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A Brief Review on Radiant Cooling Panel with Different Chilled Water Pipe Configurations

Mohammad Hakim Mohd. Radzai[1], Chin Wai Lim[1,*], Chong Tak Yaw[2], Siaw Paw Koh[2], Nur Amirani Ahmad[1], Mohammad Shakeri[2], Jagadeesh Pasupuleti[2]

[1] Department of Mechanical Engineering, Universiti Tenaga Nasional (The National Energy University), Jalan IKRAM-UNITEN, 43000, Kajang Selangor, Malaysia
[2] Institute of Sustainable Energy, Universiti Tenaga Nasional (The National Energy University), Jalan IKRAM-UNITEN, 43000, Kajang Selangor, Malaysia

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ABSTRACT

Radiant cooling systems are commonly applied in commercial applications because of their energy-saving potential. This potential can be further enhanced by evaluating the cooling performance of the radiant cooling panel in terms of flow configurations. Although studies have been conducted on the flow configurations of the radiant cooling panel, the most suitable flow configurations have yet to be determined. The conventional serpentine flow configuration does not bring out the best cooling performance of the radiant cooling panel, therefore different flow configurations are still needed to be explored. This study conducted a quick literature review on the different radiant cooling systems as well as radiant cooling panel with different chilled water pipe configurations. The objective of this review is to provide a brief comparison of the performance of radiant cooling panel with different chilled water pipe configurations and to suggest further studies for the system development. The cooling characteristics and heat transfer of the panel are investigated by using numerical study. A comparison between the designs of flow configurations is presented. In all of the cases, the plate area and flow volume are fixed. Based on the findings obtained, applying a different chilled water pipe configuration on the radiant cooling panel will affect the flow uniformity and also the temperature distribution uniformity. An optimized flow configurations for the radiant cooling panel is important for enhancing the overall efficiency of the system.

1. Introduction

Radiant cooling (RC) systems are one of the alternatives in achieving thermal comfort other than the traditional air-conditioning systems. RC systems are gaining popularity in recent years based on their energy-saving capability and the potential in achieving higher thermal comfort. RC systems also supply good indoor air quality (IAQ) compared to conventional all-air systems [1].

* *Corresponding author.*
E-mail address: lchinwai@uniten.edu.my

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The use of an RC system can cut down sensible loads thus reducing the ventilation air needs to a minimum [2]. The heat transfer for the same amount of heat is more efficient by using an RC system compared to the all-air cooling system as water has a higher thermal capacity than air [2]. Therefore, the building's energy-saving can further increase by cutting down the costs of energy used by traditional all-air cooling systems [2].

Imanari *et al.,* [3] has claimed that radiant cooling can provide more comfortable thermal conditions than conventional all-air systems. To learn more about the thermal comfort of a radiant cooling system, Tian *et al.,* [4] conducted a field study of occupant thermal comfort and thermal environments with radiant cooling slabs system in the Information and Communication Technology (ICT) building located at University of Calgary. The study conducted was a combination of field measurements and questionnaires based on American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) research project (RP)-921 project protocol [4].

Based on Tian *et al.,* [4], the average indoor air temperature was 22.3°C in both summer and winter with a temperature range of 20.7-24°C. The mean air velocity was 0.06 m/s with 36% average relative humidity in summer and 11% in winter. Based on ASHRAE 55-2004 [5], the allowable vertical air temperature difference between head and ankles is lower than 3°C and the allowable range of floor temperature is 19-29°C. The study conducted by Tian *et al.,* [4] proves that the radiant cooling system follows the thermal comfort standard with the average vertical air temperature difference between head and ankles is 0.5°C. Moreover, the average floor temperature obtained was 21°C for both of the seasons which falls in the 19-29°C range as mentioned in ASHRAE 55-2004 [5].

Tian *et al.,* [4] has claimed that the radiant cooling system provides a lower actual overall dissatisfaction than the total predicted dissatisfaction from general and local discomfort. This is due to the local discomfort produced from draft and vertical air temperature difference is effectively reduced by the radiant cooling systems compared to the mixed-air systems [4].

