ECOLOGICAL GUIDELINES of PLUS-ENERGY SOLAR HOUSE ELEMENTS for the CLIMATE RESILIENT VILLAGE MODEL

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Abstract

This research aims to ecologically supply ecological guidelines of plus-energy solar houses using renewable energy harvesting methodologies such as multi-functional color building-integrated photovoltaic (MF-BIPV), which can be well combined with passive intelligent radiant cooling (PIRC) & radiant heating systems. This research explores the influences of the possible variables on the performance of the PIRC to realize the ecological plus-energy solar house for the regio-physical climate change resilient village model (RECREVIM). The MF-BIPV is planned on the south façade of the test model house to explore the different variables such as the PV module width and length, cell ratio in the PV module, the module angle, the Albedo rate, transmittance, reflectance, and absorptance, etc based on the previous works. The PIRC and the source for the source flow ventilation is explored and tested in this study. The ecological factors and variables for guidelines including the MF-BIPV, and the PIRC system etc. are complemented by simulating and testing a house as a reasonable solution for the plus-energy solar house. A plus energy solar house concept is designed based on this process.

Keywords: Passive intelligence, MF-BIPV, Guidelines, Plus energy house, Radiative cooling & heating

1.Introduction

Energy consumption from the building sector is much higher than the other sectors. Residential buildings are the central part in the transition to a zero-energy future, as the building sectors are responsible for about 40% of the global energy consumption and about one-third of global greenhouse gas (GHG) emissions. Energy consumption for space cooling has more than tripled since 1990, especially during peak demand periods and extreme heat events. [IEA, 2021] South Korea has set the zero-energy building (ZEB) roadmap that 17 kinds of public buildings (4th Grade) over 1000 m^2 (floor area) and private apartment complex (5th Grade) with 30 or more households, over 1000 m^2 by 2025, private apartment complex (5th Grade) over 500 m^2 by 2030, and all public buildings (1st Grade) should be zero-energy ones [KEA, 2025].

It should demonstrate very low energy needs mainly covered by renewable energy sources. The zero-energy buildings are based on firstly improving the building envelope energy performance and integrating Renewable Energy Systems to cover the remaining energy demand. Among the renewable energy systems, photovoltaic systems including Building Integrated Photovoltaic (BIPV) provide a reliable solution for electricity supply either in existing or new buildings [Tina, 2020].

Recently, bifacial PV cells have attracted interest because of their potential to increase PV power production. Passive integration of bifacial PV modules into a building façade represents a significant step forward in innovative application of a reasonable technology for building. Window-to-Wall Ratio plays also a very important role on the cooling and heating load of building [Alamin, 2023]. The importance of facades for the solar PV potential has been pointed out [Garcia, 2021].

As the building energy consumption depends mainly on the regional climate and the local weather conditions, additional aspects arise in the convergence of the appropriate building energy performance and an optimal renewable energy harvesting methodologies for a successful implementation of zero-energy buildings (ZEBs). From the ecological point of view, renewable energy systems must be installed ecologically in existing or newly planned buildings according to strategically adjustable methods to harvest maximal renewable energy sources, reduce the cooling and heating load of buildings, protect against noise, to maximize the use of daylight, and to improve the thermal comfort, etc.

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The MF-BIPV is planned on the south façade of the test model house to explore the different variables such as the PV module width and length, cell ratio in the PV module, the module angle, the Albedo rate, transmittance, reflectance, and absorptance, etc based on the previous works. The PIRC and the source for the source flow ventilation is explored and tested in this study. The ecological factors and variables for guidelines including the MF-BIPV, and the PIRC system etc. are complemented by simulating and testing a house as a reasonable solution for the plus-energy solar house. A plus energy solar house concept is designed based on this process.

2.Research methodologies

2.1 Concepts of building and system

A concept of ecological plus energy solar house has been designed according to the ecological design criteria (EDC). The detailed contents regarding the EDC are followed in the chapter 4. Energy harvesting for the Multi-Functional color BIPV (MF-BIPV), passive intelligent radiant cooling system (PIRC), and optimal building envelope performance (Opaque: Walls, roofs, and floors, Transparent: Windows and glass doors) will be simulated and evaluated respectively by the EDC and the simulation programs “SolCel”, “COMFORT”, “RADIANT”, and “TRNsys” to optimize the solar house based on the previous works.(Yoo, 2019, 2022, 2024, 2025) Figure 1 illustrates the isometric preliminary design view of the plus energy solar house.(Chung, 2025)

This plus energy solar house is consulted by the EDC and SolCel simulation to realize the plus energy solar house. As shown in Figure 1, opaque envelope elements consist of walls, roofs, and floors, whereas transparent envelope elements consist of windows and glass doors. The optimal thermal transmittance factors for the opaque envelope elements will be determined by the Trnsys simulation. The length and angle of the MF-BIPV are optimized by the SolCel simulation. The optimal angle of the bi-facial MF-BIPV is 23.5^{o} considering the physical interaction and the traditional architecture in Korea according to the ecological criteria.

The shading concept of the PV module reduces 27.5~34% of the building cooling load. The bi-facial BIPV as a shade can produce 12% more electricity than mono-facial BIPV system as a shade.The increased power output caused by the uniform system usage rate of the bi-facial MF-BIPV is 46% more than one of the wall-attached BIPV system.(Yoo, 2019, 2022) The PIRC is evaluated according to the test standard.(DIN EN, 2004) Figure 2 shows the functional description of the total system including the MF-BIPV, PVT, heat pump combined with natural energy sources, different translucent color PV Modules for Agri-voltaic, a PIRC/radiant heating system, an energy storage system, and demand-controlled source flow ventilation.

