Master's Thesis of Engineering

A Study on Thermal Performance and Applicability of Flat-Plate Water Type PVT System

평판형 액체식 PVT 시스템의 열적 성능 및 적용 방안에 대한 연구

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Abstract

Since the 1970s, a Photovolataic−Thermal(PVT) system has been developed and researched to solve the problem of Photovoltaic(PV) system, whose efficiency decreases as the temperature increases.

The PVT system is a PV system that has an air tunnel or water pipe attached to the panel's back as a heat absorber. By lowering the temperature of the PV module, electrical efficiency can be increased. Using waste heat that has radiate to the surroundings, it can also produce hot water. Over the past ten years, research on PVT systems has drawn interest as the use of renewable energy sources has become a significant issue.

However, research on the architectural use of the PVT system is still insufficient. The reasons for the lack of research on the architectural use of the PVT system are as follows. First, there is a lack of information regarding the PVT panel's thermal performance. Second, there hasn't been enough research done on a HVAC system that can use hot water produced by the PVT system that is relatively low in temperature(25~45℃).

In this study, the author reviews existing literature and research on PVT system, examines the thermal performance (Produced theramal energy rate, hot water temperature) of PVT systems that vary with environmental conditions(solar radiation, outdoor temperature, wind speed), proposes and evaluates an applicable HVAC system.

Keyword : PVT, Thermal performance, Renewable energy,
Low temperature radiant floor heating system
Student Number : 2021-27250

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Chapter 1. Introduction

1.1 Background and Purpose

To deal with rapid climate change, the world is attempting to reduce carbon emissions. However, it's anticipated that energy consumption will continue to rise due to the growth of the global economy.① As a result, there is a growing demand for renewable energy sources, such as solar sources, such as solar energy, geothermal energy, hydrogen energy, etc.

Solar energy is a significant energy source that still accounts for more than 50% of the market for renewable energy, which is shrinking due to COVID-19.② Solar energy is a clean, abundant, and affordable renewable energy source that is used for electric power generation, lighting, and heating. Solar energy systems can be broadly classified into two types: photovoltaic systems and solar collector(thermal) systems.

A photovoltaic(PV) system is a system that uses solar cells that convert solar radiation energy into electrical energy. It has been developed and applied in various ways, such as being used as a building wall, as demand has grown. The power generation efficiency of a single crystalline silicon-based PV module is only about 20%, and the remaining energy of 80% or more is thermally converted, thus raising the temperature of the PV module and being radiated to the surroundings. Figure 1.1 shows the utilization of

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① IEA, 2021, World Energy Outlook 2021

② Kim Jaemin, "Study on the Performance Improvement of Solar Energy Systems Using Cooling Technologies", 2021, Master's thesis, Pusan National University

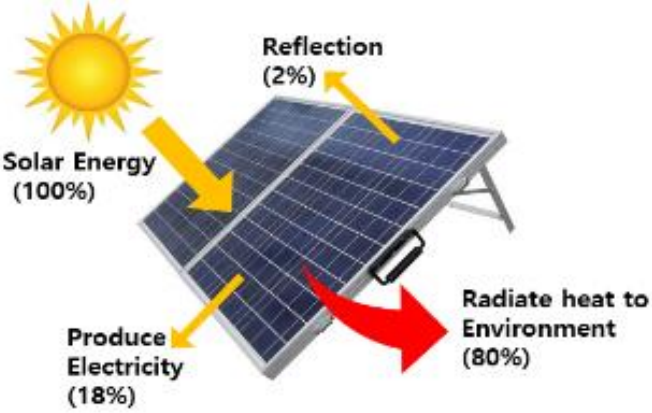

Figure 1.1 Solar energy utilization through PV panel③

solar energy through PV panel. Electrical efficiency of the PV system is affected by environmental conditions such as solar radiation and outdoor temperature. As the temperature of the PV module increases, the electrical efficiency decreases. Due to this characteristic, even when the solar panel receives enough solar radiation, high power generation efficiency cannot be anticipated. This lowers the total utilization rate of solar energy sources due to the large amount of energy that is not used and radiated around it.

Since the 1970s, a Photovolataic-Thermal(PVT) system has been developed and researched to solve the problem of the PV system, whose efficiency decreases as the temperature increases.④

The PVT system is a PV system that has an air tunnel or water pipe attached to the panel's back as a heat absorber. By lowering the temperature of the PV module, electrical efficiency can be increased. Using waste heat that has radiate to the surroundings, it can also

③ M. Chandrasekar, T. Senthilkumar, 2021, Five decades of evolution of solar photovoltaic thermal (PVT) technology – A critical insight on review articles, Volume 322

④ Kern, Jr., E. C, Russell, M. C., 1978, Combined Photovoltaic and Thermal Hybrid Collector Systems, IEEE photovoltaic specialists conference produce hot water. Over the past ten years, research on PVT systems has drawn interest as the use of renewable energy sources has become a significant issue.

However, research on the architectural use of the PVT system is still insufficient. The reasons for the lack of research on the architectural use of the PVT system are as follows. First, there is a lack of information regarding the PVT panel's thermal performance. Second, there hasn't been enough research done on a HVAC system that can use hot water produced by the PVT system that is relatively low in temperature(25~45℃).

In this study, the author reviews existing literature and research on PVT system, examines the thermal performance (Produced theramal energy rate, hot water temperature) of PVT systems that vary with environmental conditions(solar radiation, outdoor temperature, wind speed), proposes and evaluates an applicable HVAC system.

1.2 Scope and Method

In this study, the author examines the thermal performance of the PVT system through experiments and simulations. The author also proposes and evaluates an application plan. In the simulation, MATLAB and EnergyPlus were used for PVT system and building modeling. The experiment was conducted in heating season, using a lightweight flat-plate water type PVT panel. The simulation model was verified based on the results of the experiments.

This paper consists of five chapters. Chapter 1 discusses the background, purpose, scope and method of this research. Chapter 2 examines the theory of the PVT system and existing literature.

Chapter 3 investigates the thermal performance of the PVT system by performing simulations and experiments. Based on the results of Chapter 3, Chapter 4 proposes and evaluates an applicable HVAC system. Chapter 5 discusses a comprehensive conclusion on the thermal performance and application plan of the PVT system. The flow of research is shown in following **Figure 2.1**.

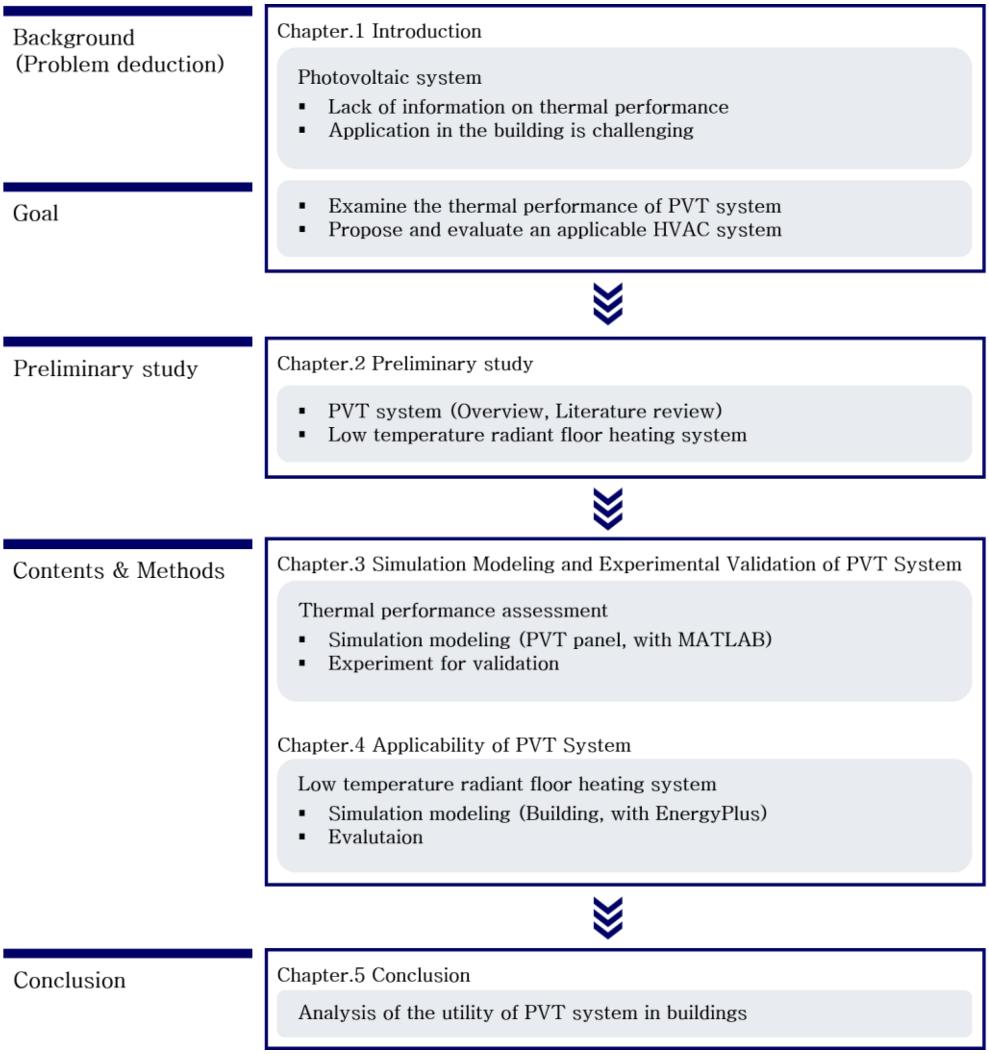

Figure 2.1 Research flow chart

Chapter 2. Preliminary Study

2.1 Photovoltaic Thermal System

2.1.1 Overview

1. Definition

PV modules can improve power generation efficiency through cooling technology that can control the temperature of PV cell. In particular, since cooling technology using refrigerant circulation exchanges heat through refrigerants, it is superior to other technologies such as air cooling technology using heat exchange by natural convection. [5]

The PVT system is a system that removes heat generated from the rear surface of the PV module simultaneously with the electricity production of the PV module using a heat medium and uses the waste heat as a necessary heat source for a building. The following figure (Figure 2.1) is a PVT module. The cooling effect of the PV module increases power generation efficiency, obtains heat energy through a heat absorber attached to the rear, and uses it for heating and hot water, which can increase solar energy utilization in buildings and reduce energy consumption. [6]

PVT modules may have higher energy conversion efficiency per unit area than independent systems of PV modules and solar collectors, but the heat collection and power generation performance of PVT modules have conflicting operating conditions, so appropriate

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[5] M. Chandrasekar, T. Senthilkumar, 2021, Five decades of evolution of solar photovoltaic thermal (PVT) technology – A critical insight on review articles, Volume 322

[6] Lee Eui June, 2006, 태양광열복합 활용 열.전기 동시 생산 설비기술 현황과 전망, Journal of KARSE, Vol23, No.1, pp.3

control is required.

