Radiant Cooling System without Any Energy Input

Seung-Ho Yoo[1], Hee-Jeong Choi[2]

[1]Solar Architecture Laboratory/Sehan University, Youngam (Republic of Korea),
[2]Department of Biomedical Science, Catholic Kwandong University, Beomil-ro 579 beon-gil, 25601 Gangneung-si, Republic of Korea

Efficient cooling and heating solutions for nearly zero-energy solar dwellings are required to mitigate climate change and to make sustainable dwellings nowadays. The installed pipeline for a radiant heating system, which is used for space heating just during the heating period, can be used also to cool the room just by the enthalpy use of the natural city water without any energy and power input by releasing the natural city water through the embedded pipeline already installed for the radiant heating. The natural city water used for radiant cooling can be used at the necessary places such as toilets flushing, car washing, wash machine, garden water, etc. which are corresponding to approximately 56% of the water we use at home. As a result, the embedded pipe of the radiant heating system can be converted to a radiant cooling system with a minimum added installation and control system without any energy or power input. Thermal comfort and behavior analyses in an enclosure with a radiant cooling system are fulfilled by experiment, mean radiant temperature simulation, and asymmetric radiation calculation. No uncomfortable asymmetric radiations are encountered for the cooling period so that the cooling spaces are well controlled within the comfortable cooling range without any energy and power input. The radiant cooling concepts by the use of natural city water could be a nice solution for comfortable and reasonable zero-energy dwellings. No extra cooling energy and power are required to cool the space just by the use of enthalpy and pressure from the natural city water.

Keywords: Radiant cooling, No energy input, On-dol heating, Mean radiant temperature, Natural water, Thermal comfort, Asymmetric radiation, Enthalpy

1. Introduction

Buildings are critical to the transition to a net-zero future, as they are responsible for about 40% of the global energy consumption and about one-third of global GHG emissions. Energy consumption for space cooling has more than tripled since 1990, especially during peak demand periods and extreme heat events. Over 10% of building energy use is used for air conditioning and indoor thermal comfort in hot seasons. Changing the air conditioning mode is one solution to meet the cooling demand without increasing power consumption and CO_2 emission. Global space cooling demand continued to grow in 2020, driven in part by greater home cooling as more people spent more time at home. Space cooling accounted for nearly 16% of the building sector's final electricity consumption in 2020. Residential AC units for space cooling in operation account for nearly 70% of the total (IEA, 2021).

An environmentally friendly or energy-efficient heating & cooling systems attract great attention, due to energy, environmental problems, and climate change, etc. Especially radiant heating and cooling system are the exact example of these cases. The heat balance of the human body is about 46-50% influenced by radiation exchange in the built environment (Rietschel and Raiss, 1963; Fanger, 1972). Therefore thermal characteristics in a radiant built environment need to be precisely accessed through an efficient evaluation method (Glueck, 1982) (Klima- und Lueftungstechnik). The heat flow density on the floor surface was determined by pipe spacing, thickness,and heat conductivity of the layer above the pipe etc (Konzelmann and Zoellner, 1982). Radiant cooling can be an energy-efficient strategy, thereby reducing both sensible and latent loads in spaces (Teitelbaum et al., 2019).

In Germany, the first reports of the application and experimentation of ceiling systems that are heated in the ceiling in the winter and used for cooling purposes at the same time in the summer appear (GI, 1938). In Switzerland, a thermal active building structure system has been applied for radiant heating and radiant cooling purpose (Koschenz and Lehman 2000).

Almost of Korean dwellings have conventionally used the On-Dol (Warm stone plate) heating system which is a traditional radiant floor heating system. A radiant cooling system attracts also much attention nowadays from the

doi:10.18086/eurosun.2022.03.02 Available at http://proceedings.ises.org

viewpoint of energy conservation and thermal comfort. Thermal behavior such as comfort characteristics and asymmetric radiation in an enclosure with a radiant cooling without any energy input, and thermal capacity of the system in a dwelling are analyzed by experiment and simulation through an application in a private house.

2. Radiant cooling system without any energy and power input

2.1 Principle of radiant cooling without any energy and power input

The conventional radiant heating system, which is used only for space heating during the heating period, can be used also to cool the room without any waste of city water and power input by releasing the natural city water through the embedded pipeline already installed for the conventional radiant heating system. That is a kind of passive intelligent radiant cooling concept. Even when the outside air temperature is over 36ºC during the cooling period, the natural city water temperature is approximately 19-20ºC in Korea at the tap water in principle because the city water is supplied at least 90 cm under the earth in Korea. The corresponding city water temperature is respectively 19-20ºC in Turkiye, and 10~14ºC in Germany and Denmark. Korean water supply facilities should be buried at least under 90cm of earth. The natural city water flows through a pipeline which is embedded in the cooling surface during occupants' water use for toilets, washing machines, cleaning, car washing, garden water, and shower which are corresponding to approximately 56% of the water we use at home (Daniels, 1994). It is a similar one of the multi-purpose principle which the room is automatically heated by the hot exhaust gas that flows into the heating flue after burning the timbers to cook something in a kitchen in a traditional On-dol (Warm stone plate) radiant heating system in Korea (Yoo, 2021). No power and water are requested to cool the room. The enthalpy of the natural city water for the radiant cooling is used to cool the room space and the used water continues to flow at the necessary places such as toilets, washing machines, car washing, cleaning, garden water etc. Fig.1 shows the principles of radiant cooling system without any energy input (Yoo, 2015).