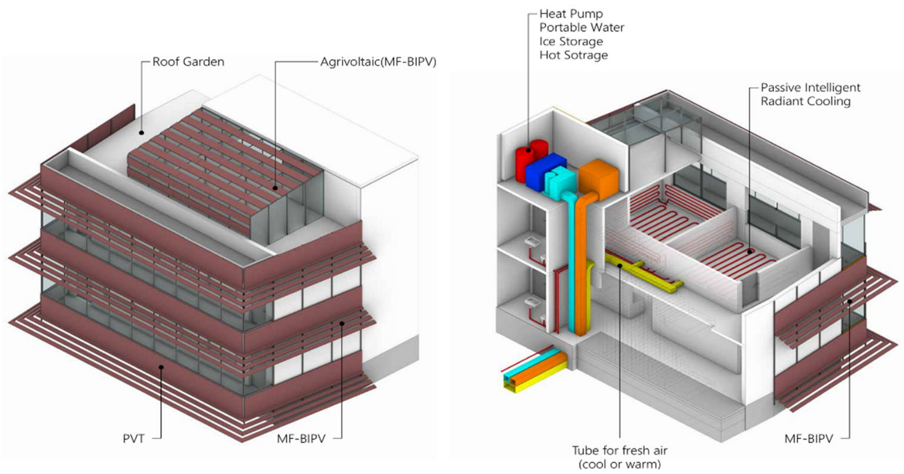

Fig.1: Isometric preliminary design view of the plus energy solar house.

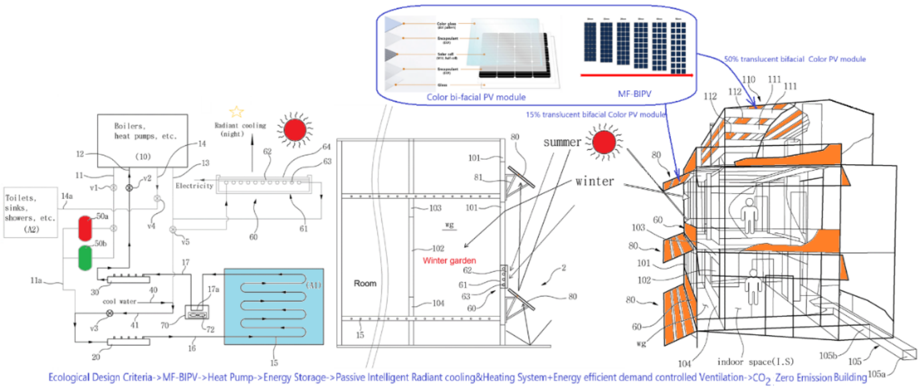

Fig.2: Functional description of the total system for the plus energy solar house

2.2 Test facility

In Figure 2, the blue area on the left, thermal behavior of floor A1 played as a PIRC and relevant fresh air intake methodologies in the 72 numbered heat exchanger (Installed at C in Figure 3) on the left side for cooling tube 105 on the right are analyzed for feasibility on a house with a glass greenhouse attached to the south of the house to explore the best solution in this study before building a plus energy solar house of Figure 1. The thermal behavior of the PIRC system is evaluated in a house located in Chung-Nam Province, Republic of Korea. Figure 3 shows the floor plan of a PIRC and radiant heating system.

The total dimensions of the house are approximately 11.7m × 8.7m × 2.5m (Horizontal axis×Vertical axis× Height) including the glass house which is attached. The glass is made up of vacuum glazing, and the outer wall has been remodeled with 5 cm thick sandwich paneling, but the interior wall remains the original 10 cm thick traditional earthen wall. The glass window between the glass house and Room a is 3mm thick. Figure 4 shows the radiant cooling and heating pipe installation section plan.

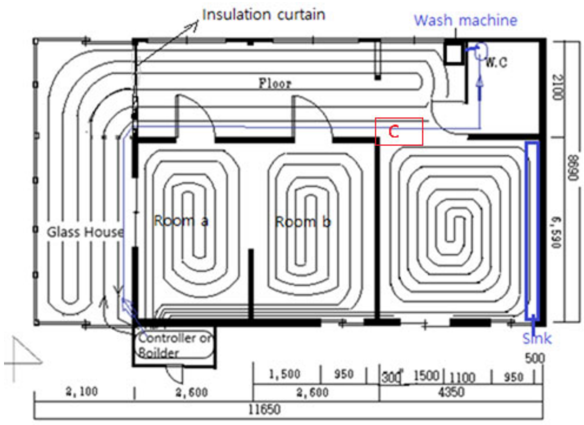

Fig.3: Floor Plan of a PIRC and radiant heating system.

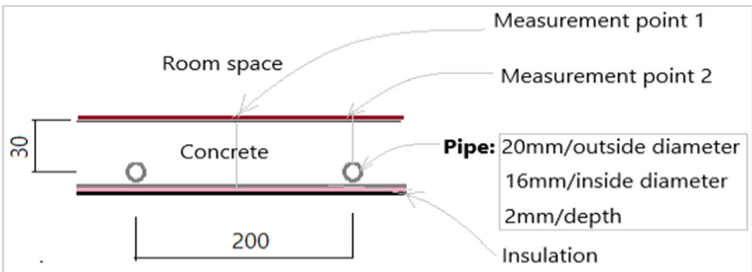

Fig.4: The section of the PIRC and radiant heating pipe installation section plan.

3.Experiment and cooling capacity for PIRC

3.1. Experiment for a PIRC

The material for the radiant cooling pipe is composed of polyethylene plastic. The distance between pipes is 200mm, and the depth of the concrete from the pipe to the floor surface is 30mm. 43 points are measured by the Data logger the vertical room air, the surface temperature of the room, and the other boundary conditions including inlet and outlet water temperature, water flow rate, solar radiation, and outdoor air temperature from August to early September. Table 1 shows the measurement detail.

Some simulations to figure out the thermal behavior of the system are fulfilled by the use of the measurement data such as air temperature, surface temperature, inlet and outlet water temperature to calculate mean radiant temperature, operative temperature, and the thermal capacity of the radiant cooling system.