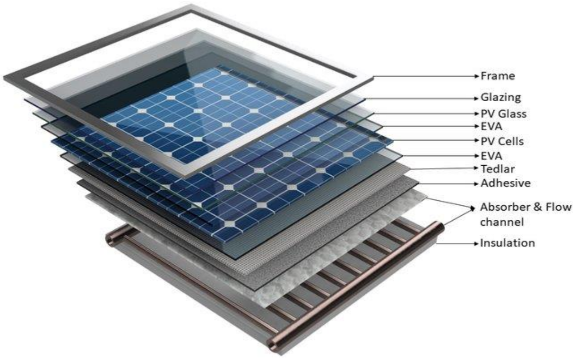

Figure 2.1 Configuration of PV panel⑦

2. Classification

PVT systems are classified into various types according to the type of heat transfer medium, the presence or absence of a glass cover, and the shape of a panel and a heat absorber. Depending on the type of heat transfer medium, it is classified into flat plate type, condensing type, and tube type according to the type of windowless type, fluorescent type, panel type, and heat absorber type according to the type of heat transfer medium. Various types of PVT systems can be represented as shown in **Figure 2.2**. In this study, a flat−plate water type unglazed PVT panel was targeted.

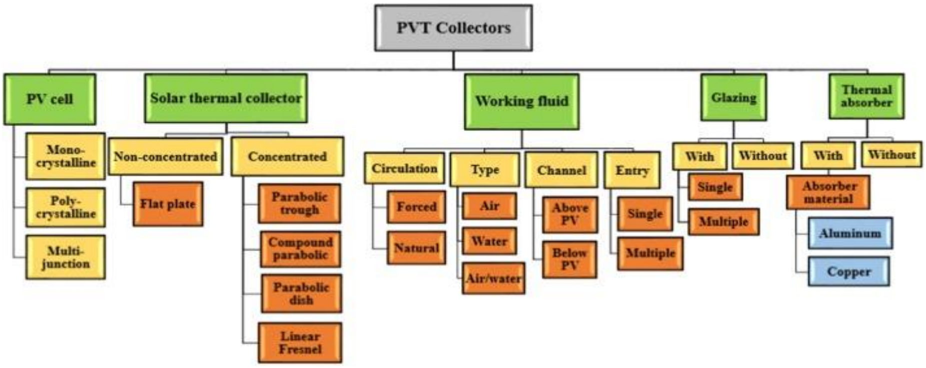

Figure 2.2 Classification of PVT collectors⑧

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⑦ Hanwha Q cell, https://q-cells.us/kr/main.html

⑧ Amal Herez et al. (2020), Review on photovoltaic/thermal hybrid solar

3. Configuration

The PVT system basically consists of a PV module, a heat absorber plate, a heat transfer medium, a heat storage tank, a heat exchanger, an auxiliary heat source, and an inverter. The basic shape of the PVT panel and the panel used in this study are shown in Figure 2.3.

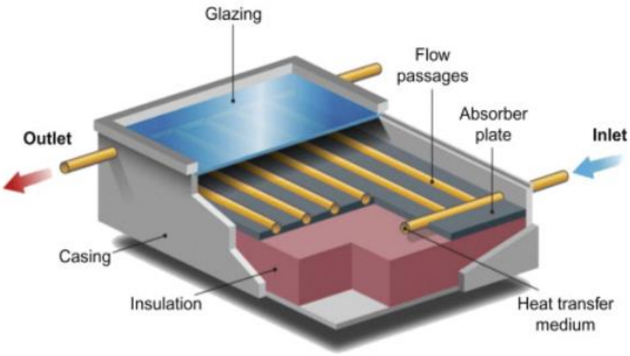

Figure 2.3 Basic shape of the PVT panel

4. Basic principle

The PVT system is a combination of a solar module and a solar module, and the shape is shown in Figure 2.5 below. The basic principles of each power generation and heat collection are as follows.

(1) A photovoltaic (PV) is a semiconductor device having a diode junction structure. In PV, when particles with light energy among solar radiation have a value of a certain solar constant (E) or higher, electrons are generated in a p-type semiconductor and electrons are generated in an n-type semiconductor. The electrons and pores made in this way move to n-type and p-type semiconductors, respectively, which generate current flow due to the movement of

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collectors: Classifications, applications and new systems, Solar Energy, Volume 207, pp. 1321-1347

Collector Designs: A Review - Scientific Figure on ResearchGate.

electrons, and generate electrical energy when loads are connected to the outside. The following figure (Figure 2.6) briefly describes the basic operating principles of PV modules.

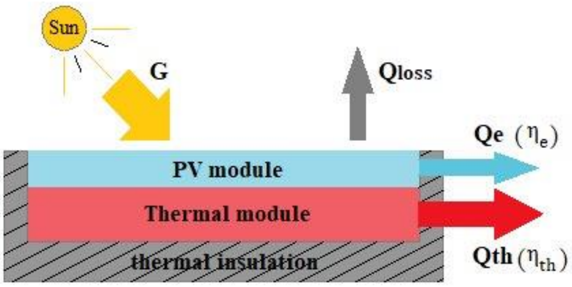

Figure 2.5 PVT system

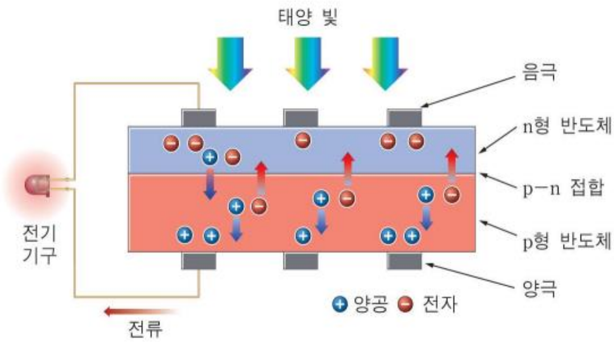

Figure 2.6 PV cell operating principle

(2) The solar collector module converts radiant energy from the sun into thermal energy and can be used or stored directly, and the solar system consists of the following figure (Figure 2.9) heat collection unit, heat storage unit, utilization unit, and control unit.

Solar energy incident on a solar module or collector is absorbed into the absorption plate in the form of heat energy, and the absorbed heat is transferred to the heat transfer medium inside the absorption plate to be stored in the heat storage unit or directly supplied to the use unit.

5. Thermal and electrical efficiency

Thermal and electircal efficiency of the PVT system follows next equations, respectively.[⑨]

$$\eta_{thermal} = \frac{Q_u}{I_T A_c} \tag{2.1}$$

$$\eta_{electrical} = \frac{I_m V_m}{G A_c} \tag{2.2}$$

⑨ EnergyPlus version 9.5 documentation, U.S. Department fo Energy, engineering reference

2.2.1 Literature Review

1. Research Trends

1) Global research trends

Foreign academic prior studies on PVT systems can be classified into the following topics, and overall, it is necessary to study performance improvement and control strategies when applied due to value engineering, especially cost reduction, and facility heat sources.

1) comprehensive, 2) design, 3) building integrated PVT, 4) concentrated PVT, 5) phase change materials, 6) nanofluids, 7) performance, 8) exergy, 9) environmental, 10) specific applications, 11) others

Photovoltaic-thermal modules technology has been developed since the 1970s, and over the past 40 years, various solar (PV) and solar (ST) combinations have been studied, and most development types have been made at an academic level, and commercialization has been relatively small. However, PVT products are steadily being released in the market, and recently, the PVT market is also forming a market for solar heat modules due to the price drop of PV and the expansion of the PV market. In recent years, market research studies have been reported for PVT dissemination and infrastructure construction, and the number and types of commercially available products have increased over the past 15 years, and there are currently about 50 PVT product manufacturers in Europe alone.

2) Domestic research trends

Previous domestic studies on the PVT system can be mainly classified into the following topics. Research cases on architectural use and application are insufficient. Research on the heating and hot water preheating system combined with smart farms, quarterly heat storage tanks, or geothermal heat has been simply conducted, and there are no research cases that have applied the PVT system as a heat source for summer facilities.

1) Check performance of systems; 2) Comparison of performance and efficiency of single PV panels, solar collectors, PVT systems; 3) Relationship between power output, solar radiation, and circulating water temperatures; 4) Airborne PVT thermal and electrical production performance; 5) Simulation performance and economic analysis; 6) Reliability verification; and others

Domestic PVT technology is being developed based on foreign technology, and research institutes and several companies are promoting commercialization development research. Recently, demand for research and development and commercialization of a photovoltaic module (PVT) in a form in which a photovoltaic module and a solar collector are combined is gradually increasing, but there is still a limit to the expansion of supply. This is due to the lack of performance evaluation criteria for solar heat modules, which makes it difficult to use them architecturally as they expand the supply of commercialized products and become a type of renewable energy source. Currently, KS C 8561 and KS B 8295 are applied in Korea to evaluate the performance of crystalline solar cell modules and solar collectors, and there is no KS certification standard for solar heat modules. For overseas, ISO 9806 and EN 12975 standards evaluate the performance of solar collectors and the performance of solar cell modules with IEC 61215. However, only ISO 9806 suggests a method for testing the thermal efficiency of photovoltaic modules, and even in overseas cases, there are almost no standards for evaluating the performance of photovoltaic modules.

