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SOCIAL-ECONOMIC BENEFITS OF A NOVEL PHOTOVOLTAIC/LOOP-HEAT-PIPE SYSTEM AND ITS ADAPTABILITY IN BUILDING ENERGY PLANT

SPOŁECZNO-EKONOMICZNE KORZYŚCI PŁYNĄCE Z NOWEGO FOTOWOLTAICZNEGO (LOOP-HEAT-PIPE) SYSTEMU ORAZ JEGO ADAPTACJI W BUDYNKU

Abstract

This article describes a novel photovoltaic/thermal (PV/T) water heating system. Through incorporating a loop-heat-pipe (LHP) and a heat pump, the system can essentially maximise the electrical return of PV panel, and simultaneously produce a reasonable amount of heat. This system can therefore harvest larger amount of solar energy and enable enhanced system performance. It is expected that such dedicated technology could become the next generation of solar driven heating system and enable a significant reduction of building's carbon footprint.

Keywords: Social-economic, PV/T, Loop heat pipe, energy envelope

Streszczenie

Artykuł ten opisuje nowe fotowoltaiczno-termiczne (PV/T) systemy ogrzewania wody. Poprzez włączenie do pętli ciepłowodów (LHP) oraz pompy ciepła system może w istocie zmaksymalizować zwrot elektryczny panelu fotowoltaicznego, a jednocześnie produkować wystarczającą ilość ciepła. System ten może więc zebrać większą ilość energii słonecznej i zwiększyć wydajność systemu. Oczekuje się, że takie dedykowane technologie mogą stać się następną generacją instalacji solarnej j i umożliwić znaczną redukcję emisji dwutlenku węgla.

Słowa kluczowe: społeczno-ekonomiczne, PV/T, pętle ciepłowodów

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Denotations

A_c – collecting area [m^2]
COP – coefficient of performance
I – solar radiation [W/m^2]
Q – energy rate [W]
W_c – work of compressor [W]
η – energy efficiency [%]
ζ – exergy efficiency [%]

1. Introduction

The PV/Thermal (PV/T) technology enables the dual solar collecting functions in one module for output of both electricity and heat. Such synergetic integration of PV and thermal collector not only results in improved PV efficiency [1], but also generates more energy per unit area whilst compared with standard-alone PV panel or solar collector. Additional characteristics of the PV/T technology lie in potential savings in material use, reduction in installation cost and homogeneous facade appearance [1]. It is now becoming a significant solution to yield more electricity and offset heating load freely in contemporary energy environment.

In recent years, the heat-pipe based PV/T technology was proposed due to its specific characteristics, such as large heat-transfer capacity, availability of anti-freezing media, hermetically sealed loop and homogeneous capillary force [2]. Loop heat pipe (LHP), as a special type of heat pipe, has large capacity of remote and passive heat transfer by circulating the working fluid in a closed loop. LHP has the separate configuration of vapour and liquid transportation lines without the entrainment between the two-phase flows, which leads to a large heat flux transported in long distance. Such feature enables the wide applications of LHP in thermal controls of satellites, spacecrafts, electronics, lighting and cooling/heating systems [3]. However, conventional gravitational LHP faces common ‘dry-out’ phenomena on the top wick surface due to the limited capillary force for liquid elevation [4]. A novel LHP structure with the top-positioned three-way feeder was therefore initiated to overcome the above difficulty. In addition, an aluminium-alloy (Al-alloy) sheet will be utilised as the PV baseboard to accelerate heat dissipation at the back of PV cells [5]. When such LHP integrates with the PV layer, a new PV/LHP module will be developed. The heat pump will be involved to remain a steady-and-low system working temperature. In line with this initiative, a social-economic study of such a PV/LHP heat-pump system will be conducted. The research result will assist the accelerated deployment of the PV/T technologies, resolve the fuel poverty and reduce carbon emission in future energy supply.

2. System Description

Fig. 1 illustrates the PV/LHP heat pump water heating system. The system comprises a modular PV/LHP collector, an electricity control/storage unit, the vapour/liquid transportation lines, a flat-plate heat exchanger, a hot water tank, a compressor, a coil-type condenser embedded into the water tank and an expansion valve.