RC systems are mostly applied in commercial applications and are widely installed in airports [6-9], offices [10-13], schools [6, 14-16], museums [8, 17-20], and etc. [21-27]. The places of installation are in large public areas that need extensive cooling [28, 29]. However, an RC system can also be installed in a residential area, but it needs to be controlled carefully [23, 30-32].

Most RC home applications use ceiling radiant cooling panels (CRCP) in which chilled water is circulated in the water pipe installed on aluminium panels suspended from the ceilings [1, 31, 33]. CRCP cools down the surface temperature of the ceiling thus absorbing heat radiated by everything in the room including the occupants [33]. Sensible heat is removed from the occupant body mainly by thermal radiation and heat exchange only occurs between people and object without the need of cooled air. Therefore, thermal comfort of the occupant can be achieved with warmer interior air temperatures. The general idea of RC is shown in Figure 1 [34].

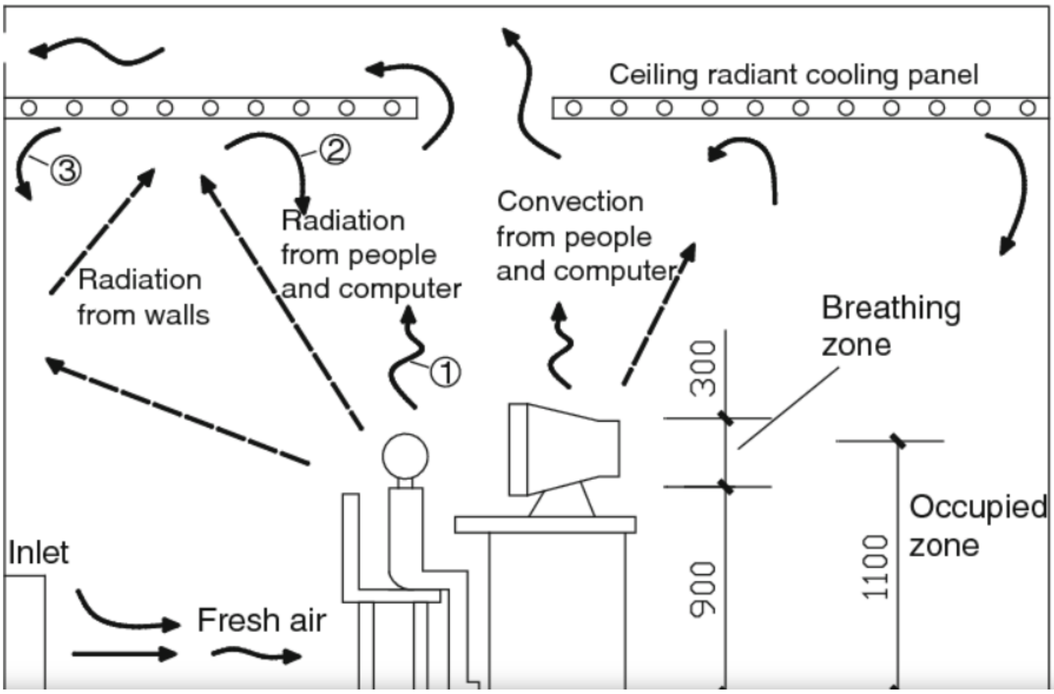

Fig. 1. General Idea for Radiant Cooling System [34]

For the RC system to be effective, the minimum exterior temperature of the panels must be kept slightly higher than the dew point temperature within the house [33, 35, 36]. If the surface temperature of the panel is lower than the dew point temperature, condensation may occur thus decreasing its effectiveness [36]. On the other hand, it is recommended to use a dedicated outdoor air system (DOAS) together with the radiant cooling system [1, 37, 38]. As long as radiant panel loop temperature control and DOAS are operating correctly, condensation can be avoided [1, 37-39].

This study conducted a quick literature review on the different radiant cooling system as well as radiant cooling panel with different chilled water pipe configurations. The objectives of this review are to provide a brief comparison of the performance of radiant cooling panel with different chilled water pipe configurations and to suggest further studies for the system development.