2.2 Low Temperature Floor Heating System[10]

According to the study of existing heating systems in Korea, the hydronic heating system is currently the only option for apartment houses, compare to forced air systems in that they heat the circulating liquid thermal medium, which in turn heats the environment air in the building or room. In a forced−air system, the air is warmed directly and mixed with the ambient air in the building to reach the requested temperature. Hydronic heating systems typically consist of three basic elements: a heating system for the generation of hot water, a distribution system for transporting hot water, and a heat exchange system for heat transfer to space. With radiant floors, the most common heat exchange system of space heating in Korean apartment buildings, once the geometric factors of the radiant floor heating panels mounted in the room have been clearly determined, the heating performance of the system during its operation is completely contingent on the working conditions of the thermal fluid flowing through it.

For Hydronic heating systems, various options for each subsystem exist. Depending on the heat source to be used for the entire heating system, both district heating systems, and individual heating systems are currently used in apartment houses in Korea. As an alternative, the heating system can also be categorized based on the temperature of the hot water delivered in the distribution system. According to the related research, the heating system may be divided into a high−temperature heating system, medium−temperature

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[10] Choi, Chang-Sik et al. "Analysis on the heat source and the distributionsystem operation of apartment house complex using a district heatingsource." Proceedings of the SAREK Conference (2015): 545-546.

heating system, low-temperature heating system, and very low temperature heating system respectively in accordance with the temperature of the heat medium. The supply and return water temperature of each type of system is generally shown in table. [11]

Table 4.1 Water temperature of Space Heating (District Heating System)[12]

System	Supply flow	Return flow
High temperature	90 ℃	70 ℃
Medium temperature	55 ℃	35~40 ℃
Low temperature	45 ℃	25~35 ℃
Very low temperature	35 ℃	25 ℃

[11] Xue Yan, "A Study on the Applicability of Low-temperature Heating System for Maintaining Thermal Comfort and Reducing Heating Energy in High-Insulation, High-Tightness Apartment Houses.", 2022, Master's thesis, Seoul National University

[12] Seoul Housing & Communities Corporation, Facilities Manager TechnicalTextbook

Chapter 3. Simulation Modeling and Experimental validation of PVT System

In this chapter, the thermal performance of PVT panels, which varies depending on environmental factors such solar radiation, ambient temperature, and wind speed, was tested. An analysis simulation model was developed to examine the thermal performance of PVT panels under various environmental conditions based on the experimental results and equations.

3.1 Simulation modeling

The author used MATLAB to develop a simulation model that replicates the appropriate PVT system based on the experimental results. References for the thermal and electrical study of PVT panels and heat collectors include Energy Plus Engineering Reference, Modeling of Solar Storage Tanks by Newton[13], and Duffie and Beckman's Solar Engineering of Thermal Process.[14]

1. Thermal modeling

The simulation model is a system as shown in the following figure, and thermal analysis of the PVT panel and the heat storage tank is required, respectively. It was modeled using the following equation, and the necessary parameters were determined by referring to the results obtained through the experiment and the actual physical properties.

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⑬ Newton, B. J. (1995). Modeling of solar storage tanks.
⑭ John A. Duffie, William A. Beckman, 2013, Solar Engineering of Thermal Processes 4th ed, Wiley

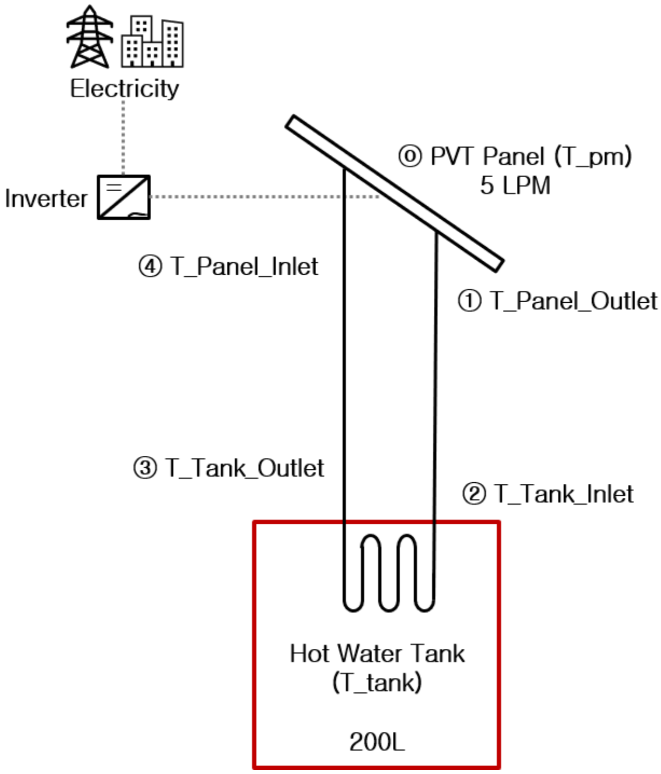


Figure 3. 13 PVT system diagram

1) PVT panel modeling

According to KS B ISO 9806, thermal analysis for PVT panels is the same as that of general solar collectors. Therefore, we modeled PVT panels with the following figure according to the flat−plate collectors heat analysis method of Solar Engineering of Thermal Process by Duffie and Beckman. The actual installed PVT shape is as shown in Figure, but it was simplified and interpreted as shown in Figure.

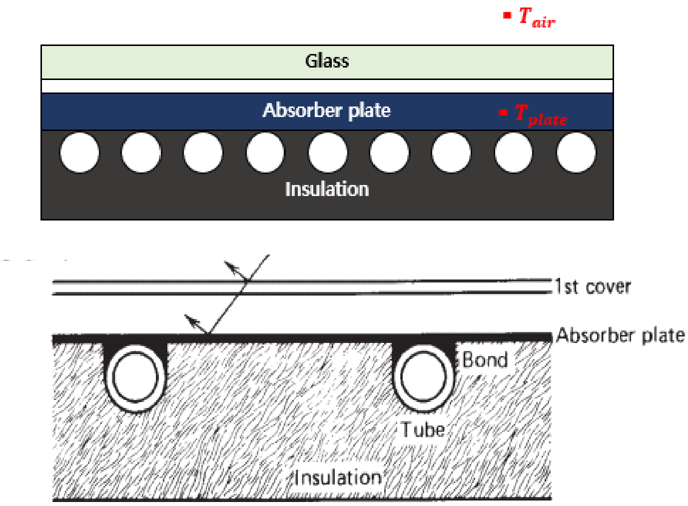


Figure 3.14 Unglazed PVT panel & sheet−and−tube solar collector

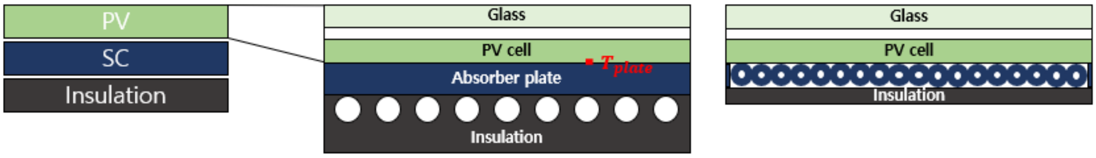


Figure 3.15 COOL−PV panel

The heat collection amount obtained through the PVT panel, the temperature of the PVT panel, and the temperature of the PVT panel outlet fluid follow the following equation. Ac is the area of the PVT panel, FR is the fin efficiency coefficient, S is the solar radiation amount reached the panel, UL is the total heat loss coefficient of the panel, Tinlet is the panel inlet heat medium temperature, Ta is the outside air temperature, ṁ is the flow rate, and Cp is the constant pressure specific heat of the heat medium.

$$Q_u = A_c F_R [S - U_L (T_{inlet} - T_a)] \quad (3.1)$$

$$T_{pm} = T_{inlet} + \frac{Q_u A_c}{F_R U_L}(1 - F_R) \quad (3.2)$$

$$T_{outlet} = T_{inlet} + \frac{Q_u}{\dot{m}C_p} \quad (3.3)$$

① Collector overall heat loss coefficient (U_L)

The following equation is used to calculate the amount of heat lost through the upper, rear, and side surfaces of the solar collector. U_t is an empirical equation for calculating the heat loss coefficient of the upper surface of the collector. U_b and U_e are equations for calculating the heat loss coefficients for the back and side surfaces of the collector, respectively. k and L are the insulation thermal conductivity and thickness, respectively.