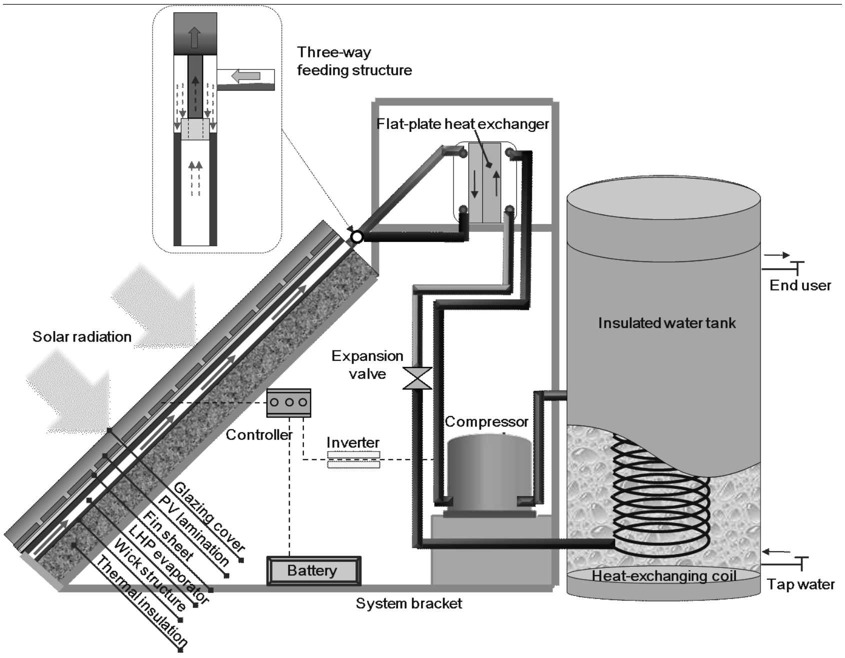

Fig. 1. Schematic of the solar PV/LHP heat pump water heating system

A prototype PV/LHP heat pump system was designed with a total effective absorbing area of 0.612m^2. The PV/LHP module was fixed to the 30^o tilted frame and fitted with the single glazing cover on top. The PV cells, consisting of totally 36 (4 × 9 array) pieces each with sizes of 125 × 125 × 0.3 (mm × mm × mm), took up nearly 90% of the absorbing surface. Table 1 presents the values of the characteristic parameters relating to the PV cells under the standard testing conditions. When making-up the PV layer, a black 5052 aluminum alloy sheet coated with 20μm anodic oxidation film (electrical insulation) was used to replace the conventional TPT (Tedlar-Polyester-Tedlar) base-board for the PV cells. A 5 mm thick aluminum Ω-type fin sheet, embracing a wicked pipe (with 160 × 60 copper meshes), was adhered to the PV base-board using the silicon sealants. This pipe, when being connected to the liquid and vapour transportation lines and condensing heat exchanger, formed up a loop that was evacuated and then filled with 75ml of water/glycol mixture (95%/5%) as the working fluid. The detailed technical data relating to the loop components are given in Table 2. The system employed a 0.735 kW-rating heat pump with the evaporation/condensation temperatures of 10°C/55°C, which was charged with 300g of R134a refrigerant. A 35-liter water tank with a built-in copper heat exchanging coils was also installed and connected to the heat pump to obtain heat and store the heating water. The electrical parts of the system include a 12 V (10A) controller, 500W DC/AC inverter, a 100AH (12 V) battery, and the connection wires.

Table 1

Photovoltaic characteristics of the PV module under standard testing conditions

At short-circuit current	$I_{SC} = 5.54$ A, $V_{SC} = 0$ V
At open-circuit voltage	$I_{OC} = 0$ A, $V_{OC} = 22.32$ V
At the maximum power point	$I_{mp} = 4.89$ A, $V_{mp} = 18.23$ V ($P_{mp} = 89.1$ W, $\eta_o = 16.8\%$)

Table 2

Design parameters of the LHP operation and heat exchanger

Parameters	Value	Unit
Diameter of heat pipe	0.022/0.0196	[m]
Internal diameter of vapour column (three-way fitting)	0.014	[m]
Operating presssure in heat pipe	1.3×10^{-4}	[Pa]
Heat pipe evaporator length	1.2	[m]
Evaporator-to-condenser height difference	0.3	[m]
Liquid filling level	75	[ml]
Heat pipe transportation line length	1.0/0.9	[m]
Wire diameter (wick layer I/II)	$7.175 \times 10^{-5}/12.23 \times 10^{-5}$	[m]
Layer thickness (wick layer I/II)	3.75×10^{-4}	[m]
Mesh number (wick layer I/II)	6299/2362	[m]
Heat exchanger plate cluster width/ length/ height	0.076/0.055/0.206	[m]