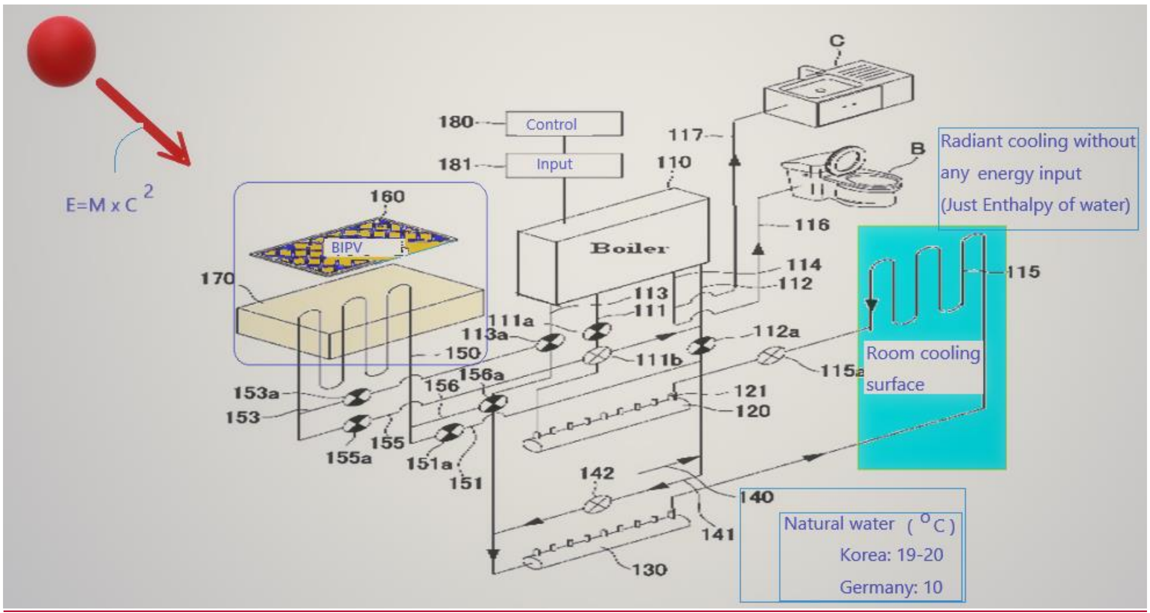

Fig.1: Principles of radiant cooling system without any energy input

2.2 Description of the passive intelligent radiant cooling system

The thermal behavior and capacity of the passive intelligent radiant cooling system is evaluated in the house where is located in Chung-Nam Province, Republic of Korea. The radiant cooling system is composed of two different parts. There are the 1st one converged to a BIPV as a night cooling which is numbered 160 and 170 on the left side and the 2nd one converged to a radiant heating system on the right side of Fig.1. The right side is the target of this study. Figure 2 shows the floor plan of the private house with the attached glass house which the radiant floor heating system is installed.

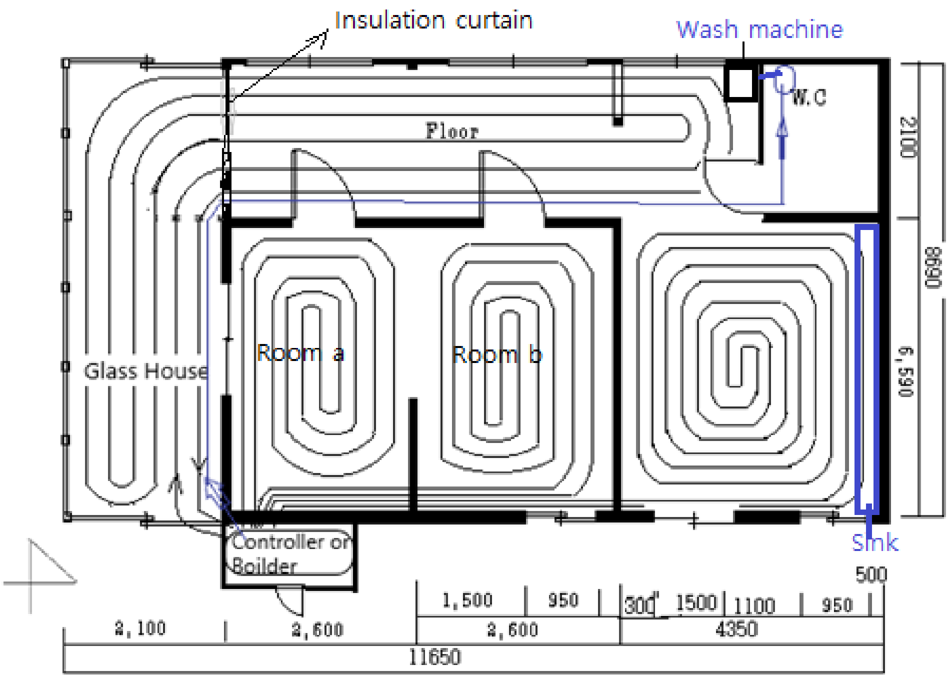

Fig.2: Floor Plan of radiant cooling and heating system with an attached glass house

The total dimension of the house is approximately 11.7 M × 8.7 M × 2.5 M (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. But the glass window between the glass house and the room a is 3 mm thick. Figure 3 shows the section of the radiant cooling and heating pipe installation plan.