2. Types of Radiant Panel System

Various types of radiant cooling systems have been developed to suit better in different climates and surroundings. Their performance might differ from place to place. The radiant cooling system is divided into three groups which are the thermally active building systems, radiant cooling panel, and capillary tube system.

2.1 Thermally Active Building Systems (TABS)

A thermally active building system (TABS) uses water pipes that are thermally coupled to the building structure such as walls and slabs [40-42]. A schematic of TABS is shown in Figure 2. The water pipes are embedded in the concrete floor and utilize the concrete thermal mass for heating and cooling in the building’s structure [42-44]. Therefore, sensible cooling in the building is mainly contributed by the chilled surface of walls, ceilings, and floors [44-46].

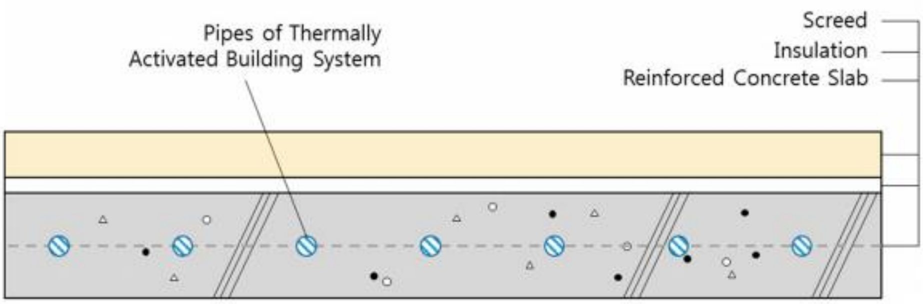

Fig. 2. Section view of thermally active building systems (TABS) [47]

TABS can provide adequate thermal comfort with low energy usage [48, 49]. TABS are also cost effective as it is installed during the construction phase and is capable to persist for the whole life of the building structure [48-50]. Besides that, TABS can ensure healthy indoor environment by providing optimal indoor temperature through a silent system that does not circulate air, dust, and draught [48-50]. The main disadvantage of TABS is that it is not feasible to be installed in an existing building. It is only used in new construction projects that prioritize green design element [50].

2.2 Thermally Radiant Cooling Panel (RCP)

A radiant cooling panel (RCP) is a panel consists of integrated water pipes and the panel is mostly suspended under the ceiling [1]. RCP can be used in both retrofitted and new buildings as the panel provides flexibility for zoning and easy installation compared to the radiant system types that have to embed water pipes in the concrete layer of the building [1, 35]. Metal ceiling RCP is widely installed and used on T-bar grids to support the suspended panel under the ceiling [51-55]. There are top insulated ceiling RCP and free-hanging ceiling RCP without topside insulation. The top insulated ceiling RCP is to prevent heat gain from the plenum space while the free-hanging ceiling RCP uses both top and bottom panel surfaces as heat transfer surfaces [51-55]. A sample of RCP is shown in Figure 3.