Table 1: Measurement detail.

<table>
<tr><th>Measurement factor (Position)</th><th>Method</th></tr>
<tr><td>Solar Irradiance (2.3m)
Outdoor air temperature (1.5m)</td><td rowspan="5">Pyranometer (RICO)
K-type thermocouple
+
Data logger (Graphtec)
+
K-type thermocouple
+
+
+
+
+
K-type thermocouple
+
Electromagnetic flow meter
(M-1500 DA)</td></tr>
<tr><td>Vertical room temperature
(Floor surface, 0.1m, 0.8m, 1.1m, 1.7m, 2m, 2.1m(Ceiling surface))</td></tr>
<tr><td>Vertical floor temperature (Floor surface, 0.1m, 0.8m)</td></tr>
<tr><td>Inside surface temperature at 110cm height
(South wall, south window, west wall, north wall, Ceiling, floor surface 1, 2, 3)</td></tr>
<tr><td>Inside temperature of the glass house
-Surface (Floor, south, east, and inclined glass ceiling)
-Vertical air (0.1m, 0.8m, 2.3m)
- Inlet and outlet water temperature (Pipe surface temp.)
Water flow meter</td></tr>
<tr><td>Globe temperature (Room and Glass house)(0.8m)</td><td>Globe thermometer</td></tr>
<tr><td>Room humidity (0.75 m)</td><td>SK Sato Model: SK-L754-2</td></tr>
</table>

Figure 5 shows the boundary conditions (temperature and solar radiation around rooms A and B) for the PIRC experiment conducted from 10:12 to 10:27 on Sept.10. This study uses spring water as a cooling medium by pumping groundwater from an underground well directly in front of the building. The water temperature and Relative humidity are measured respectively about 17~18°C and 79.1%(Average) during system operation.

Figure 6 illustrates room wall surface and air temperature at 110cm height. The PIRC system was activated from 10:12 (3) to 10:27 (18) during the shower. Except for the window surface, which has very poor insulation, the temperature on all wall surfaces was lower than the ambient air temperature at the same height (110 cm) due to the cold radiant heat between the cold PIRC surface and the corresponding wall surfaces.

Figure 7 illustrates the inlet, outlet water temperature, and water flow rate for the PIRC. It took about 15 minutes to shower, and 53.4 L of water was consumed. The average flow rate was 0.05 kG/s. The average temperature difference between the inlet and outlet water temperatures was 2.35°C. The right vertical axis indicates the flow rate (kg/s). Study inlet or outlet temperature means corresponding temperature of Room a.

Figure 8 illustrates a vertical temperature distribution of the PIRC. The PIRC system was operated for 15 minutes, from 10:12 AM to 10:27 AM, for a shower. The floor surface temperature and the temperature at a height of 10 cm were similar. The highest temperature was at 170 cm, approximately 80% of the total height.