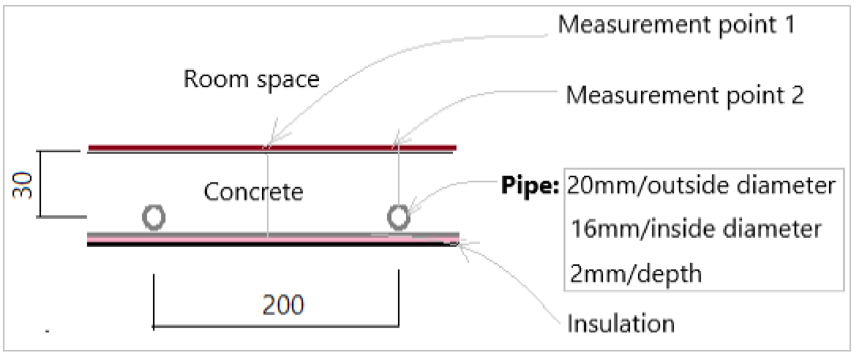

Fig.3: The section of the radiant cooling and heating pipe installation plan

The distance between pipes is 200 mm, and the depth of the concrete from the pipe to the floor surface is 30 mm. The house had been originally constructed by an On-dol (Warm stone plate) radiant heating system heated by the hot gas through timber combustion during cooking in a kitchen approximately since the end of 1800. Then the On-dol radiant heating system has been converted to the present hot water On-dol radiant heating system since early 1980. Namely, almost all such traditional On-dol radiant heating systems have been improved to a radiant heating system heated by the hot water which flows through the pipeline embedded in concrete floor. The hot water is circulated through the embedded pipeline to heat the room in winter by the boiler.

The glass house has been attached since the late 1990. The target radiant cooling system without any energy and power input has been converted to cool the house since 2018.

In summer the natural city water flows to cool the room through a pipeline embedded in the floor surface. No power and no extra water are required to cool the room space. The more people live in the radiant cooling space, the more city water automatically flows to cool the room space by the water pressure of city water because the people use more water as per the increased number of occupants. The amount of the city water flows approximately 0.112-0.115 kg/s during using the water system such as wash machine, toilet, cleaning, etc. while the occupants stay at home.

2.3 Research methodologies

32 thermal points have been measured by the Data logger per every 30 or 60 minutes the vertical room air, surface temperature of the room, and the other boundary conditions including inlet and outlet water temperature for the room, and outdoor air temperature. Tg means the glass house temperature. Tr means room temperature. The table 1 shows the measurement detail.

Table 1: Measurement detail

Measurement factor (Position)	Method	Accuracy
Outdoor air temperature (1.5 m)	Data logger + T-type Thermo couple	±0.75%
Vertical Air temperature (0.1 m, 0.8 m,2.3 m)		
Inside surface temperature (South wall, south window, west wall, north wall, floor surface 1, 2, 3, 4, Ceiling surface)		
Inside temperature of the glass house -Surface (Floor, south, east, and inclined glass ceiling) -Vertical air (0.1 m, 0.8 m, 2.3 m) - Inlet and outlet water temperature(Pipe surface temp.)		
Glove temperature(Room and Glass house) (0.8 m)	Glove thermometer+ T-type Thermo couple	
Room humidity (0.2 m)	Asman humidity meter	

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, the thermal capacity of the radiant cooling system.

3. Thermal Behavior of the Radiant cooling system

3.1 Evaluation of mean radiant temperature (MRT) and Operative temperature (OT)

A cubic box model which has the same surface area as the human body is used to evaluate the thermal comfort characteristics such as MRT and OT. The human body surface area is calculated according to the following equation (1)(Fanger, 1970).

$$A_{du} = 0.203 \times W^{0.425} \times H^{coef} \quad (1)$$

Herein, the coefficient coef is 0.696 for a sitting person. Weight W of a person is 70 kg, Height H is 110 cm for a sitting person. MRT is calculated by the following equation (2) (ISO7730, 2005).

$$T_{mrt} = \sqrt[4]{\sum_{i=1}^{n} ((\Phi_{b,si}) \bullet T_{si}^4)} \quad (2)$$

$Ø_{b,si}$: View factor between human body model and room surface,

T_s^4: Absolute temperature of the surrounding surface s

Operative temperature T_{ot} is calculated by the following equation (3) (ISO7730, 2005).

$$T_{ot} = a \bullet T_{air} + b \bullet T_{mrt} \quad (3)$$

Herein a+b=1, a:0.5, b:0.5.

3.2. Asymmetric radiation

A small cubic box of $1cm^2$ on the height of 0.6 m is considered to calculate the asymmetric radiation among the room surfaces including the floor cooling surface. The asymmetric radiation (Asym) is calculated by the following equation (4) (ISO7730, 2005).

$$Asym=|T_{MRTu}-T_{MRTo}| \quad (4)$$

Herein, T_{MRTu} is MRT for the underside, T_{MRTo} is MRT for the opposite side. The simulation program 'COMFORT (Yoo, 2018)" is used to calculate MRT, OT and Asymmetric radiation which can evaluate thermal behavior including thermal comfort characteristics for the target house.

4. Experiment and Simulation results

4.1 Radiant cooling concept and experiment results for the target house

A radiant heating system, which is used only for space heating during the heating period, can be used also to cool the room by releasing the natural city water through the embedded pipeline already installed for the radiant heating system. The city water used for radiant cooling can be used at the necessary places such as toilets flushing, car washing, wash machine, garden water, etc. For this purpose, even when the outside air temperature is maintained over 36°C during summer, the city water is approximately 19-20°C in the Republic of Korea, 10°C (Germany) for tap water, so that the cooling surface flows through a pipeline embedded in the floor, wall, or ceiling where it is not needed to drink water, whenever the occupants use the water system. No power is needed to flow the water. No wastewater results either. The amount of the city water flowed was approximately 0.112-0.115 kg/s. Figure 5 shows the temperature variations during the radiant cooling operation depending on the time-sequential process.

