rate in each water tube is the same, then

$$0.25\pi d_i^2 \rho_f C_f \frac{\partial T_f}{\partial t} dy = \frac{m_f C_f}{N} \frac{\partial T_f}{\partial y} dy + \frac{T_c - T_f}{\dfrac{dy}{h_f \pi d_i} + R_{bond}} dxdy \quad (5)$$

where T_f is the temperature of water in the water tube. ρ_f , C_f and λ_f are the density, thermal capacity and thermal conductivity of water, respectively. m_f is mass flow rate and N is the number of water tubes.

2.5 Water in Water Tank

If the temperature of the water in the water tank is uniform, the heat transfer equation is expressed as

$$M_{wb}C_f\frac{\partial T_{wb}}{\partial t}=m_fC_f\left(T_f-T_{wb}\right)+\frac{T_{ai}-T_{wb}}{R_{in}}A_{wb} \tag{6}$$

where T_{wb} is the temperature of the water in the water tank. M_{wb} is the mass of the water in water tank and A_{wb} is the outside surface area of the water tank. T_{ai} is the temperature of the air in the room, and is thought as constant in the whole simulation period.

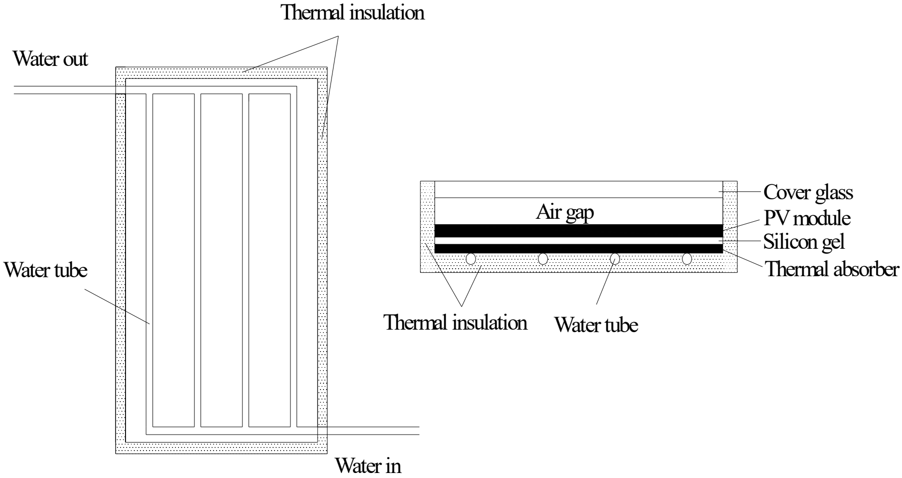

Fig. 1 Cross-section of the BIPVT module

3 Simulation prerequisites

Fig. 1 shows the cross-section schematic of the BIPVT module. The dimension of the BIPVT module is 1.6m×0.8m. The water tubes are connected in parallel. The reference electrical efficiency of the PV cell is set as 16% and the coving factor of the PV cell is 1.0. The orientation of the BIPVT module is due south and its tilt angle is set as 20°. The weather data come from a selected day of the year of 1989[9] in Hong Kong and the simulation period is from 9:00am to 16:00pm. Table 1 shows physical properties of main components of the BIPVT module and several configuration parameters of the initial design.

Table 1. Physical properties and initial design parameters

1.Cover glass	
1.1Thickness	3mm
1.2Emmissivity	0.88
1.3Density	2515kg/m^3
1.4Thermal capacity	810J/(kg·K)
1.5Thermal conductivity	23.7W/(m·K)
2.Air gap	
2.1Thickness	20mm
2.2Density of air	1.29kg/m^3
3.PV module	
3.1Thickness of PV cell	0.5mm
3.2Emmissivity of PV cell	0.88
3.3Absorptivity of PV cell	0.9
3.4Density of PV cell	2330kg/m^3
3.5Thermal capacity of PV cell	700J/(kg·K)
3.6Thermal conductivity of PV cell	150W/(m·K)
4.Thermal absorber (Aluminum)	
4.1Thickness	5mm
4.2Density	2700 kg/m^3
4.3Thermal capacity	880 J/(kg·K)
4.4Thermal conductivity	237W/(m·K)
4.5Resistance of insulation	0.83(m^2·K)/W
4.6Resistance of bond	7.6×10^{-5}(m^2·K)/W
4.7Resistance of Silicon gel	3.8×10^{-3}(m^2·K)/W
5.Water tube	
5.1External diameter	22mm

5.2Internal diameter	20mm
5.3Spacing of water tubes	0.2m
6.Water tank(cylinder)	
6.1Diameter	0.4m
6.2Height	0.8m
7.Mass flow rate	0.01kg/s

4 Simulation and results discussion

The BIPVT module can produce electrical power and generate hot water simultaneously. The thermal heat used for heating hot water can be converted into electrical power by the electrical efficiency of conventional power plant. The electrical efficiency of 38% used in this simulation is recommended by Hung [1]. Then both the electrical performance and thermal performance of the BIPVT module are compared in the term of the electrical power.