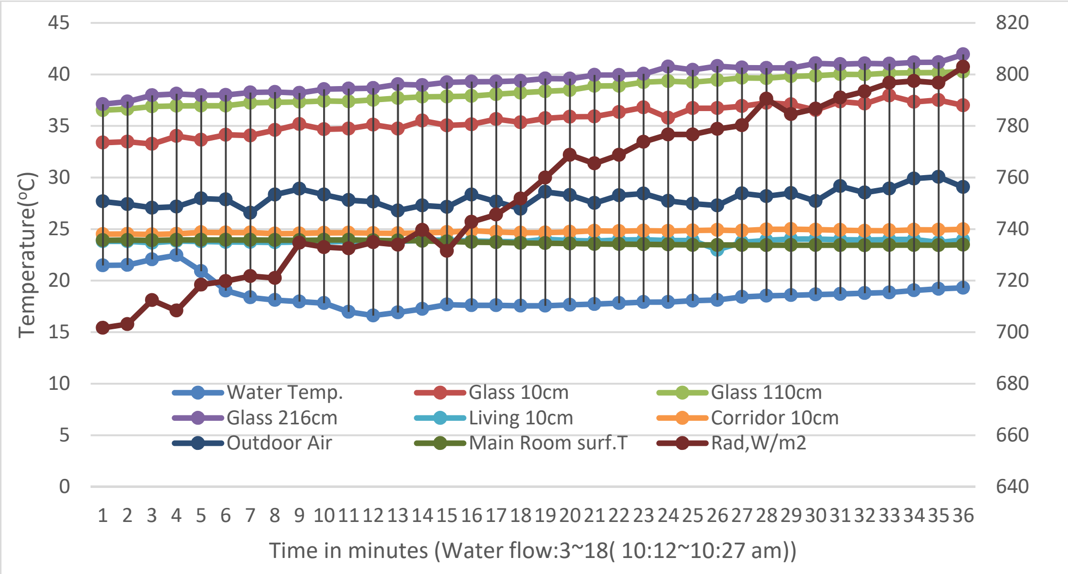

Fig.5: Boundary conditions for the experiment of the PIRC

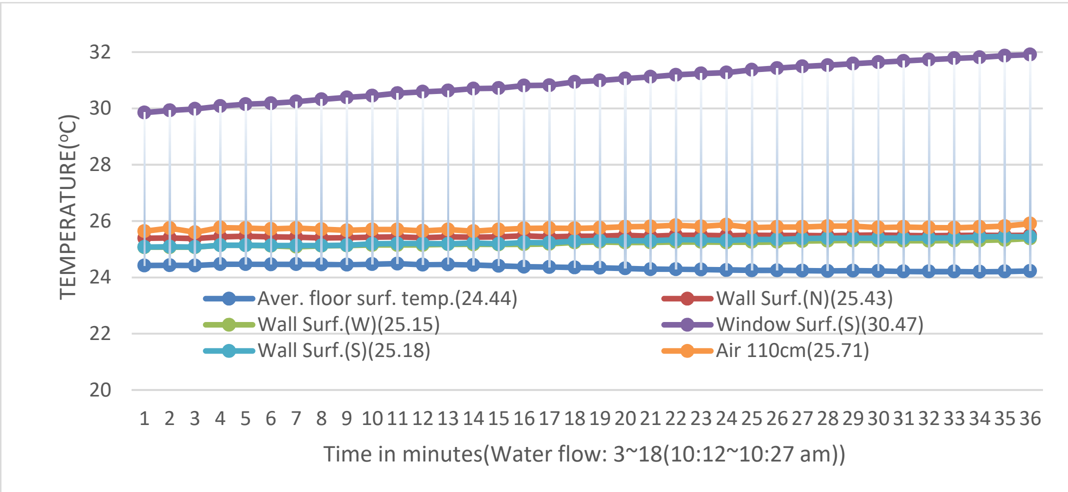

Fig.6: Room wall surface and air temperature at 110cm

Figure 9 illustrates the boundary conditions (temperature and solar radiation around rooms A and B) for the PIRC experiment conducted from 12:32 to 14:43.

Figure 10 illustrates room wall surface and air temperature at 110cm height. The PIRC system was activated from 12:32 (1) to 14:43 (129) during the laundry. Except for the window surface, which has very poor insulation, the temperature on all wall surfaces was lower than the ambient air temperature at the same height (110 cm) due to the cold radiant heat between the cold PIRC surface and the corresponding wall surfaces.

Figure 11 illustrates a vertical temperature distribution of the PIRC. The PIRC system was operated on laundry for 2 hours and 11 minutes, from 12:32 PM to 2:43 PM. The floor surface temperature and the temperature at a height of 10 cm were similar for the first 30 minutes, but the floor surface temperature gradually decreased, while the temperature at a height of 10 cm remained constant until the wash was completed. The highest temperature was 170 cm, approximately 80% of the total height, during the first 30 minutes. However, after 30 minutes of operation, the two temperatures became similar.

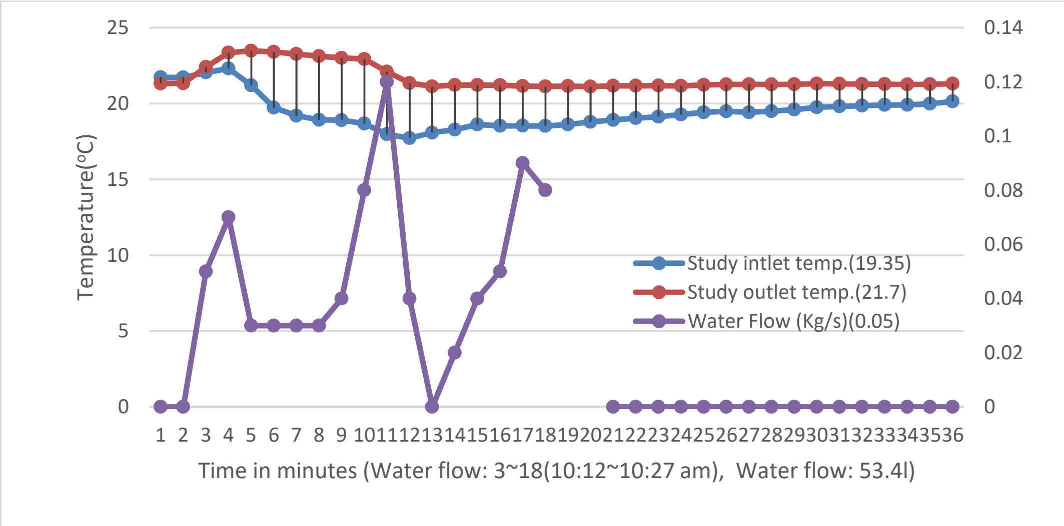

Fig.7: Inlet, outlet water temperature, and water flow rate.

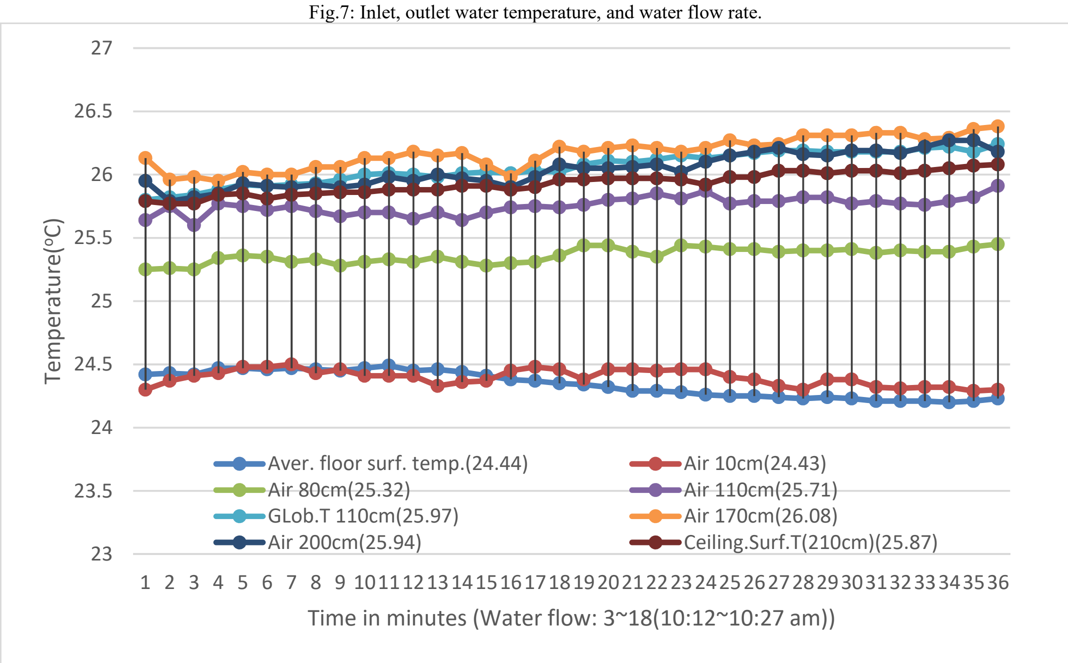

Fig.8: A vertical temperature distribution of the PIRC.