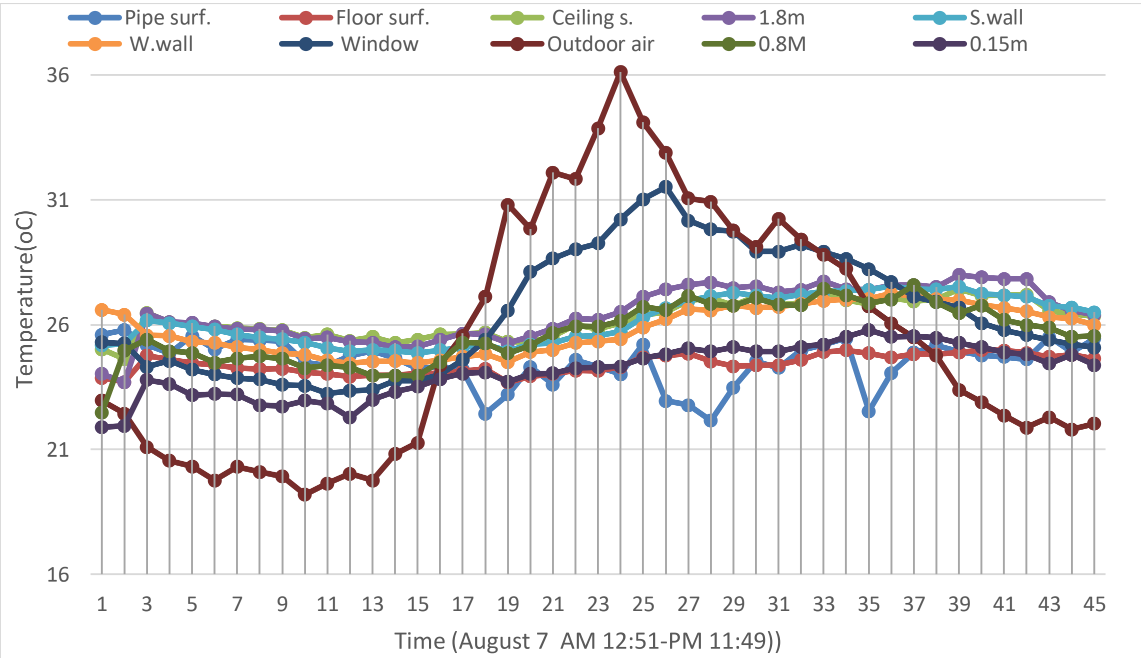

Fig. 5: Temperature variations of the radiant cooling space depending on the time-sequential process

Measurement was made every 30 minutes from 1-45 (am 12:51-pm 11:49) for 24 hours. The highest outdoor air temperature is 36.1°C at 12:51. The gardening water was supplied from AM 09:30-09:45. The sequential time is corresponding to 17-18 (AM 09:12-09:44) in Fig. 5. A person took a shower from am 11:00-11:12 (21: 11:17:36). The washing machine did the laundry from pm 13:35-15:25 (25: PM 1:22:51, about 75L water consumption per one laundry). The gardening water and car washing were done from 18:05-18:33 (34: pm 6:04:38). A person took a shower from 21:00-21:10 (40: pm 9:12:31). A person usually used to go to WC 8-9 times per day. If the water is used during the shower, the laundry, and the WC usage, etc, the embedded pipe surface temperature automatically goes down, so that the concrete structure that contacts the cooling pipe falls in temperature to cool the corresponding room. This causes to fall the surrounding surface temperature including ceiling, wall, and window surfaces to increase the thermal comfort for the occupant due to the cold radiation effects. During the laundry, the floor surface temperature is 24.69°C while the temperature at 0.15m height is 24.64°C. The ceiling surface temperature is 26.4°C while the air temperature is 27.1°C at the near position of the ceiling surface. The west wall surface, south wall surface, south window surface temperature, and air temperature at the 0.8 m height are respectively 26.22°C, 26.67°C, 31.51°C, and 26.71°C. The temperature difference profile between surface temperature and air temperature at the same height shows a similar distribution to the temperature profile between the floor surface and 0.15m height air temperature due to the cold radiation effect. But the temperature difference profiles near the vertical surfaces and ceiling surface show respectively 0.7°C (Ceiling: 27.1-26.4), 0.5°C (West wall: 26.71-26.22), 0.04°C (South wall: 26.71-26.67), and -4.8°C (Window: 26.71-31.51). The similar and revered temperature at the South wall and window comes from the poor insulation of the south wall and the window and the high air temperature of the glass house. Figure 6 shows the temperature variations of the radiant cooling space depending on the time-sequential process.