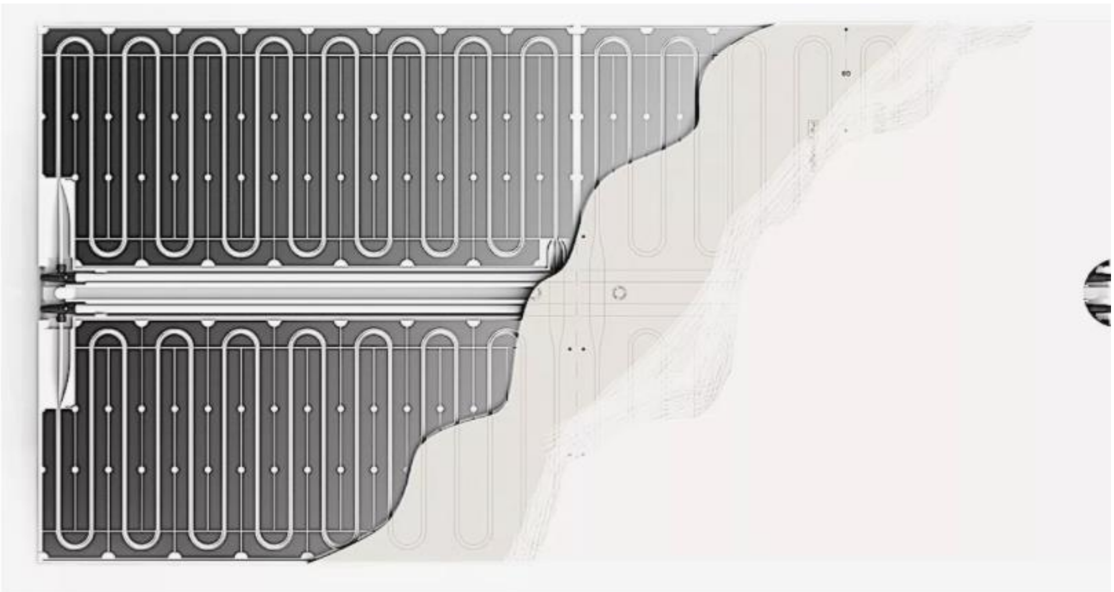

Fig. 3. Messana radiant cooling panel [56]

RCP have the same benefit as TABS and capillary tube system (CTS) where it can provide adequate thermal comfort with low energy usage and also can provide quiet cooling solution. What makes RCP stand out among other radiant cooling systems is the ease of installation [57, 58]. RCP have seamless integration where the installation of the system is the easiest compared to TABS and CTS [58]. However, RCP also suffer from condensation problem and can be prevented by increasing the supply water temperature to be higher than the dew point temperature of the room.

2.3 Capillary Tube System (CTS)

Capillary tubes are placed closely with each other on the cooling grid and are usually embedded in plaster or gypsum board [51, 59]. A capillary tube system can also be mounted on the ceiling panels and can be made in a form of a mat [59-61]. This system can ensure uniform surface temperatures as the tubes have narrow spacing between them. Figure 4 is one of the samples of CTS.