Figure 12 illustrates the inlet, outlet water temperature, and water flow rate for the PIRC. The wash took approximately 2 hours and 11 minutes, consuming 279.1 L of water. The average flow rate was 0.056 kG/s. The average temperature difference between the inlet and outlet water temperatures throughout the entire wash was 1.58°C. However, during the first 15 minutes, the average temperature difference was 2.5°C. As the wash time increased, the average temperature difference also decreased. The right vertical axis indicates the water flow rate (kg/s).

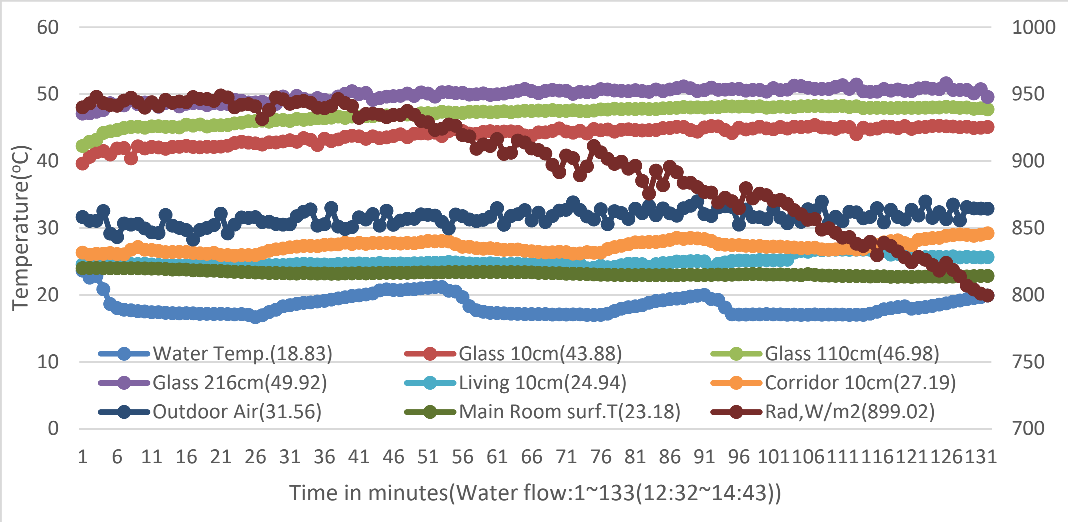

Fig.9: The boundary conditions for the PIRC experiment (from 12:32 to 14:43)

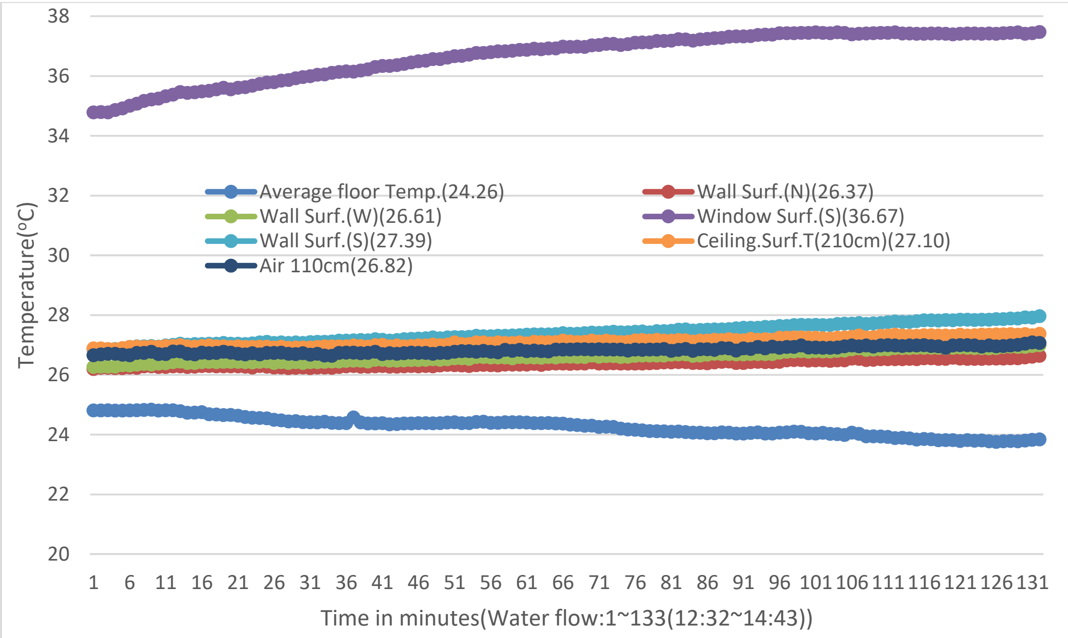

Fig.10: Room wall surface and air temperature at 110cm height.