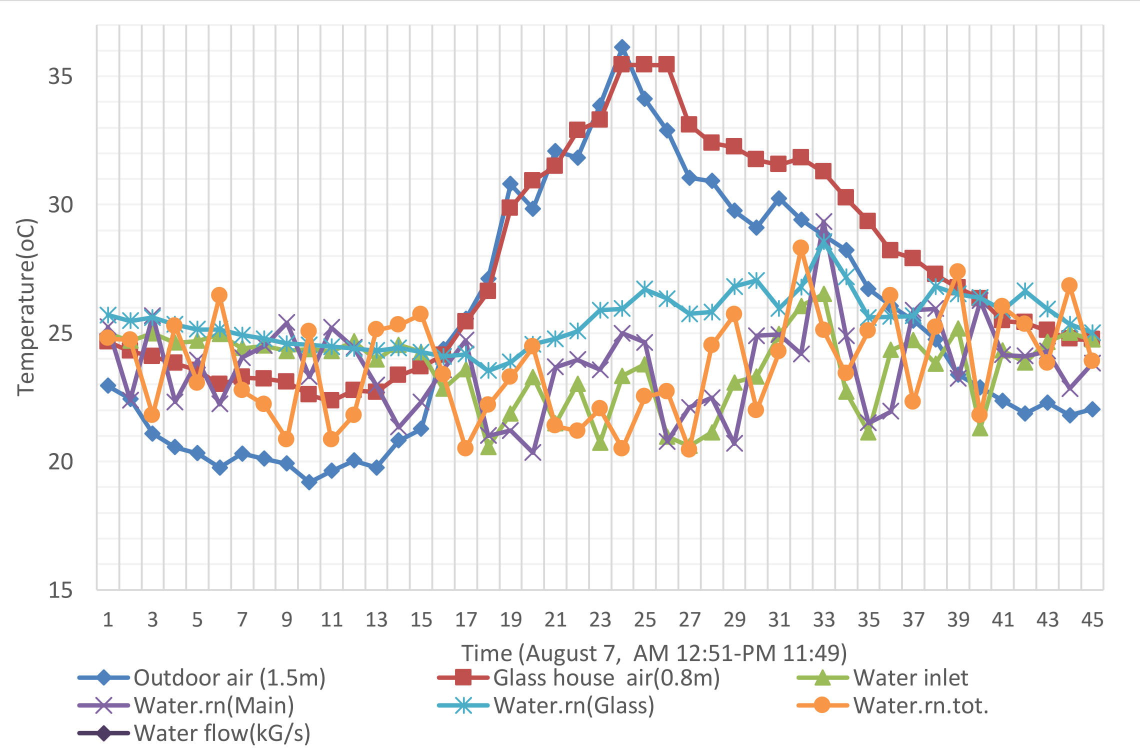

Fig.6: Temperature variations of the radiant cooling room depending on the time-sequential process

The maximum outdoor air temperature was 36.12°C at pm 12:51. The glasshouse is lasting high for 1 hour 30 minutes from pm 12:51. The returned water was shown to be the highest temperature in the glasshouse. This demonstrates the returned water (26-27°C) from the glasshouse can be reasonable for taking a shower in Summer. The inlet (City) water temperature was approximately 19-20°C. Figure 7 shows the average vertical temperature profile for the room for one day.

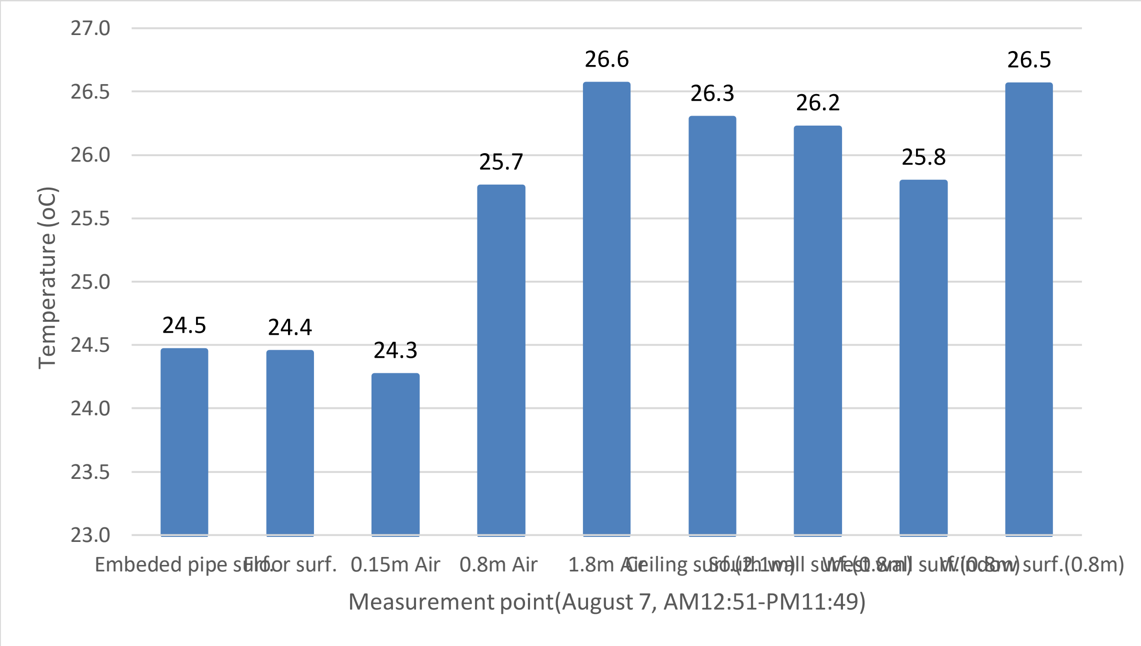

Fig.7: Vertical average temperature profile for the room for one day

The average outdoor air and glass house temperature for one day is respectively 25.4ºC and 27.5ºC. The average room air temperature at 0.15 m height is the lowest one 24.3ºC which could be comfortable for the occupants. The interesting one is the temperature at the 1.8m height which the ceiling surface temperature is 0.3ºC lower than the air temperature near the ceiling due to the cold radiation effect mainly from the floor radiant cooling surface. Figure 8 shows the vertical temperature profile for the room on pm 12:51.