The losses through the edge should be referenced to the collector area. If the edge loss coefficient-area product is (U/A) edge, then the edge loss coefficient, based on the collector area Ac follows the equation. The total heat loss coefficient U_L for the collector is the sum of U_t, U_b, and U_e.

$$U_t = \left(\frac{N}{\frac{C}{T_{pm}}\left[\frac{(T_{pm}-T_a)}{(N+f)}\right]^e} + \frac{1}{h_w} \right)^{-1} + \frac{\sigma(T_{pm}+T_a)(T_{pm}^2+T_a^2)}{\frac{1}{\varepsilon_p+0.00591Nh_w}+\frac{2N+f-1+0.133\varepsilon_p}{\varepsilon_g}-N} \quad (3.4)$$

Where

N : number of glass covers (1)

f : $(1+0.089h_w-0.1166h_w\varepsilon_p)(1+0.07866N)$

C : $520(1-0.000051\beta^2)$

e : $0.439(1-100T_{pm})$

β : collector tilt (deg)

ε_g ; emittence of glass (0.88)

ε_p : emittence of plate

T_a : ambient temperature (K)

T_{pm} : mean plate temperature (K)

h_w : wind heat transfer coefficient ($W/m^2 \cdot ℃$)

Loss through bottom

$$U_b = \frac{k}{L} \tag{3.5}$$

Loss through edge

$$U_e = \frac{(UA)_{edge}}{A_c} \tag{3.6}$$

Overall loss

$$U_L = U_t + U_b + U_e \tag{3.7}$$

② Collector efficiency factor (F_R)

It is convenient to define a quantity that relates the actual useful energy gain of a collector to the useful gain if the whole collector surface were at the fluid inlet temperature. This quantity is called the collector heat removal factor or collector efficiency factor F_R.

$$F_R = \frac{\dot{m}C_p(T_{outlet} - T_{inlet})}{A_c[S - U_L(T_{outlet} - T_a)]} \tag{3.8}$$

③ Absorbed solar radiation (S)

The prediction of collector performance requires information on the solar energy absorbed by the collector absorber plate. The amount of solar energy incident on a tilted collector follows next equation. This incident radiation originally has three different spatial distributions, beam radiation, diffuse radiation, and ground-reflected radiation. Each must be treated separately, and following equation does not consider the ground-reflected radiation.

$$S = I_b R_b (\tau\alpha)_b + I_d (\tau\alpha)_d \left(\frac{1+\cos\beta}{2}\right) \tag{3.9}$$

2) Storage tank modeling

The storage tank is set to a fully−mixed model so all water in the tank is at the same temperature. To calculate the water temperature, the model analytically solves the differential equation governing the energy balance of the storage tank. The temperature of the tank over time follow the following equation.

$$\rho V C_p \frac{dT}{dt} = m C_p \frac{dT}{dt} = q_{net} \quad (3.10)$$

Where

ρ : the density of water

V : the volume of the tank

c_p : the specific heat of water

T : the temperature of the tank water

t : the time

q_{net} : the net heat transfer rate to the tank water

$$q_{net} = q_{heater} + q_{oncycpara} + q_{oncycloss} + q_{use} + q_{source} \quad (3.11)$$

$$q_{oncycloss} = UA_{oncyc}(T_a - T_{tank}) \quad (3.12)$$

$$q_{use} = \varepsilon_{use}\dot{m}_{use}C_p(T_{use} - T_{tank}) \quad (3.13)$$

$$q_{source} = \varepsilon_{source}\dot{m}_{source}C_p(T_{source} - T_{tank}) \quad (3.14)$$

$$m C_p \frac{dT}{dt} = q_{heater} + q_{oncycpara} + UA_{oncyc}(T_a - T_{tank}) + \varepsilon_{use}\dot{m}_{use}C_p(T_{use} - T_{tank}) + + \; + \varepsilon_{source}\dot{m}_{source}C_p(T_{source} - T_{tank}) \quad (3.15)$$

$$\frac{dT}{dt} = \left[\frac{1}{mC_p}\left(q_{heater} + q_{oncycpara} + UA_{oncyc}T_a + \varepsilon_{use}\dot{m}_{use}C_pT_{use} + \varepsilon_{source}\dot{m}_{source}C_pT_{source}\right)\right] + \left[-\frac{1}{mC_p}\left(UA_{oncyc} + \varepsilon_{use}\dot{m}_{use}C_p + \varepsilon_{source}\dot{m}_{source}C_p\right)\right]T_{tank} \quad (3.16)$$

$$\frac{dT}{dt} = a + bT_{tank} \quad (3.17)$$

$$a = \frac{1}{mC_p}\left(q_{heater} + q_{oncycpara} + UA_{oncyc}T_a + \varepsilon_{use}\dot{m}_{use}C_pT_{use} + \varepsilon_{source}\dot{m}_{source}C_pT_{source}\right) \quad (3.18)$$

$$b = -\frac{1}{mC_p}\left(UA_{oncyc} + \varepsilon_{use}\dot{m}_{use}C_p + \varepsilon_{source}\dot{m}_{source}C_p\right) \quad (3.19)$$

$$T_{tank}(t) = \left(\frac{a}{b} + T_{initial}\right)e^{bt} - \frac{a}{b} \quad (3.20)$$

2. Electrical modeling [15]

The amount of power E produced through the PVT panel is calculated by multiplying the total amount of solar radiation received by the panel by the efficiency $\eta_{electrical}$ as shown in the following equation. $\eta_{irradiance}$ follows the following figure with the efficiency according to the intensity of solar radiation, and $\eta_{temperature}$ follows the imperial equation with the efficiency according to the panel temperature. The η_{year} is efficiency according to the usage time and follows the following figure, but this study assumes 1 without considering it.

$$\eta_{electrical} = \eta_{irradiance}\eta_{temperature}\eta_{year} \quad (3.21)$$

$$\eta_{temperature} = 1 - 0.0039(T_{pm} - 25℃) \quad (3.22)$$

$$E = \eta_{electrical} S A_c \quad (3.23)$$

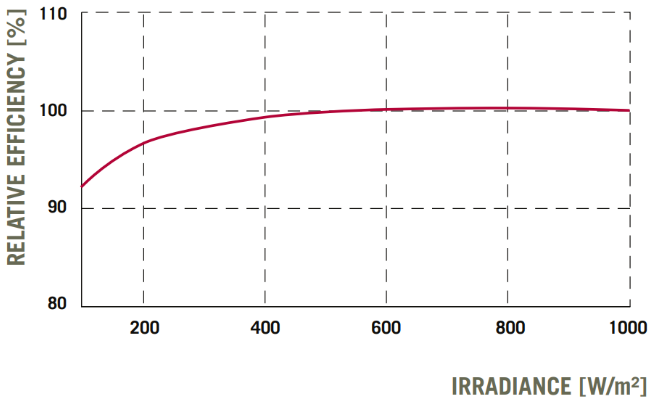


Figure 3.16 Performance at low irradiance

[15] Hanwah Q cell, https://q-cells.us/kr/main.html

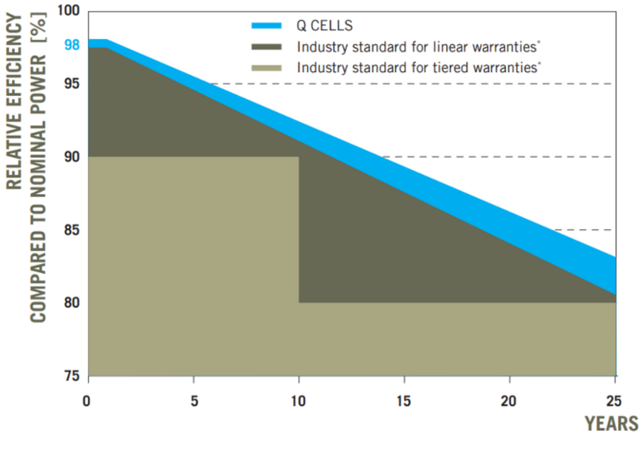


Figure 3.17 PV cell performance warranty

For Figure 3.16, typical module performance under low irradiance conditions in comparison to STC conditions(25℃, 1000W/㎡).

For Figure 3.17, at least 98% of nominal power during first year. Thereafter max, 0.6% degradation per year. At least 92.6% of nominal power up to 10 years. At least 83.6% of nominal power up to 25 years. All data within measurement tolerances. Full warranties in accordance with the warranty terms of the PV cells sales organization of your respective country.

3.2 Experiments for validation

3.2.1 Condition and Method

The experiment was conducted on the rooftop of a container box simulating a single-story building of S company located in Asan, Cheonan, South Korea.

The following figure is the shape of the experiment, and the PVT system of the same system as the following figure was constructed. Two PVT panels with an area of 2m2 were installed at a slope of 30° , and circulated within the closed loop system while maintaining a flow rate of 5lpm. The initial heat storage tank was filled with 12° C time water, and ethylene glycol 30% antifreeze was used as the heat medium flowing through the pipe connected to the PVT system to prevent freezing.

Like a solar collector, the PVT system has different thermal performance depending on the collector fluid inlet temperature, ambient air temperature, and insolation, and the panel inlet and outlet temperature difference varies greatly depending on the fluid flow rate. Therefore, this experiment was conducted in accordance with ASHRAE 93-77 (Solar Collector Performance Test Method) and KS B ISO 9806 (Solar Energy-Solar Collector-Test Method) performance measurement guidelines. Environmental conditions such as solar radiation, ambient air temperature, wind speed, and the amount of power produced through the PVT system, heat collection, production hot water temperature, and panel surface temperature were measured. The power generation efficiency and heat collection efficiency were calculated by comparing the measured solar radiation amount with the produced power amount and heat collection amount.

Figure 3.1 Sight of the outdoor experiment

3.2.2 Equipment

The experimental device is a system of the following figure and consists of a PVT panel, a hot water tank, a flowmeter, a control valve, and a insulated pipe. Detailed information on the experimental apparatus is as follows.

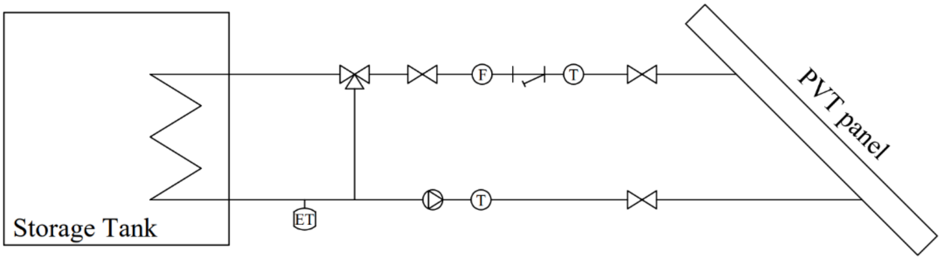


Figure 3.2 Diagram of the outdoor experiment

1. PVT panel

The PVT panel used a flat liquid−free PVT panel (COOL−PV) provided by Janghan Technology Co., Ltd. in the form of a combination of a solar panel and a solar collector as shown in the following figure. The specifications of the solar panel and the solar collector are shown in the following table, respectively. The panel is a lightweight panel made of polyethylene to solve the problems of conventional collectors that are not economical in terms of maintenance due to pressure loss and scale inside the metal. The panel was installed on a stand manufactured to adjust the slope horizontally based on the straight south direction as shown in the following figure.