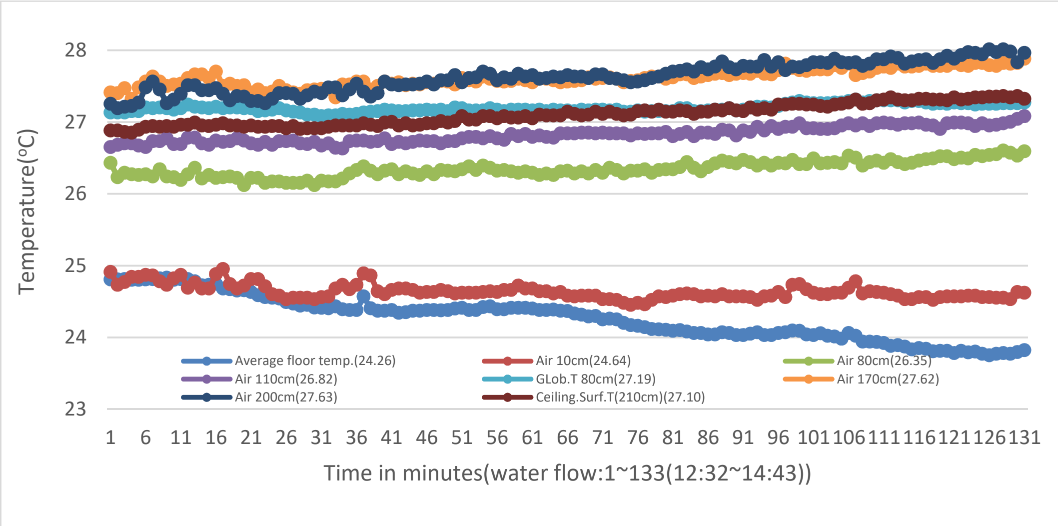

Fig.11: A vertical temperature distribution of the PIRC.

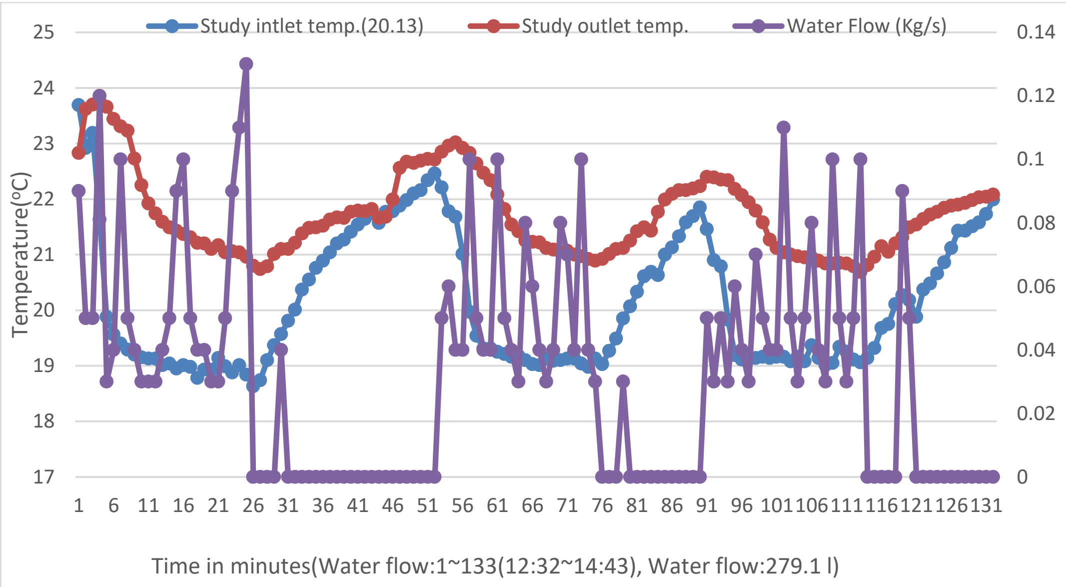

Fig.12: The inlet, outlet water temperature, and water flow rate for the PIRC.

3.2 Cooling capacity of PIRC

The cooling capacity of the PIRC is calculated according to Equation (1)

$$Q = m \times (h_2 - h_1) \qquad (1) \qquad (1)$$

Herein, $h_2 - h_1 = 4.186 \times (t_2 - t_1)$ in kJ/kg, m is the water flow rate (kg/s), t_1 is the inlet temperature, and t_2 is the outlet temperature. Equation (1) is proportional to the water flow rate and inlet and outlet temperature difference. (DIN EN, 2004)

Figure 13 illustrates cooling capacity of the PIRC depending on the temperature difference of inlet and outlet while taking a shower. From the third minute of operation, water is consumed to take a shower, and the indoor inlet and outlet temperatures drop respectively 19.2°C and 22.22°C, a level that remains relatively constant during morning showers. Cooling capacity fluctuates from approximately 15 W/m² to 61 W/m², resulting in an average cooling capacity of 19.3 W/m² during the total period of 15 minutes. This is likely due to the low water flow rate and the heat storage effect of the concrete floor from using Room a prior to showering.

Figure 14 shows the cooling capacity of the PIRC according to the temperature difference between the PIRC inlet and outlet during washing. From the beginning of operation, water is consumed to wash for laundry, and the indoor inlet and outlet temperatures drop respectively 20.0°C and 21.68°C, a level that remains relatively constant during washing. Cooling capacity fluctuates from approximately 15 W/m² to 48 W/m², resulting in an average cooling capacity of 15.9 W/m² during the total period of about 2 hours. This is likely due to the low water flow rate and the cold storage effect of the concrete floor from using Room a including taking the shower prior to washing.