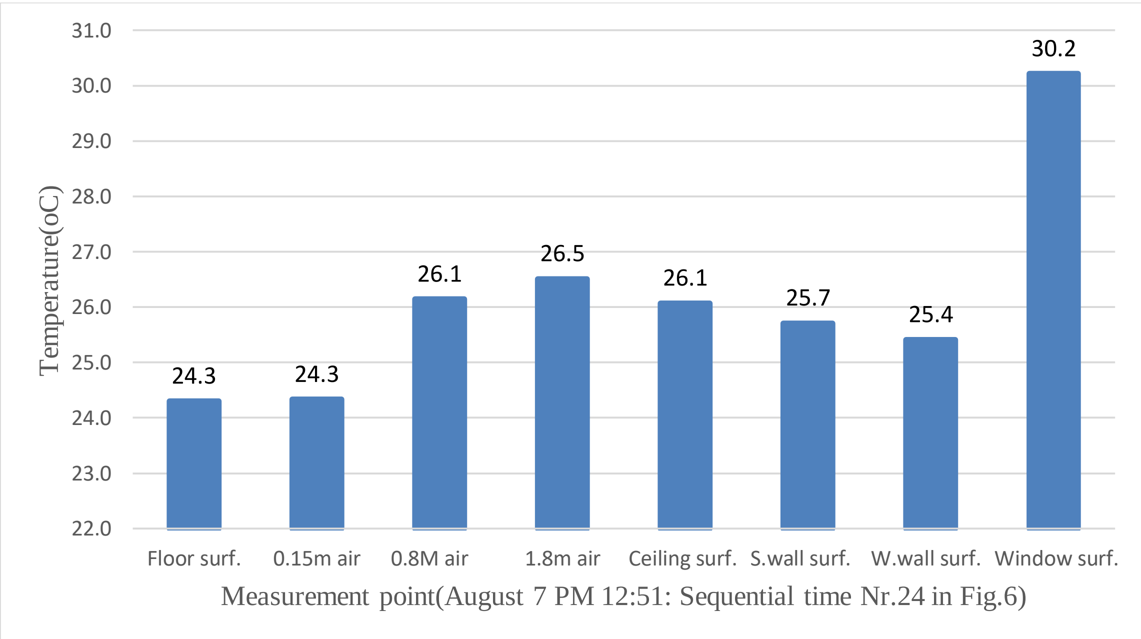

Fig.8: Vertical temperature profile for the room for one instant

At this moment, the radiant cooling floor surface temperature is similar to the air temperature at 0.15 m height (near the floor cooling surface) so there is little convective heat transfer on the floor radiant cooling surface. Alternatively, radiant cooling floor surface radiates to the ceiling surface, south wall surface, west wall surface, and window surface to fall in surface temperature. Therefore the surface temperature of the ceiling and the west wall at 0.8 m height is lower or similar to the air temperature at 0.8 m height. But the inside surface temperature of the window is 4.1ºC higher than the air temperature at 0.8m height due to the high temperature (35.5ºC) of the adjacent glasshouse.

4.2 Mean radiant temperature (MRT) and Operative temperature (OT) calculation

MRT and OT are calculated by the simulation program COMFORT based on equations (1), (2), and (3). Figure 9 shows the MRT distribution for the radiant floor cooling system for the house.

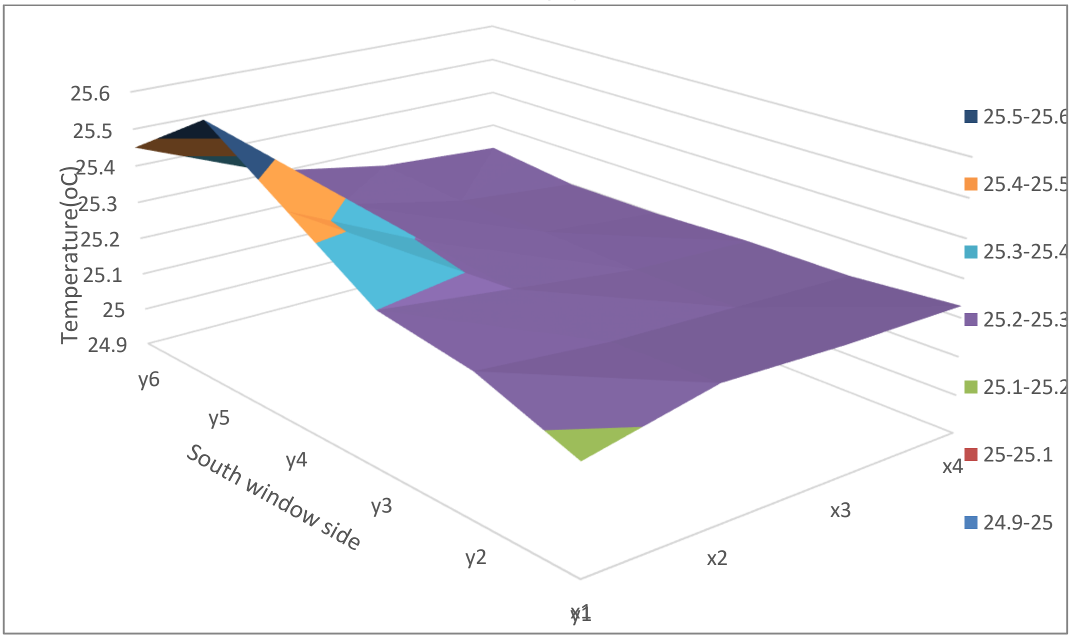

Fig.9: MRT distribution for the radiant floor cooling system for the house (August 7, pm 12:51, Outdoor air temperature: 36.1ºC)

A total of 24 points which keep 1m distance from every 4 different room surface orientations were chosen to simulate the MRT and OT. The average temperature of MRT was 25.27ºC. But the temperature at the window side was relatively higher than the inner side due to the high window surface temperature from the adjacent glass house. But the effect of the floor surface temperature on the MRT is the most influential factor and the average floor surface temperature 24.4ºC is within the lowest percentage dissatisfied range as per the local thermal discomfort caused by warm or cold floors (ISO7730, 2005). Figure 10 shows the operative temperature (OT) distribution for the radiant floor cooling system for the house.