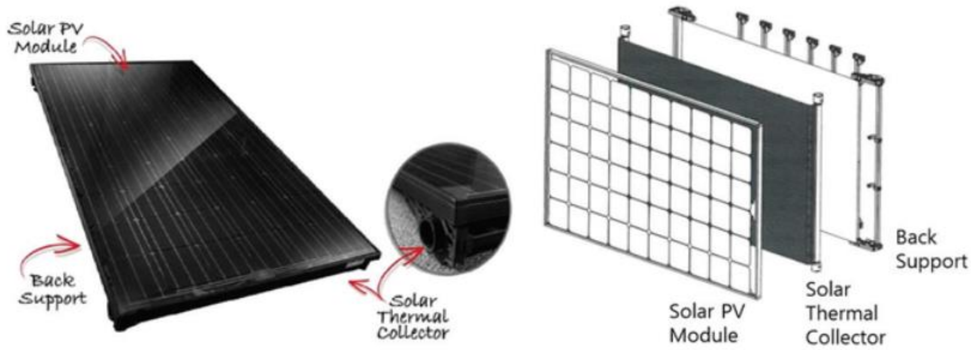


Figure 3.3 PVT panel (COOL-PV)

Table 3.1 Specification of PVT panel

Type	Unglazed flat−plate water type PVT module & Crystalline silicon PV module						
Product specification	PVT module dimensions (H*W*D)	1,000 * 1,994 * 35 (mm)					
	PV module dimensions (H*W*D)	918 * 1,810 * 1000 (mm)					
	Area	1.99 ㎡					
	Weight	34.5 kg					
Design criteria	Operating temperature	Max	80 ℃	Appropriate	−5 ~ 45 ℃	Min	−30 ℃
	Operating flow rate	Max	0.1 kg/s	Appropriate	−0.03 ~ 0.08 kg/s	Min	0.02 kg/s
	Maximum Pressure	1.5 kgf/㎠					
Installation recommendation	Tilt angle	15 ~ 45 ˚					
	Fluid type	Propylene glycol(30%) and water(70%)					

Table 3.2 Specification of components

PVT module	Material: Polyethylene Main branch: External diameter ϕ 5.3 mm * Thickness 0.6 mm * Length 1,810 mm * Number 187 ea Heater: External diameter ϕ 38.1 mm Header connection: External diameter ϕ 50.4 mm	
PV module	Type (Material): Heat−reflective insulation (Polyethylene foam) Thickness: 13 mm Thermal conductivity: 0.02 ~ 0.03 (w/m · K)	
Junction	Header cover	Material: Aluminum Thickness 1.5 mm * Number 2 set
	etc	Material: Aluminum Thickness 1.5 mm * Number 6 set

2. Storage tank

In a system that uses solar energy, a heat source can be secured only while solar radiation is pesent. Therefore, a heat storage tank should be used to store heat and supply heat energy to the destination at the necessary time. The heat storage tank used a 200L water heater (SBS-200) provided by SBC SUNHO BOILER. The following table shows the specifications of the heat storage tank, and the next figure shows the heat storage tank installed.

Figure 3.6 Storage tank and the specification

Table 3.3 Specification of storage tank

Model	SBS-020
Capacity (L)	200
Power consumption (kW)	2
Diameter * Height (mm)	575 * 1,250
Thickness (cm)	1.5 ~ 3.0

3. Pyranometer

Solar radiation is one of the environmental factors that most affect the performance of the PVT system. Therefore, it is important to measure the exact amount of insolation where the PVT panel is installed. This experiment used Huxseflux's SR05−D1A3−O3 model, and the product appearance and detailed specifications are as shown in the following figure and table.

Figure 3.7 Pyranometer and the specification

Table 3.4 Specification of pyranometer

Model	SR05−D1A3
Measurand	Hemispherical solar radiation
ISO classification	Second class pyranometer
Calibration uncertainty	< 1.8 %
Rated operating temperature range	−40 ~ 80 ℃
Rated operating voltage range	5 ~ 30 VDC
Communication protocol	Modbus over RS=485
Digital output	Irradiance in W/㎡
Analogue output	0 ~ 1 V

4. Wind speed meter and wind direction meter

WSS100 and WDS100 provided by RGYO INNPITRON were used to measure wind speed and wind direction, and the appearance and detailed specifications are as shown in the following figure, table.

Figure 3.8 Wind speed meter and wind direction meter

Table 3.4 Specification of wind speed meter and wind dire

Model	WSS100	WDS100
Measurement range	0.7 ~ 50.0 m/s	0 ~359˚
Accuracy	± 0.15 m/s or ± 2.5 %	± 2.5˚

5. Data collector and data logger

National Instruments' module was used for signal input and output of measuring equipment, and Laboratory Virtual Instrument Engineering Workbench (LabVIEW) was used for control program. Solar radiation, ambient temperature, wind speed, PVT panel surface temperature, and heat medium temperature were measured every 5 seconds through a data logger, and real-time monitoring and storage was performed through a PC.

Figure 3.10 LabVIEW control panel

3.2.3 Experiment Results

Table shows the results of the experiment conducted from December 13 to 16, 2022 and January 6 to 8, 2023.

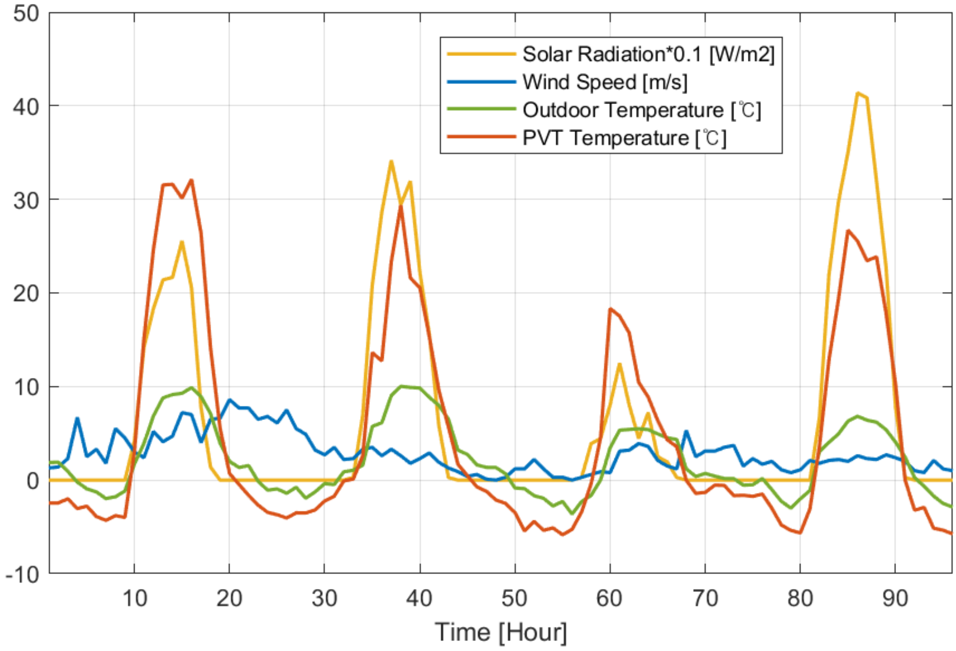


Figure 3.12 Experiment results in December (12/13-12/16)

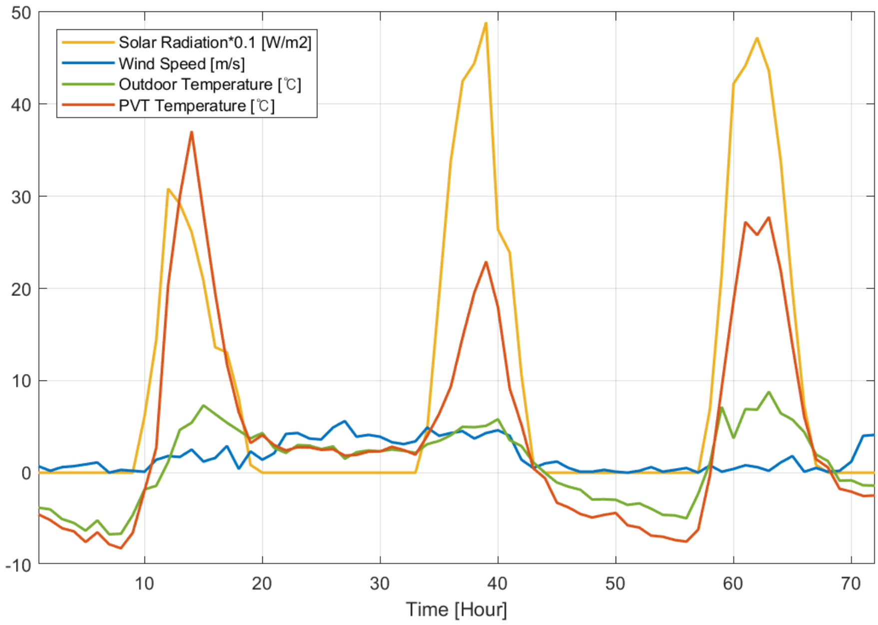


Figure 3.13 Experiment results in January (01/06−01/08)

The solar radiation was high in the order of December 13, December 14, December 16, and December 15. On December 13, the maximum solar radiation was about 800 to 1000 W/㎡, on December 14 and December 16, the maximum solar radiation was 600 to 800 W/㎡ and on December 15, the maximum solar radiation was 600 W/㎡ or less.