3. Results and Discussion

3.1. Modelling results

The annual operational performance of the prototype system could be predicted by using the established computer model, which has already been proved with a reasonable accuracy [6]. The input weather data of Shanghai (121.8°E, 31.2°N) are derived from the Energy-plus software (583670_IWEC) [7]. It was found the mean electrical, thermal and overall energetic/ exergetic efficiencies of the PV/LHP module were 9.13%, 39.25% and 48.37%/15.02% respectively. The system performance coefficient (COP) was almost 5.51. The available amount of solar radiation in Shanghai was 1516 kWh/m^2-yr. As a result, the annual electrical generation, thermal output, heat-pump power consumption, and heat-pump condensation heat production of the system were estimated at 85 kWh/yr, 364kWh/yr, 81 kWh/yr and 445 kWh/ yr respectively. The initial water temperature was assumed at 16°C on average in the 35L tank, referring to the ground water temperature at depth of 0.5 m while the temperature criteria of hot water supply were set at 45°C. Thus, the annual hot-water demand will be around 432 kWh/yr. It is seen that this system can meet the hot-water load throughout the year by outputting additional electricity of 4kWh/yr while subtracting the electricity consumption of compressor from the PV generation.

3.2. Energy, Economic and Environmental Benefit

Performance of such a novel LHP and associated solar PV/T system presents several remarkable advantages over the existing straight heat pipe and LHPs and associated solar thermal collecting and PV/T systems in Fig. 2 [8–15]: (1) heat transport capacity of the new LHP was 6.75 and 1.55 times that of the straight HP and LHP in gravitational field; (2) solar efficiency of the new LHP based solar thermal collecting system was 18% higher than that for the conventional solar thermal collecting systems; (3) solar exegetic efficiencies of the new LHP based PV/T system was 24% higher than that of the existing PV/T systems; and (4) Coefficient of performance (COP) of the new LHP based solar heat pump system was 1.5 times that of the conventional solar heat pump systems.

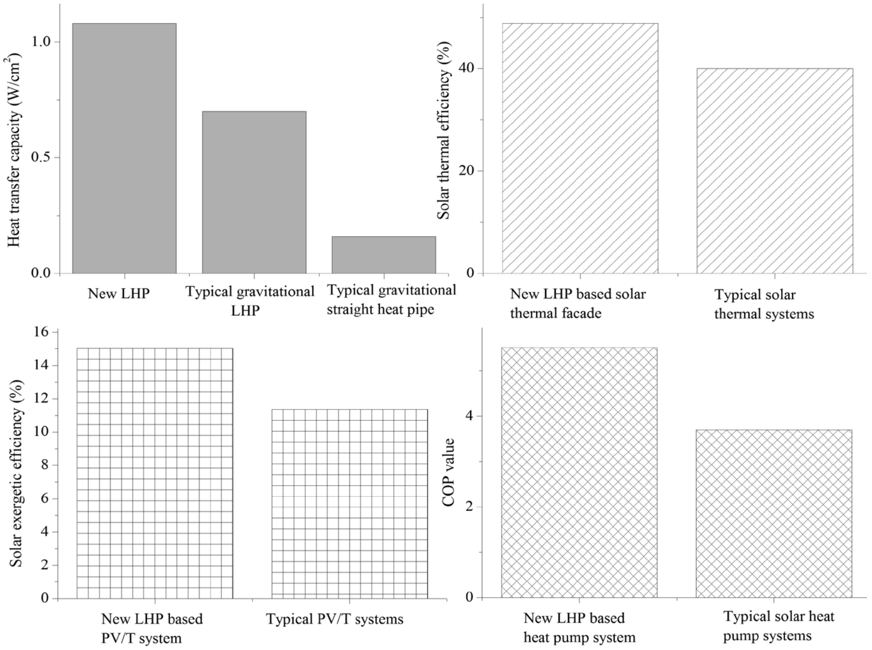

Fig. 2. The new LHP and associated thermal and power systems against the conventional ones

A simple analysis into the economic and environmental benefits of the PV/LHP heat pump water heating system was carried out using the mean values from above simulation results. The electricity price from national grid is CNY￥0.8/kWh [16] and electricity from the distributed PV panels in Shanghai is CNY￥1.35/kWh [17]. Capital cost of the system is about CNY￥6,050. To replace with a conventional electric water heater of 90% heating efficiency, the system's payback periods were estimated at nearly 16 years in Shanghai. The CO_2 emission reduction was estimated at 12 tons by the electricity-to-CO_2 conversion factor (0.997 kg CO_2/kWh-heat in Shanghai [18]) throughout its life span of 25 years.

3.2. Adaptability to Future Building Energy Plant

The overall concept, as shown in Fig. 3, is to use an LHP device to cool the PV cells, thus enabling improvement in PV efficiency and, meanwhile, make feasible use of the absorbed heat through a heat pump for one or more of the following purposes: space heating, hot water supply, desiccant and evaporative cooling, and natural ventilation in buildings. Electricity generation from the PV cells, either exported to the national grid or stored in batteries, will meet the building electrical load and drive the heat pump compressor. The LHP device can passively transfer a large amount of heat for a long distance using its capillary power, thus eliminating the need for a circulation pump. The combination of these concepts is expected to create a low (zero) carbon heating, ventilation and air conditioning (HVAC) and hot water supply system driven by solar energy.