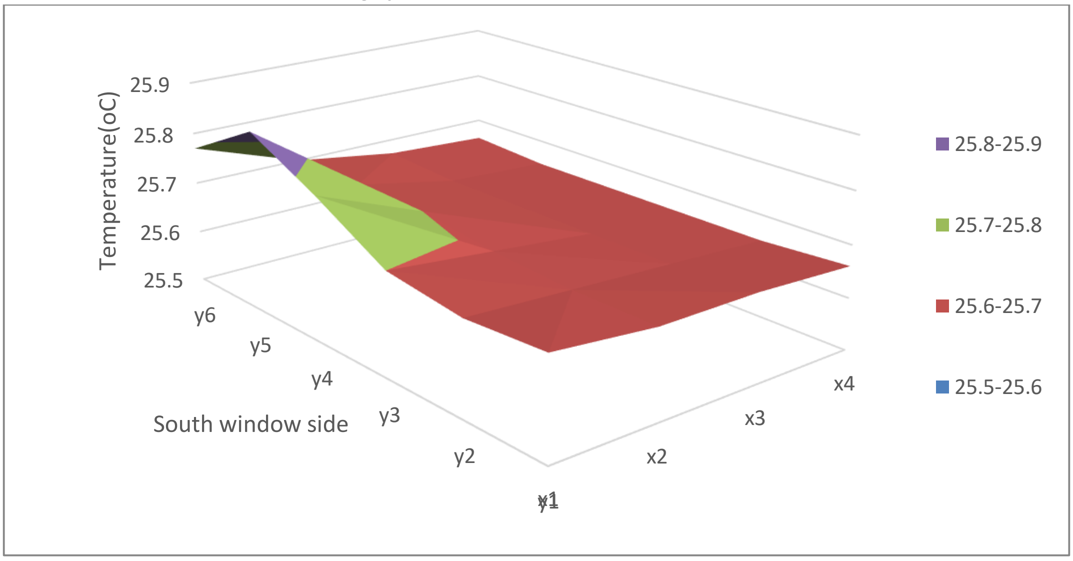

Fig.10: Operative temperature (OT) distribution for the radiant floor cooling system for the house (August 7, pm 12:51, Outdoor air temperature: 36.1ºC)

The average temperature of OT was 25.69°C which is a comfortable range for the occupants. The room OT range is 25.5~25.8°C even on the hottest day. But the temperature at the south window side was relatively higher than the inner side due to the higher south window surface temperature.

4.3 Asymmetric radiation simulation

The asymmetric radiation simulation for 6 different positions which keep 1m distance from the south window and wall was fulfilled by the use of the simulation program COMFORT based on the equation (4). The possible biggest temperature difference orientations between two different opposite surfaces were chosen to calculate the radiant asymmetry, namely ceiling and floor surface, south window side and north sidewall surface, east and west wall. Figure 11 shows the calculation results for asymmetric radiation on August 7 PM12:51 (Sequential time Nr.24 in Fig.6)

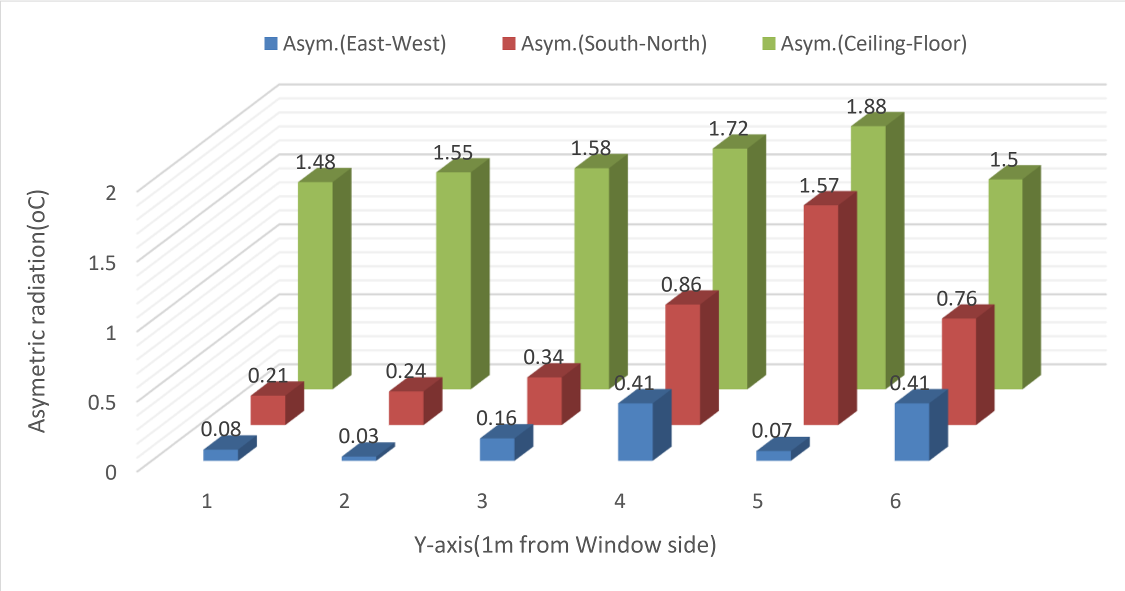

Fig.11: Asymmetric radiation (August 7 pm12:51)

The maximum asymmetric radiation (1.88°C) is raised at the y5 (Ceiling and floor at the window side). Asymmetric radiation does not happen in this radiant cooling space because the floor radiant cooling radiates to the surrounding surfaces mostly by the radiation. The highest radiant asymmetry is 1.88 °C near the south window side. This means that the local thermal discomfort is not caused by the radiant cooling system without any energy input in any position of the house (ISO7730, 2005).