On December 13, when the maximum solar radiation was high, the hot water temperature produced from the PVT panel surface and PVT panel rose to about 35 degrees. On December 14 and 16, when the maximum solar radiation was 600 to 800 W/㎡, the hot water temperature produced from the PVT panel surface and PVT panel rose from 25 to 30 degrees. On December 15, when the maximum solar radiation was the lowest, the hot water temperature produced from the PVT panel surface and PVT panel rose to up to 19 degrees. Comparing December 15 and December 16, when outdoor temperature conditions were similar, it was found that the hot water temperature produced from the PVT panel surface and the PVT panel was predominantly affected by solar radiation.

The temperature of the heat storage tank, which was initially 12 degrees, rose to a maximum of 15 degrees on December 13, about 14 degrees on December 14 and 16, and about 13 degrees on December 15.

Table 4.3 Performance of PVT and PV panel (experiment)[16]

Date	Flow rate per panel [lpm]	Solar radiatoin [W/㎡]	Produced heat [KWh]	Thermal efficiency [%]	Generated electricity [KWh]	Electrical efficiency [%]
2017. 07. 26.	2	586.8	3.3	27.9	1.7	14.0
2017. 07. 25.	3	553.8	2.9	25.7	1.6	15.2
2017. 08. 02.	4	572.8	2.5	21.5	1.6	13.9

16 류경호(Kyung Ho Ryu),and 이근휘(Keun Hui Lee). "태양광열(PVT) 융합패널과 계간축열 및 지열히트펌프를 활용한 신재생 융복합 열에너지 공급시스템." 대한설비공학회 학술발표대회논문집 2019.11 (2019): 298-301.

3.3 Thermal performance of the PVT system

1. PVT panel temperature

Under the same conditions as the experiment, environmental conditions such as solar radiation, outside temperature, and wind speed were changed, and the heat amount, hot water temperature, and power generation amount produced by the PVT panel were calculated. The results are as follows.

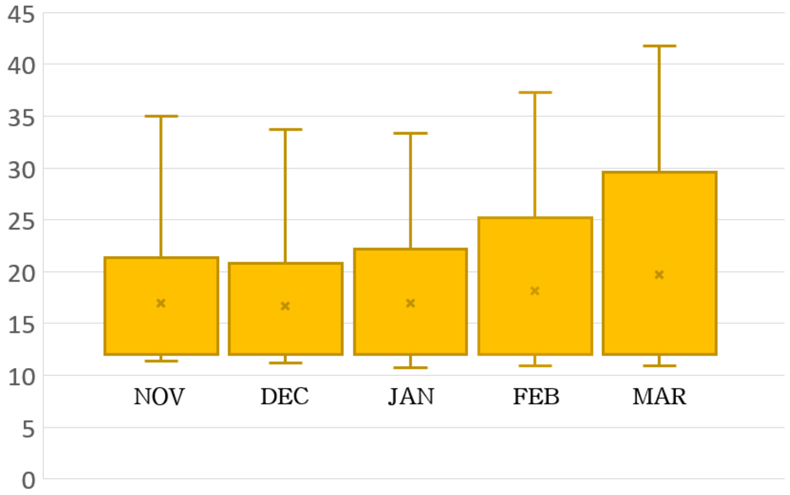
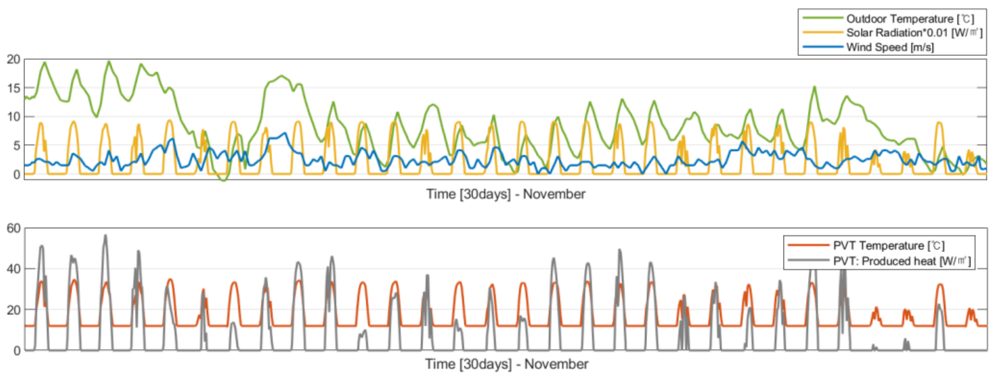


Figure 3.18 Temperature of the PVT panel



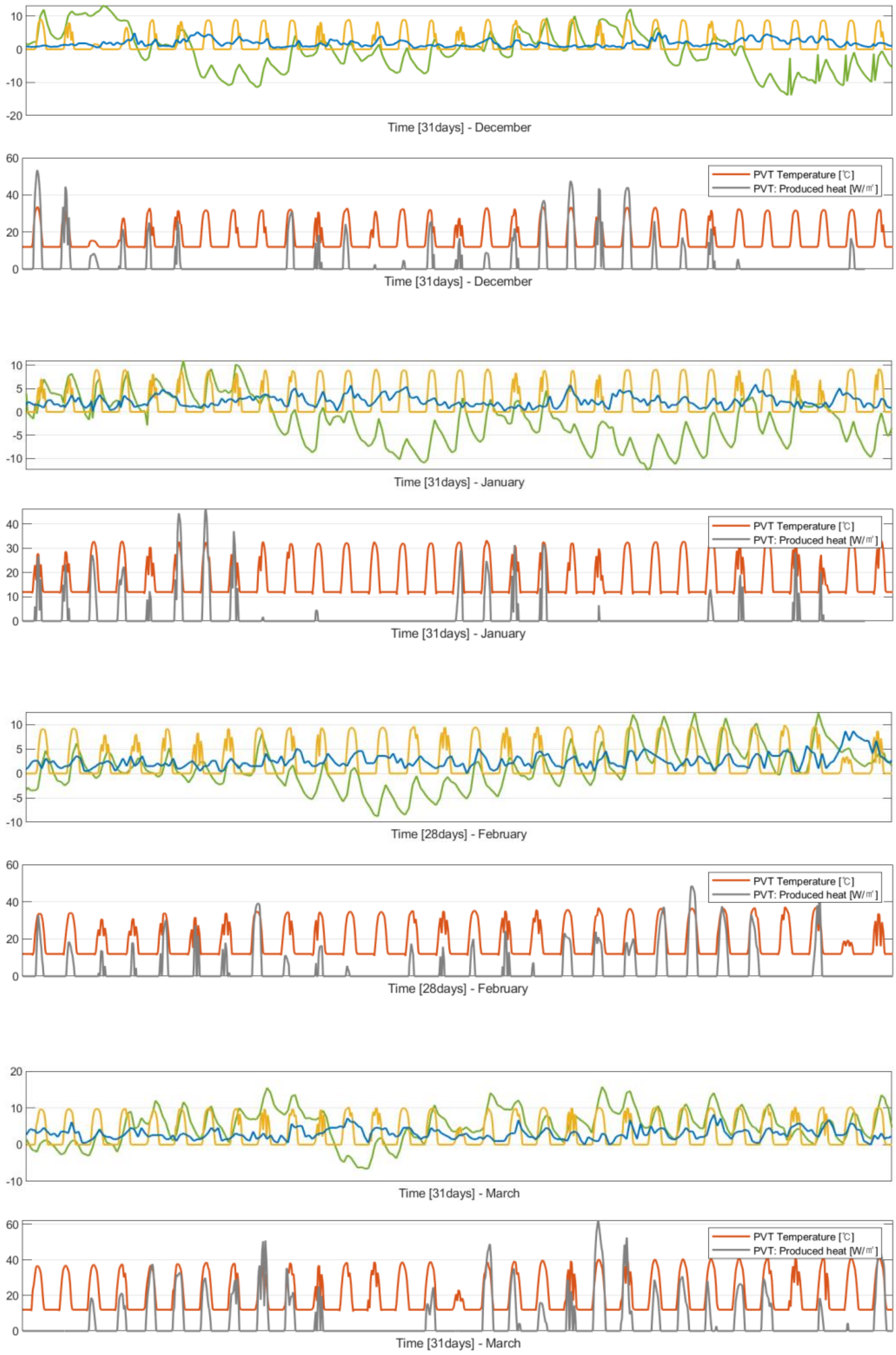


Figure 3.19 PVT system simulation results

2. Generated heat and electricity rate

The heat and electricity production and efficiency produced are as shown in the following figures. It was verified through the results of the empirical experiment in the table below.