4.1 Thickness of Cover Glass

The electrical power produced by PV module (PV) and Hot Water (HW) for varied thickness of the cover glass is shown in Fig. 2. As the cover glass thickness increases from 1mm to 6mm, electrical power of PV decreases while electrical power of HW almost does not change. Thus the BIPVT module with small cover glass thickness produces more electrical power. The cover glass thickness of 1mm is the best choice.

4.2 Thickness of Thermal Absorber

As shown in Fig. 3, electrical power of HW decreases and PV increases as the thickness of the thermal absorber increases form 3mm to 10mm. It is indicated that the amount of electrical power reduction of HW is larger than the electrical power increase of PV. Thus the BIPVT module with the thermal absorber thickness of 3mm produces more electrical power than that of larger values.

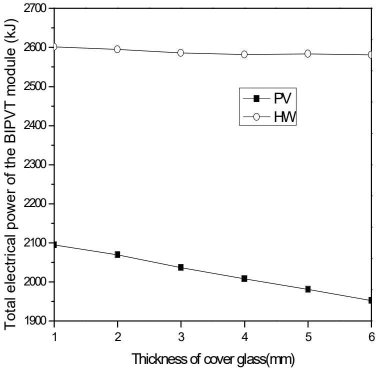

Fig. 2 Electrical power for varied thickness of cover glass

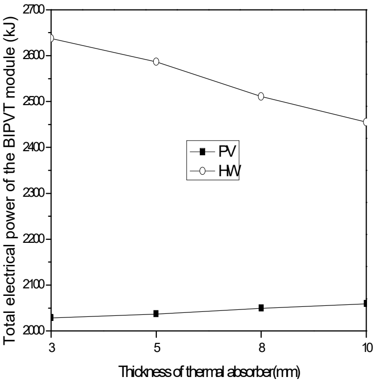

Fig. 3 Electrical power for varied thickness of thermal absorber

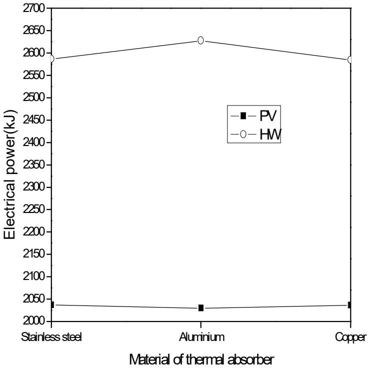

Fig. 4 Electrical power for varied mate of thermal absorber

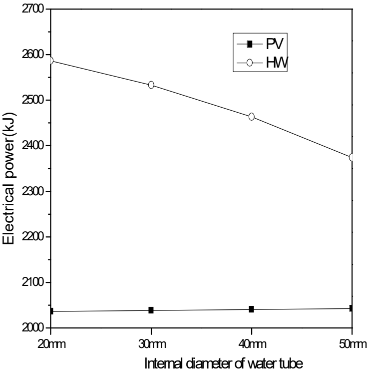

Fig. 5 Electrical power for varied internal diameters of water tube

4.3 Material of Thermal Absorber

The electrical power of PV and HW for three kinds of thermal absorber material, including Stainless steel, Aluminium and Copper, are shown in Fig. 4. The thermal absorber material almost does not affect the electrical power of PV because the electrical power of PV is nearly the same for three different materials. For the electrical power of HW, the thermal absorber made of Aluminium has the best performance. Therefore, Aluminium is the preferred material of the thermal absorber.

4.4 Internal Diameter of Water Tube

The electrical power of PV and HW for varied internal diameters of water tube is shown in Fig. 5. The electrical power of PV increases as the internal diameter of the water tube increases. While the electrical power increase of PV is so insignificant that it is neglected. The electrical power of HW decreases quickly as the internal diameter of the water tube increases. When the water tube internal diameter is 50mm, the electrical power of HW is 2374.1kJ, reducing by 8.2% compared with 2586.8kJ of 20mm. Therefore, the BIPVT module with water tubes of smaller internal diameters is more cost-effective.