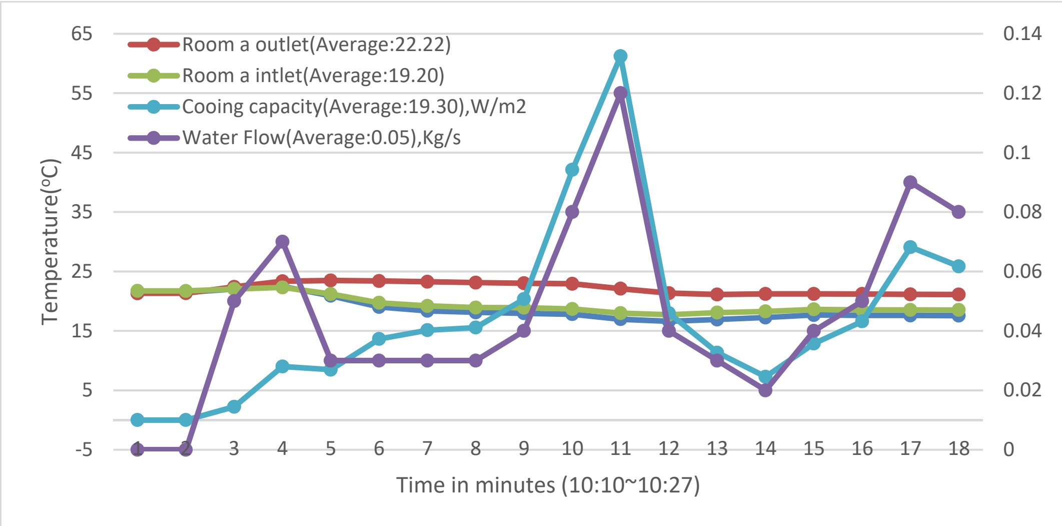

Fig.13: Cooling capacity of the PIRC depending on the temperature difference

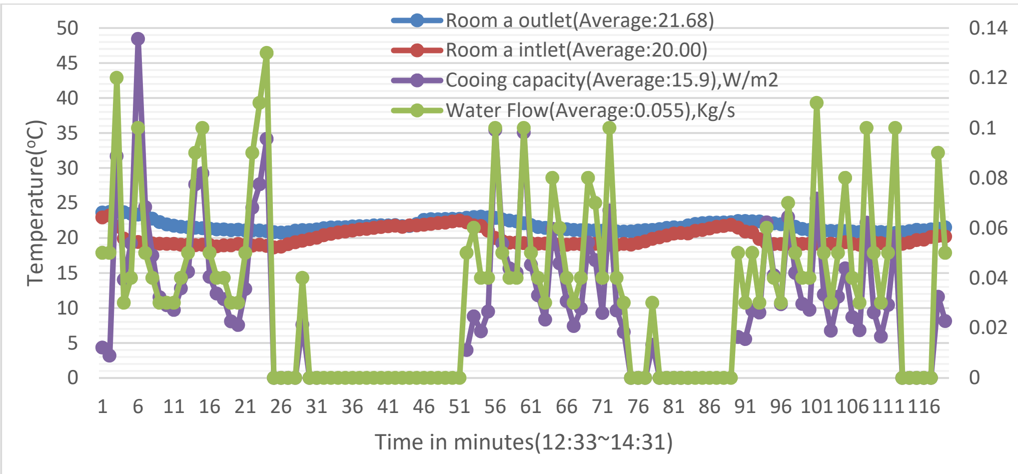

Fig.14: Cooling capacity of the PIRC according to the temperature difference during washing.

3.3 Cool tube for intake of low temperature fresh air

The Source Flow Ventilation System (SFVS) compensates for PIRC during extreme heat events, maintaining a consistently comfortable environment. The optimal temperature for the SFVS is approximately 18°C, and it draws in fresh air from the lower part of the room. Figure 15 illustrates the cool tube for fresh air intake to the room of the plus energy solar house.(Chung, 2025)

Figure 16 illustrates a temperature difference between before exchanger and after one by the heat exchanger. The vertical axis of right side illustrates delta t. After water flows through the floor-mounted pipes, it passes through a heat exchanger. The temperature difference before and after the heat exchanger remains approximately 1.68°C throughout the entire process. However, during using the water, the temperature difference exceeds 2°C. This temperature difference provides the relevant hint to draw in outside air through the cool tube and supply the cool, fresh air at the required 18ºC indoors for the source flow ventilation.

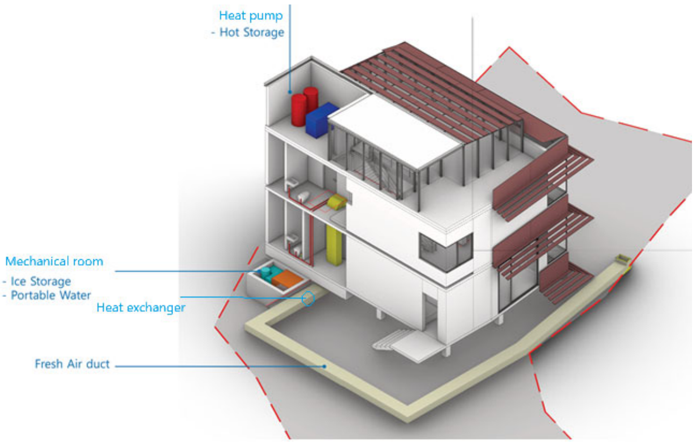

Fig.15: Cool tube for fresh air intake to the room.

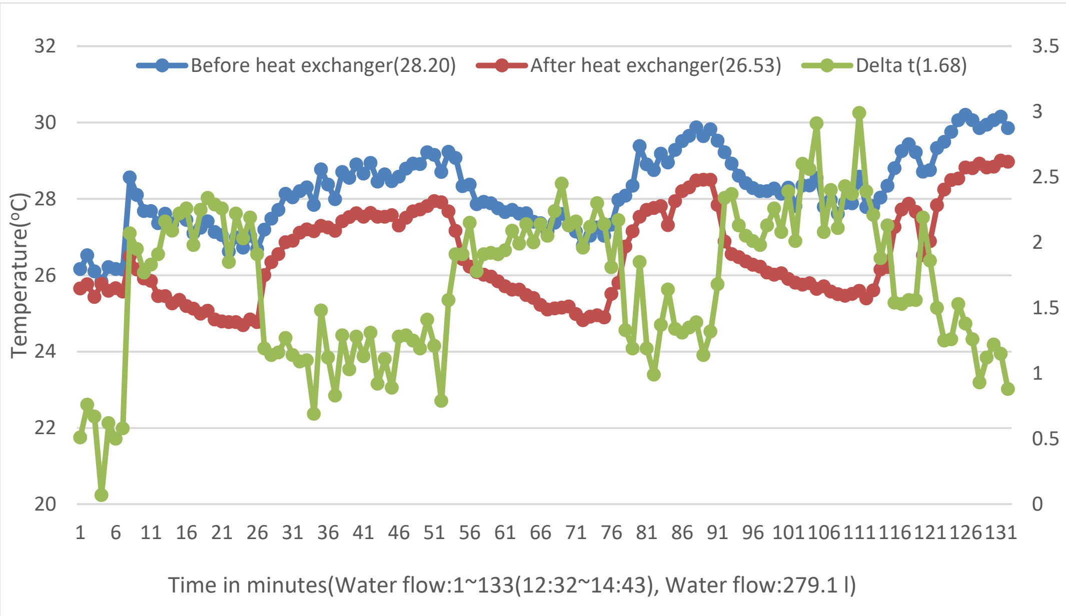

Fig.16: Temperature difference by the heat exchanger.