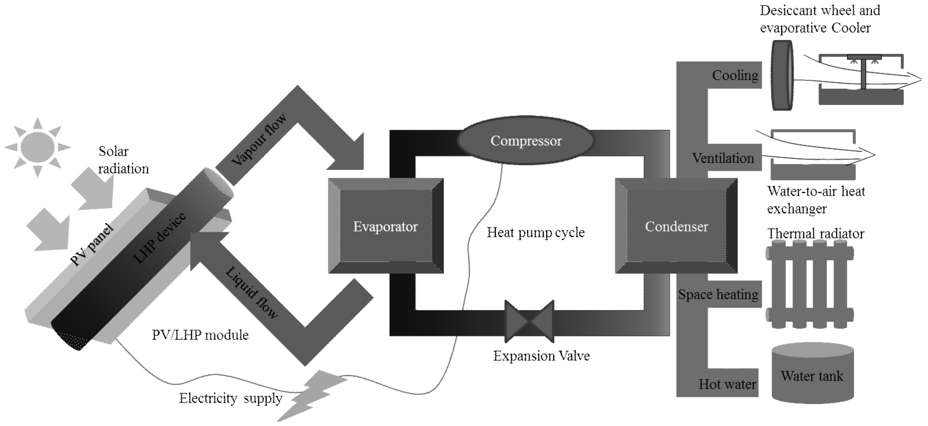

Fig. 3. Schematic of the PV/LHP heat pump micro-generation system for building services

To enable a widespread deployment of such hybrid solar technology, the explicit benefits and challenges for PV/LHP stakeholders have been identified as summarised in Table 3 [1], which need to be elaborated during the coming years. What seems necessary is the establishment of an interdisciplinary working group which can attain sound information exchange of results related to R&D, design specifications, design tools, test methods, installation barriers, market surveys, and policy development. This interdisciplinary cooperation may lead to a clear understanding of various problems over the PV/LHP developments.

Table 3

Opportunities and challenges for PV/LHP stakeholders

Stakeholders	Opportunities	Challenges
R&D institutes	Quest for new technological solutions	• Performance and reliability standards • Increased system performance
Engineering Consultants	Innovative and high profile technology	• Design tools development • New system concepts development
Architects	New solutuions for integration	• PV/LHP integrated with building design • New building concepts
Installers	Reduced installation effort	• Plug-and-play integration in comfort systems • Combination of two professional specialisms
Building Industry	Increased energy performance	• Integration of module into building facade • Prefabrication possibilities
Manufacturers	Enlarged markets	• Cost-effective production • Plug-and-play systems
Policy makers	More effective path to renewable targets	• Building regulations, market and R&D support

4. Conclusions

This article illustrates a PV/LHP heat-pump water heating operation in Shanghai. Performance of such a novel LHP and associated solar PV/T system presents remarkable advantages over the existing straight heat pipe/LHPs and associated solar thermal and PV/T systems.The analysis of economic and environmental benefits demonstrated this system might be competitive in future energy supply with its payback period of 16 years and life-cycle carbon reduction of 12 tons. Explicit benefits and future challenges were brought forward for PV/LHP stakeholders to accelerate the development of such technology.

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MATHEMATICAL FORMULAE

Thermal efficiency of a PV/LHP module is the ratio of useful thermal energy (Q_{th}) to incident irradiation (I) striking on the collecting area (A_c):

$$\eta_{th} = Q_{th} / IA_c \qquad \text{\\* MERGEFORMAT} \qquad (1)$$

Electrical efficiency of a PV/LHP module is the ratio of electricity generated from PV cells (Q_e) to the overall incident irradiation:

$$\eta_e = Q_e / IA_c \qquad \text{\\* MERGEFORMAT} \qquad (2)$$

The overall efficiency of a PV/LHP module will be the sum of above two efficiencies. The overall exergetic efficiency could be derived as:

$$\xi_o = \eta_c \eta_{th} + \eta_e \qquad \text{\\* MERGEFORMAT} \qquad (3)$$

where:

η_c – the ideal Carnot efficiency determined by the working fluid and surrounding air.

The performance coefficient (*COP*) of a heat pump system is defined as the ratio of heating or cooling generated (Q_w) to the electrical energy consumed (W_c):

$$COP = Q_w / W_c \qquad \text{\\* MERGEFORMAT} \qquad (4)$$