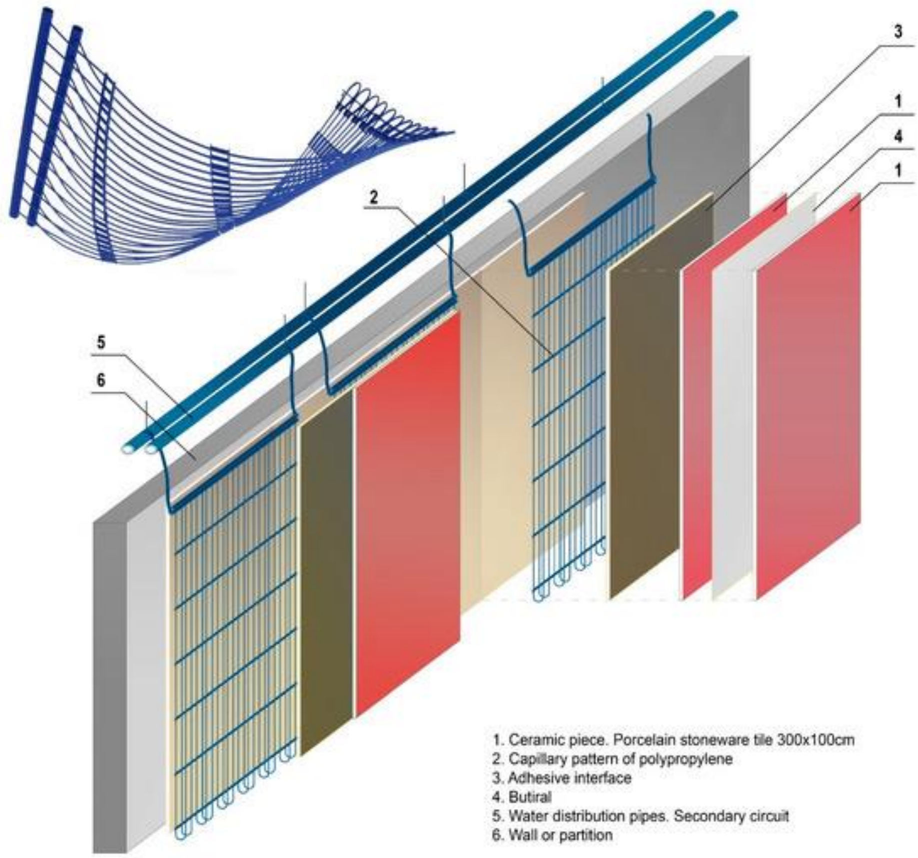

Fig. 4. Ceramic thermal conditioning panel using capillary tube system [65]

Interior surfaces with capillary tube mats have continuous temperature stability and allow for rapid dissipation of cooling loads or distribution of heat requirements, which is roughly 60% by radiation and 40% through convection [62]. The capillary tube mats have easy installation and can be installed under the surface decorative materials on walls, ceiling and floor. The energy transfer by this system produces zero noise thus thermal comfort can be achieved without any noise pollution by the system[63]. However, installations of the CTS in cold climatic zones are limited mostly by the system's heating power while the uses of the CTS in high-humidity areas are limited by the need to prevent condensation [64]. Clogging of the radiant cooling system can also be a problem when using plastic capillary tubes due to the tiny tubes that are commonly used in capillary tube mats [64].

2.4 Summary of Radiant Panel System

A summary of advantages and disadvantages for radiant panel system is shown in Table 1.

Table 1
Advantages and disadvantages of the radiant panel system.

Types of Radiant Panel System	Advantages	Disadvantages
Thermally Active Building Systems (TABS)	• Provide adequate thermal comfort with low energy usage. • Cost effective as it is installed during the construction phase. • Ensure healthy indoor environment by providing optimal indoor temperature.	• Cannot be installed in an existing building. • Only used in new construction projects that prioritize green design element.
Thermally Radiant Cooling Panel (RCP)	• Can be used in retrofitted and new buildings as the panels provide flexibility for zoning and easy installation. • Provide adequate thermal comfort with low energy usage.	• Have condensation problem. • Need high supply water temperature.
Capillary Tube System (CTS)	• Ensure uniform surface temperatures. • Interior surfaces with capillary tube mats have continuous temperature stability. • Easy installation and can be installed under the surface decorative materials. • Provide adequate thermal comfort with low energy usage.	• Have condensation problem. • Clogging of the radiant cooling system due to the closely arranged tiny tubes.

3. Results Performance of RCP with Different Flow Configurations

The flow configurations of RCP are divided into serpentine design and canopy-to-canopy design.

3.1 Serpentine Flow Design

A typical radiant panel has a copper pipe with a serpentine flow design set on top of an aluminum plate [66-70]. The panel is covered with an insulation layer that has a small gap filled with air [71]. In other words, a single pipe of fixed diameter is bent into an S-shaped and positioned parallel to each other to create the serpentine layout. Some sample of serpentine flow arrangement are shown in Figure 5.

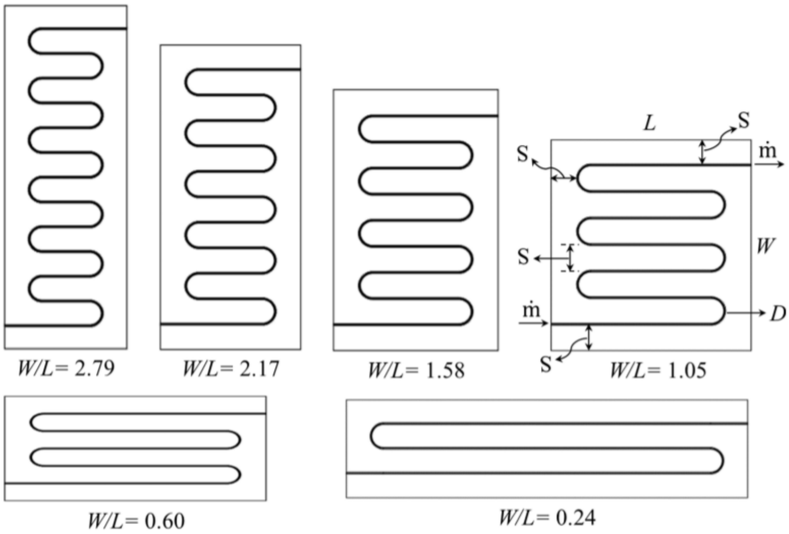

Fig. 5. Sample of serpentine flow arrangement with the different aspect ratio [66]