4.5 Spacing of Water Tube

Fig. 6 shows that as the spacing of water tubes increases, electrical power of PV and HW both decrease. It is clear that the impact of spacing of water tubes on electrical power of HW is more significant than that of PV. When the spacing of water tubes is 0.2m, the total electrical power of BIPVT module equals 4623.8kJ. As the water tube spacing increases to 0.8m, the total electrical power decreases to 2469.3kJ, reducing by 53.4% compared with that of 0.2m. Although the initial cost of the BIPVT module with the water tube spacing of 0.2m is high, it is more cost-effective if the total energy benefits during the life time are considered.

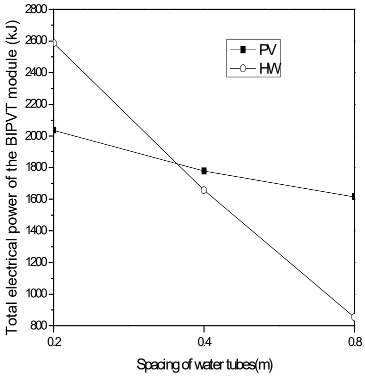

Fig. 6 Electrical power for varied spacing of water tubes

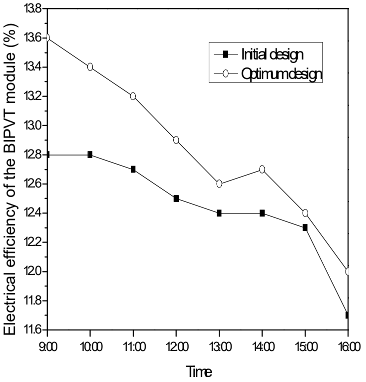

Fig. 7 Electrical efficiency of BIPVT module

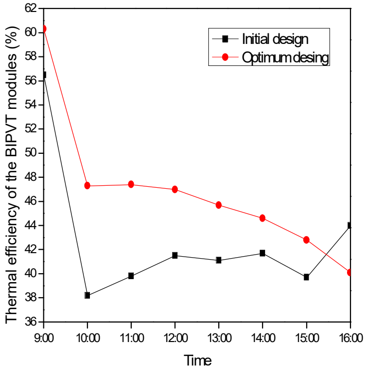

Fig. 8 Thermal efficiency of BIPVT module

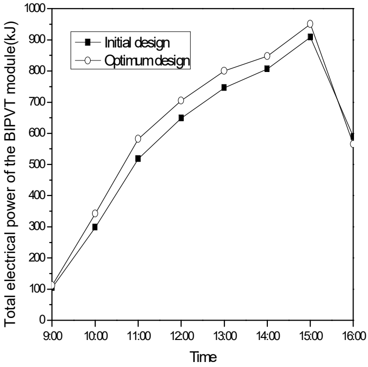

Fig. 9 Total electrical power of BIPVT module

4.6 Optimum Design

The comparison for configuration parameters mentioned above between the initial design and optimum design are shown in Table 2. There are small changes of parameters between two designs. Fig. 7-9 show the hourly electrical efficiency, hourly thermal efficiency and total electrical power of the BIPVT module for the initial design and optimum design. The hourly electrical efficiency of the BIPVT module in the optimum design has improved compared with that of the initial design. The largest increase of the electrical efficiency of 6.3% occurs at 9:00am, and the smallest one of 0.8% at 15:00pm. The hourly thermal efficiency of the BIPVT module in the optimum design increases during the most of the simulation period except the hour of 16:00pm. The energy performance of the BIPVT module for the initial design and the optimum design has been summarised in Table 3. It indicates that the effect of these configuration parameters on the thermal efficiency is more significant than the electrical efficiency.

Table 2. Configuration parameters of the BIPVT module

Parameter	Initial design	Optimum design
Thickness of cover glass	3mm	1mm
Thickness of thermal absorber	5mm	3mm
Material of thermal absorber	Aluminium	Aluminium
Internal diameter of water tube	20mm	20mm
Spacing of water tubes	200mm	200mm

Table 3. Energy performance of the BIPVT module

Item	Initial design	Optimum design	Increase ratio
Average electrical efficiency	12.4%	12.9%	4.0%
Average thermal efficiency	42.8%	46.9%	9.6%
Total electrical power	4623.9kJ	4907.9kJ	6.1%

5 Conclusions

A dynamic simulation model has been developed and utilized to evaluate the energy performance of the BIPVT module. From the simulation results presented in this paper it is shown that configuration parameters of the BIPVT module can be varied to maximise the energy performance. The fact is that little improvement of the configuration parameters of the BIPVT module can significantly increase the energy performance, especially the thermal efficiency of the BIPVT module. The analysis of these configuration parameters and simulation results are good references for design and utilization the BIPVT module in Hong Kong.

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