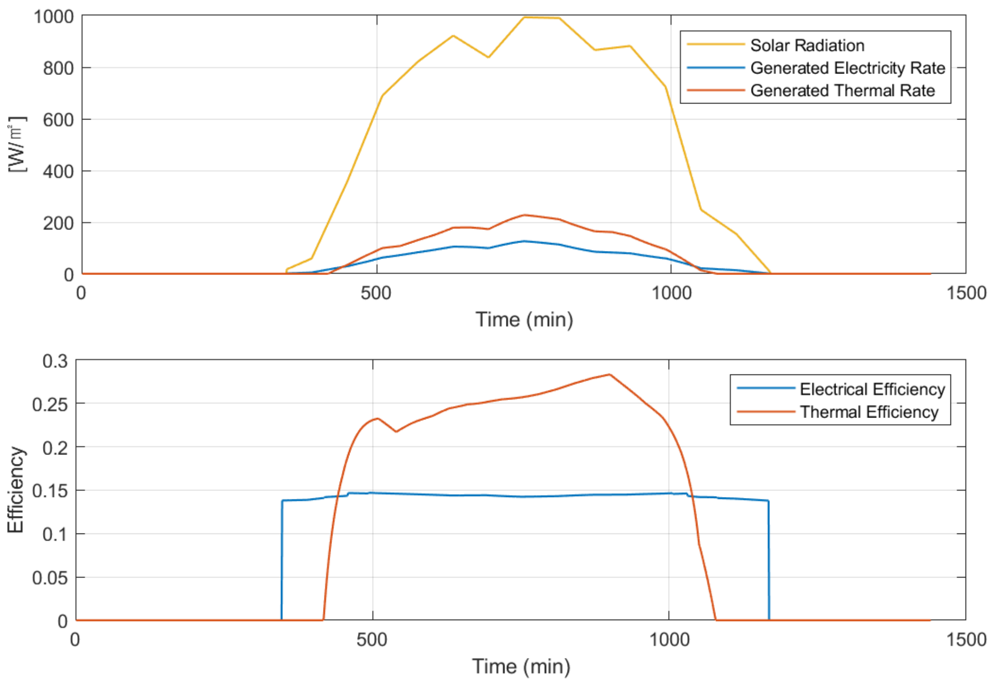


Figure 4.10 Performance of PVT and PV panel (simulation)

Table 4.3 Performance of PVT and PV panel (experiment)[17]

Date	Flow rate per panel [lpm]	Solar radiatoin [W/㎡]	Produced heat [KWh]	Thermal efficiency [%]	Generated electricity [KWh]	Electrical efficiency [%]
2017. 07. 26.	2	586.8	3.3	27.9	1.7	14.0
2017. 07. 25.	3	553.8	2.9	25.7	1.6	15.2
2017. 08. 02.	4	572.8	2.5	21.5	1.6	13.9

17 박태국(Tae-Kook Park),배승훈(Seung-Hoon Bae),김상교(Sang-Kyo Kim),김선민(Seon-Min Kim),김대환(Dae-Hwan Kim),엄학용(Hak-Yong Eom),and 이근휘(Keun-Hui Lee). "태양광열 시스템의 신뢰성 평가에 관한 연구." 신재생에너지 16.4 (2020): 49-64.

Chapter 4. Applicability of PVT System

4.1 Application Plan

Based on the thermal performance results analyzed in Chapter 3, this Chapter proposes an application plan that can thermally utilize the PVT system. In previous studies, heat obtained from PVT was used in various methods such as space heating and a hot water preheating system. However, the amount of heat that can be produced and the hot water temperature vary depending on the characteristics of the PVT panel, such as material, shape, and composition, so the available methods are different.

The flat-plate water, unglazed type PVT panel covered in this study produces relatively low-temperature hot water between about 15~35℃, so that it is difficult to use in heating or cooling systems that require high temperatures. Therefore, this study attempts to simulate a low-temperature radiant floor heating system using hot water produced from PVT panels as a heat source, and analyze the utility of the PVT system in winter season.

4.2.1 Building System Modeling

The configuration of the building model, and the radiation floor heating model entered in EnergyPlus is as shown in the following figures. The diameter of the pipe is 16mm, the thickness is 0.15mm, and the conductivity is 0.35 W/m · k. The heating curve follows following equation.

$$T_{supply} = 35 - 0.6T_{outdoor} \qquad (4.1)$$

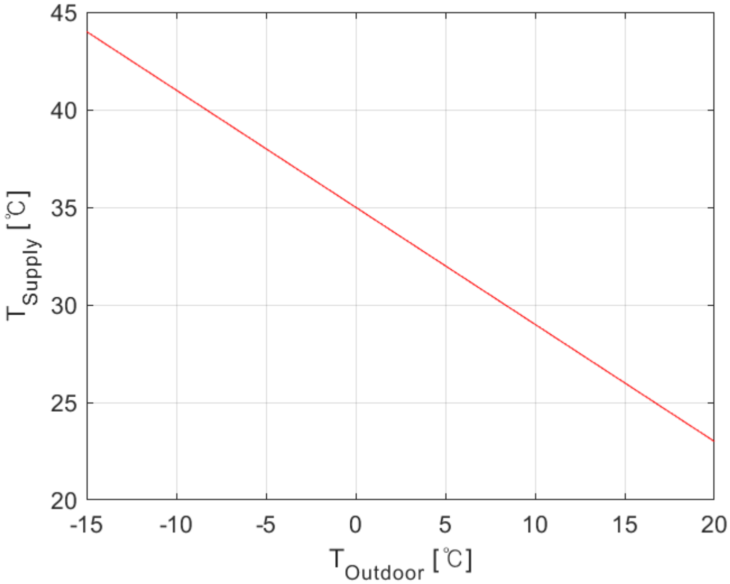


Figure 4.1 Heating curve

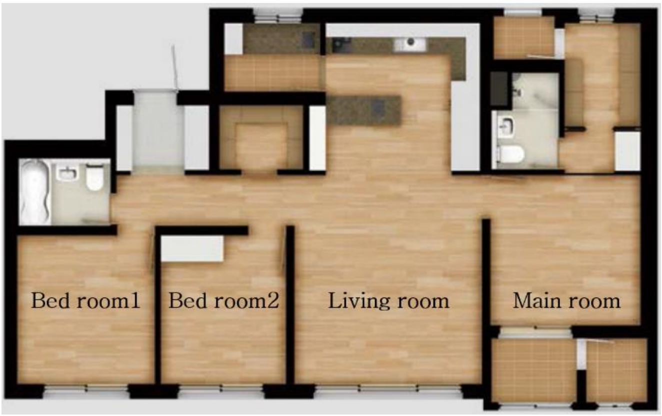


Figure 4.2 Building model[18]

[18] Hansam interior, http://hanam02.pagecheck.co.kr/index.php?module=Html&action=SiteComp&sSubNo=17

Thermal transmittance of its envelope and the schedule of internal heat gains is set as shown in the following tables.

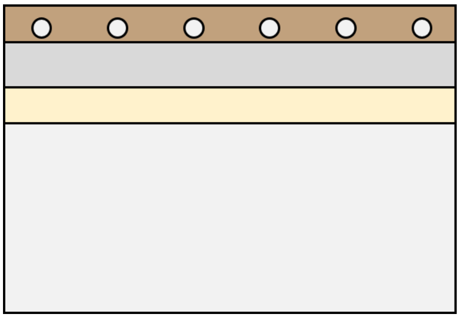


Figure 4.3 Configuration of radiant floor heating panel

Table 4.2 Thermal transmittance of the study object envelope[19]

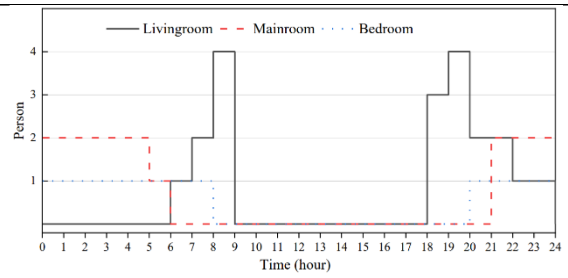
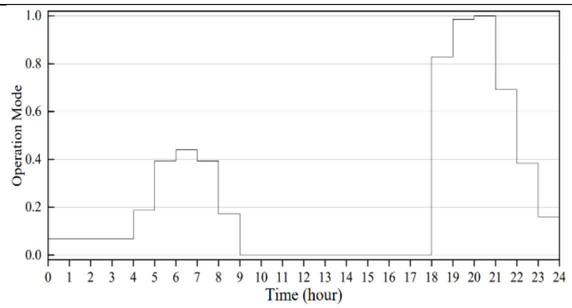
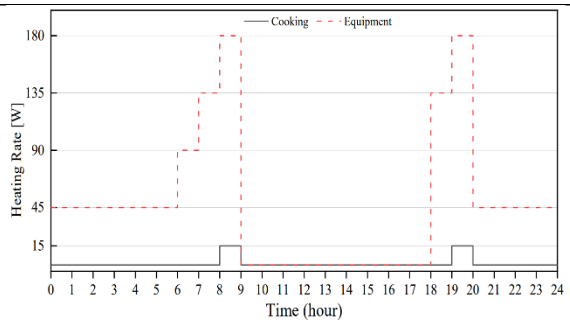
Structure		U-value
Wall		0.16 W/㎡ · K
Roof		0.16 W/㎡ · K
Floor	Ground	0.20 W/㎡ · K
	Middle	0.60 W/㎡ · K
Window		0.80 W/㎡ · K

Table 4.3 Building information

Diameter	Thickness	Conductivity	Spacing
16 mm	0.15 mm	0.35 W/m · K	150 mm

[19] Satyavada, Harish, and Simone Baldi. "Monitoring energy efficiency ofcondensing boilers via hybrid first-principle modelling and estimation."Energy 142 (2018): 121-129

Table 4.3 Simulation conditions of the building for analysis[20]

Input object	Value	
Weather dataset	Seoul	
Simulation period (Month)	12, 1, 2 (Heating season) 3, 11 (Semi-heating season)	
Indoor air temperature setpoint	21 ℃	
Infiltration	0.2 ACH (Minimum)	
Internal heat gain	People	Sensible: 70 W/person
		Latent: 45 W/person
		Activity: Seated, very light work
		
	Light	Sensible: W/㎡
		Convection(28%), Radiation(72%)
		
	Equipment	

20 Mun, Jung-Hyon, Lee, Jong-Ik, and Kim, Min-Sung. "Study on Estimationof Infiltration Rate (ACH natural) using Blower Door Test Results." Proceedings of Korean Institute of Architectural Sustainable Environmentand Building 14.6 (2020): 687-698.

4.2 Evaluation

1. Thermal comfort

The following figure shows that the indoor temperature is comfortably maintained at more than 20℃ throughout the heating period from November to March.

2. Energy consumption and heat generation from PVT system

The monthly amount of heat required for local heating during heating and the total heat produced from the PVT system are as shown in the following figure. Based on house space heating, as of October 2022, the reduced cost rate is as shown in the following figure.