4.Ecological Design Guidelines (EDGs) for Plus Energy House Elements

The EDGs for the ecological design of a plus energy solar house element have been continuously developed in the form of documents and simulation programs (Yoo, 2015, 2019, 2022, 2024, 2025) to use for optimizing the ecological plus energy building (EPEB) and disseminating the EPEB worldwide to mitigate climate change and adaptation and have become also the official standard of Korean Solar Energy Society (KSES, www.kses.re.kr) and the Korean Society of Living Environment System (KSLES, www.ksles.org/) since 2013 in the slightly different name such as “Solar architecture”.

The EDGs are supplemented for this EPEB and shown in Table 2. The sum of the dependent variables should equal 100. The vernacular concepts for architectural elements are supplemented to consider the ecological values of regional architectural elements which are handed down for many generations. By adding the ecological value of the Ondol heating system and eaves, which are important features of traditional Korean houses, to these criteria, the criteria revives the indigenous ecological values that have been passed down from generation to generation and enable residents to feel comfortable in ecological, energy, and psychological aspects.

Table 2: Ecological design guidelines for EPEB

Category	Evaluation Factor	Independent variable	Dependent variable
Solar Radiation (1 Item)	Effective Solar Irradiance (ESR)	Effective Solar Irradiance Factor (x1)	F(x1)
Energy (3 Items)	Ecological Energy Conservation through efficient Ventilation	Natural Ventilation consideration(x21)	F(x21)
	Regio-physical concepts and systems for EPEB including heating, cooling, and storage combined to renewable energy harvesting system etc.	Total Energy Elimination Factor for Transparent Envelope (x22)	F(x22)
		Total Energy Transmittance Factor for transparent Envelope (x23)	F(x23)
		Thermal transmittance for opaque Envelope (x24a)	F(x24a)
		Regio-physical EPEB systems (x24b)	F(x24b)
	Consideration for Power Generation Improvement	No shaded Area on the solar system (x25)	F(x25)
		Convergence idea (x26)	F(x26)
Aesthetic View (1 Item)	Harmony with Architecture or Building Envelope	Harmony with Architecture (x31)	F(x31)
		Finish Material (x32)	F(x32)
Indoor Environmental Quality (3 Items)	Acoustic Environment	Buffer factor (x41)	F(x41)
	Thermal Environment	Thermal Comfort (OT) (x42)	F(x42)
	Lighting Environment	Daylighting factor (x43)	F(x43)
		Glare protection (x44)	F(x44)
Maintenance (3 Items)	Building Energy Management system	Intelligent energy management system (x51)	F(x51)
	Monitoring	Energy harvesting monitoring system (x52)	F(x52)
	Cleaning for Module Surface	Cleaning availability (x53)	F(x53)
Practical Use of Structure (2 Items)	Application for a New Building	Ecological application for new build (x61)	F(x61)
	Application for a Remodeling	Application for an existing building (x62)	F(x62)
Safety (1 Item)	Safety to Wind speed	>50m/s (x7)	F(x7)
Sustainability (1 Item)	CO_2 Evaluation through Life Cycle Analysis of a System	$LCCO_2$ (x8)	F(x8)
Vernacular concept of architectural element (1 Item)	Passive intelligent concept	Renewable multi-purpose use of a vernacular concept (x9)	F(x9)
Sum: 9 categories	16 Evaluation Factors	1st Grade: 90, 2nd Grade: 80, 3rd Grade: 70	100

5.Conclusions

Buildings affect the environment on a global scale. Since 1990, the requirements of cooling energy in buildings have tripled during particular peak load periods. Concepts for a plus energy solar house have been developed by the EDG, PIRC, MF-BIPV, PV thermal, etc. The EDG and applied green technologies can contribute to optimizing EPEB for RECREVIM. The optimal angle of the bi-facial PV module as a shade is 23.5°. The MF-BIPV can reduce 27.5~34% of the building cooling load. The bi-facial MF-BIPV can produce 12% additional power output in comparison to conventional mono-facial BIPV. The increased power output of the bi-facial MF-BIPV is 46% more than one of the wall-attached BIPV. PIRC systems that use only the enthalpy and pressure of natural water can be an ecological solution for cooling the buildings for climate change mitigation and adaptation, as they do little require any cooling energy or additional water to cool the building. The temperatures on all indoor surfaces including ceiling surface are lower than the air temperature at the same level due to the cold radiation effect between the cold PIRC surface and the corresponding indoor surfaces, so that this PIRC can be more comfortable and energy efficient rather than air conditioning system. The highest vertical temperature is approximately at 80% of the total height, so that ventilation outlet can be recommended to set up around the range. The use of heat exchanger within the cool tube can be very efficient. The Source Flow Ventilation System with heat exchanger compensates for PIRC during extreme heat events, maintaining a consistently comfortable environment. In the future, the building envelope performance (walls, windows, MF-BIPV, etc.) will be optimized by simulating and evaluating it using simulation programs such as “TRNsys” and “SolCel.”

6.Acknowledgments

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