4.4 Recommendations for an energy-efficient dwelling with the passive intelligent radiant cooling system without any energy input

The author recommend the following considerations for an energy-efficient dwelling with the passive intelligent radiant cooling system without any energy input. The radiant cooling system could meet the condensation problem on radiant cooling surface depending on the thermal capacity of the system and the room humidity condition. Therefore the outside shading is recommended to reduce the cooling load as possible which can reduce the cooling load by up to 34% to prevent the possible condensation problem in Seoul, Korea (Yoo et al., 2021). The source flow ventilation system is recommended for the radiant cooling system without any energy input to compensate for the system as per the radiant cooling floor surface temperature is similar to the 0.15m height room air temperature so that the source flow ventilation system can be very effective.

5. Conclusion

Efficient cooling and heating solutions for nearly zero-energy solar dwellings are requested to mitigate climate change and to make sustainable dwellings nowadays. The passive intelligent radiant cooling system without any energy input has been converted from the radiant heating system over 3 years in summer. The pipeline embedded for a radiant heating system, which is used for space heating just during the heating period, can be utilized also to cool the room just through the enthalpy use of the natural city water without any energy and power input by releasing the natural city water through the embedded pipeline already installed for the radiant heating. The natural city water used for radiant cooling can be used at the necessary places such as toilets flushing, car washing, wash machine, garden water, etc. which are corresponding to approximately 56% of the water we use at home. As a result, the embedded pipe of the radiant heating system can be converted to a radiant cooling system with a minimum added installation and control system without any energy or power input. Thermal comfort and behavior analyses in an enclosure with a radiant cooling system are fulfilled by experiment, mean radiant temperature simulation, and asymmetric radiation calculation. No uncomfortable asymmetric radiations are encountered for the cooling period so that the cooling spaces are well controlled within the comfortable cooling range without any energy and power input. The radiant cooling concept by the use of natural city water could be a nice solution for comfortable and reasonable zero-energy dwellings. No extra cooling energy and power are requested to cool the space just by the use of enthalpy and pressure from the natural city water.

The radiant cooling floor surface temperature is similar to the air temperature near the floor cooling surface so there is little convective heat transfer on the floor radiant cooling surface. Alternatively, radiant cooling floor surface almost all radiates to the ceiling surface, south wall surface, west wall surface, occupant, and window surface to fall in surface temperature. This passive intelligent radiant floor cooling concept automatically causes to fall in the surrounding surface temperatures including 0.7°C at the ceiling and 0.5°C at the west wall against the room air temperature near the corresponding surface to increase the thermal comfort of the occupant just by the radiation from the radiant cooling floor surface. The average OT was 25.69°C which is a comfortable range for the occupants. The room OT range is maintained at 25.5~25.8°C even on the hottest day. The house can be cooled very well without any ventilator or air-conditioner all summer just in the aspect of comfort temperature. But the source flow ventilation system is recommended for the passive intelligent radiant cooling system without any energy input to compensate for the system as per the radiant cooling floor surface temperature is similar to the 0.15m height room air temperature so that the source flow ventilation system can be very effective.

In the future the heat flow density on the radiant cooling floor surface will be precisely evaluated in the experimental set-up by pipe spacing, thickness, the heat conductivity of the layer above the pipe, etc.

6. Acknowledgments

This research is supported by Sehan University.

7. References

Daniels, K., 1994. The Technology of Ecological Building, Birkhaeuser Verlag, Basel Boston, Berlin.

Delmastro, C. et al., IEA. 2021. Cooling, Tracking report.

Fanger, 1970. Thermal Comfort, McGraw-Hill Book Company.

Gesundheit-Ingenieur(GI), 9/1938.

Glueck, B., 1982. Strahlungsheizung-Theorie und Paxis, Verlag C.F.Mueller Karlsruhe.

Hongshan, G. et al., 10.2019. Simulation and measurement of air temperatures and mean radiant temperatures in a radiantly heated indoor space, Energy.

IEA, 11 2021. The Role of Energy Efficient Buildings on the Path to Net-Zero - Strategies for policy makers.

IEA, 2021. EBC Annual Report 2020, Energy in buildings and communities programme.

ISO7730, 2005. Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.

Konzelmann, M., Zoellner, G., 1982. Waermetechnische Pruefung von Fussbodenheizungen, HLH 33.

Koschenz, M., Lehman, B., 2000. Thermoaktive Bauteilsysteme tabs, EMPA.

Mehmet, F.O., Cihan, T., 2022. A comprehensive comparison and accuracy of different methods to obtain mean radiant temperature in indoor environment, Thermal Science and Engineering Progress.

Rietschel, H., Raiss, W., 1963, Heiz-und Lueftungstechnik, Springer Verlag, Berlin/Goettingen/Heidelberg.

Teitelbaum, E. et al., 2019. The Cold Tube: Membrane assisted radiant cooling for condensation-free outdoor comfort in the tropics. J. Phys.: Conf. Ser. 1343 012080.

Yoo, S.H., Choi, H.J., 2021. Solar architecture integrated bi-facial photovoltaic system as a shade. Processes, https//doi.org/10.3390/pr9091625.

Yoo, S.H., 2021. Radiant colling and heating system for zero energy solar aechitecture, SWC 2021, ISES.

Yoo, S.H., 2015. Warem and cold water cycle structure of boiler, Korean intellectual Property office.

Yoo, S.H., Sohn, J.R., 2014. A Radiant Floor Cooling System for the Use of Natural Energy by Convergence of traditional Ondol and hot water Ondol heating system, KFMA.