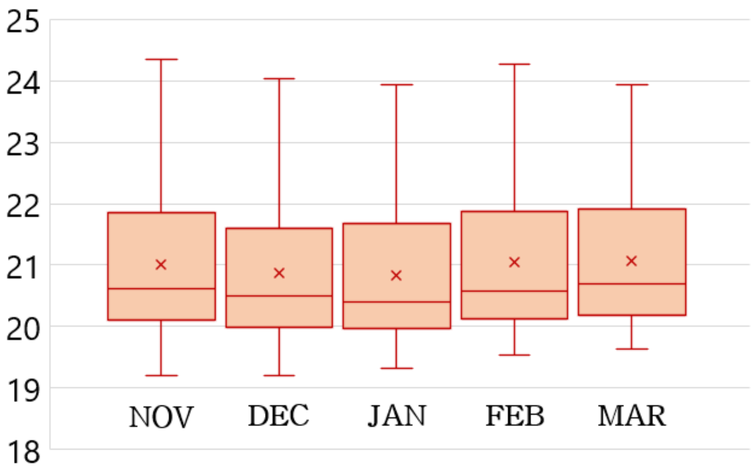


Figure 4.4 Indoor temperature

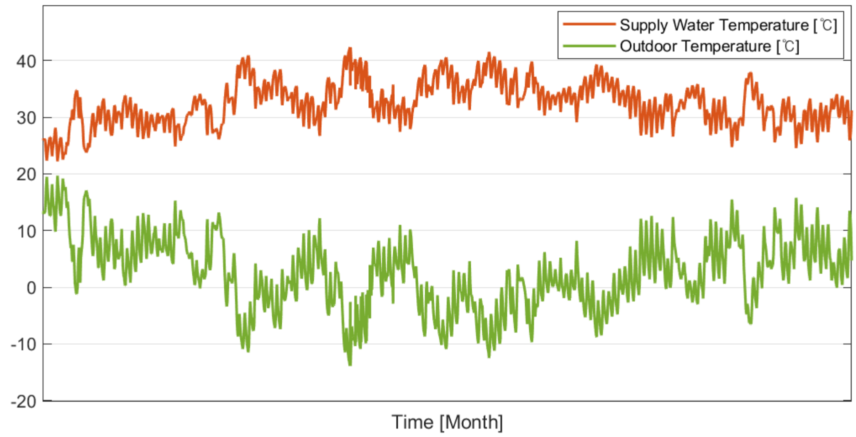


Figure 4.5 Supply Water Temperature

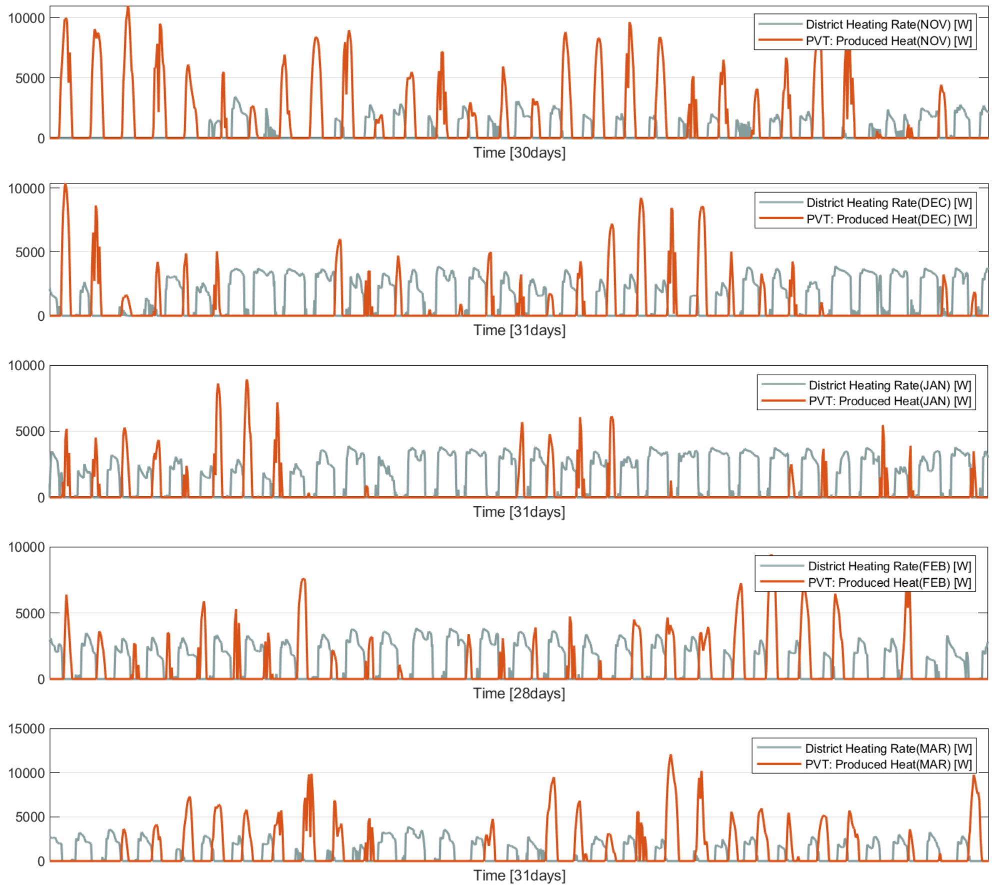


Figure 4.6 District heating rate and produced heat by PVT system

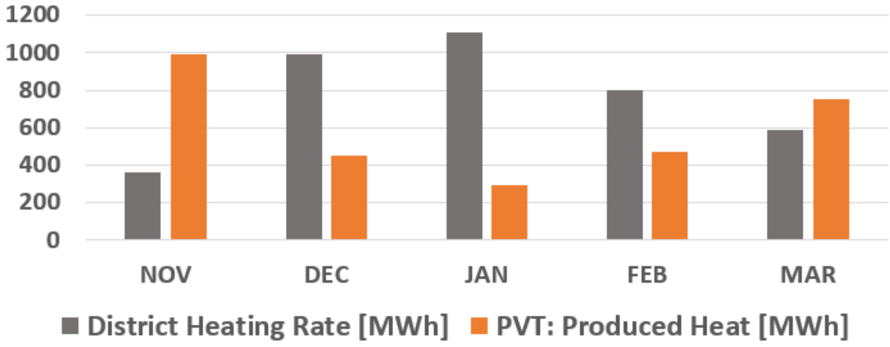


Figure 4.7 District heating rate and produced heat by PVT system

3. PVT panel temperature

Following figures show the temperature of the PVT panel surface, the temperature of the hot water produced through the PVT panel, and the temperature of the tank water. The temperature of the PVT panel and the working fluid existing the PVT panel outlet are nearly same.

Figure 4.8 Supply water temperature and PVT panel temperature

Chapter 5. Conclusion

5.1 Summary

The results of this study are summarized as follows.

1. Experimental results show that the PVT panel surface and outlet temperature are dominated by solar radiation conditions, producing hot water of about 35℃ under solar radiation up to 1000 W/㎡ conditions and about 18℃ under solar radiation 500 conditions.

2. The PVT system simulation shows that the spring equinox (March, up to about 1000 W/㎡) hot water temperature with excellent solar radiation rises to up to 42 ℃, with a heat collection efficiency of about 25% and a power generation efficiency of about 15%.

3. The utility of the PVT system in the low-temperature water floor heating system was confirmed. During the period when most of the supply hot water temperature and heat consumption conditions are satisfied (Semi-Heating season, November and March), the possibility of independent heat source supply was confirmed only with the PVT system. However, during periods when it is difficult to meet the supply hot water temperature and heat consumption conditions, such as December, January, and February, it is necessary to find a way to secure necessary heat sources such as branch prevent heat loss through pipe insulation and heat use auxiliary heat sources such as heat pumps.

5.2 Future Study

1. In the case of a heating season in which it is difficult to meet the hot water temperature condition to be applied to low−temperature water floor heating, other heat sources such as a heat pump are required. Research is needed on an algorithm that controls heat sources to be satisfied according to environmental conditions and indoor load conditions. This is also related to energy consumption analysis and economic analysis for PVT systems.

2. Research will also be conducted to use it as a heat source for air conditioners, such as using it as a renewable heat source for a decicant system that combines ceiling radiation cooling panels.

3. A study will be conducted to link PVT system and building modeling into one simulation.

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Hansam interior, http://hanam02.pagecheck.co.kr/index.php?module=Html&action=SiteComp&sSubNo=17

Satyavada, Harish, and Simone Baldi. "Monitoring energy efficiency ofcondensing boilers via hybrid first-principle modelling and estimation."Energy 142 (2018): 121-129

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국문 초록

사용 온도가 높을수록 발전 효율이 감소하는 기존 PV 시스템의 문제를 해결하기 위해 1970년대 이후부터 태양광열(PVT) 시스템이 개발되고 연구되어 왔다. PVT 시스템은 PV 패널 뒷면에 수배관 혹은 공기터널 등의 흡열판을 부착한 시스템으로, PV 모듈의 온도를 감소시켜 발전량을 증가시키고 주변으로 방열되던 폐열을 이용하여 온수를 생산할 수 있다. 신재생 에너지원 사용의 필요성이 대두됨에 따라 최근 10년간 PVT 시스템 연구에 대한 관심도가 높아지기 시작했으나, 건축적 활용에 대한 연구는 미비한 현황이다.

PVT 시스템의 건축적 활용에 대한 연구가 아직 미비한 이유는 다음과 같다. 첫 번째, PVT 패널 자체의 열적 성능에 대한 데이터가 부족하다. 두 번째, PVT 시스템으로부터 생산된 저온(약 25~45℃)의 온수를 활용할 수 있는 설비 시스템에 대한 연구가 부족하다.

따라서 본 논문에서는 PVT 시스템에 대한 기존 문헌 및 연구를 조사하고, 시뮬레이션 및 실험을 통해 기후(일사량, 외기 온도, 풍속)에 따른 PVT 시스템의 열적 성능(집열량, 생산 온수 온도)을 확인하였으며, 적용 가능한 설비 시스템을 제안 및 평가하였다.