A simulation on the different aspect ratios of serpentine flow design was carried out by Mohamed Mosa *et al.,* [66] to find the best flow configuration for a radiant cooling panel. Based on the simulation, the researcher found out that a serpentine flow with an aspect ratio of 0.24 has a more uniform panel temperature but it is said that the plate temperature is hotter than a higher aspect ratio panel. The cooling capacity of a higher aspect ratio panel is enhanced slightly compared to that of a panel with a lower aspect ratio. However, there is a greater pressure drop across the panel with a higher aspect ratio due to the increasing number of bends over the serpentine pipe total length. More pumping power is required on a serpentine pipe with higher aspect ratios. Mohamed Mosa *et al.,* [66] proofed that increasing the aspect ratio of the serpentine flow design does not improve the panel's cooling capacity significantly. Therefore, exploration of different flow arrangements and configurations are required to improve the overall performance of the radiant cooling panel.

3.2 Canopy-to-Canopy Flow Design

A canopy-to-canopy design is taken from a tree structure design [66, 72, 73] and is shown in Figure 6. D_1 is the main pipe diameter which is also known as the tree trunk while diameter D_2 is its branches. The canopy-to-canopy flow design has one inlet and one outlet. Cooling fluid enters the inlet and then flows into equally spaced pipes that are parallel with each other before merging back into the outlet pipe.

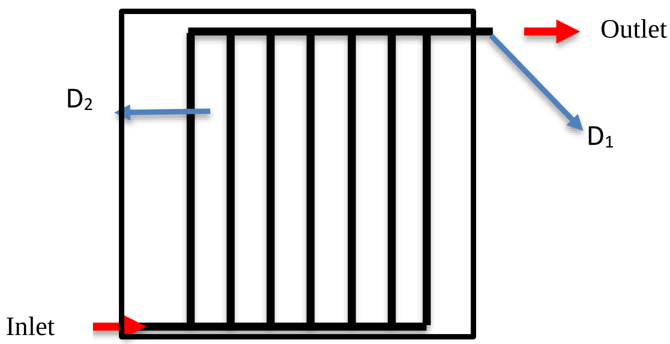

Fig. 6. General of Canopy-to-canopy flow design

There were two simulations done by Mohamed Mosa *et al.,* [66] through manipulating the pipe's diameter (D_1 and D_2). The first simulation was conducted with a constant D_1 throughout the pipes while the second simulation was conducted by changing the D_1 and D_2, meaning that there were two different diameters in the second simulation. Based on the results of the simulations, it concluded that the panel aspect ratio does not affect the flow distribution of the single diameter canopy-to-canopy flow design significantly. However, for the two diameters canopy-to-canopy flow design, the mass flow rate distribution is smoothened in the parallel channels without taking the panel aspect ratio into account. A minimum pressure drop is achieved by the canopy-to-canopy flow design with two different diameters.

3.3 Summary of Flow Design

Mohamed Mosa *et al.,* [66] claimed that the canopy-to-canopy flow design produced a better cooling capacity per pumping power compared to the serpentine flow design. The two-diameter canopy-to-canopy flow design with a 1.05 aspect ratio has a better performance than any other flow design. Based on this investigation, a two-diameter design can improve the cooling capacity of the panel with low pumping power demand. Nevertheless, there is a lot more possible designs that can be implemented in the radiant cooling panel to achieve a better panel temperature distribution and smaller pumping power.

A multi segmented mini-channel radiant ceiling cooling panel (MCRCP) is a new RCP design proposed by Lan Ding *et al.,* [74]. The schematic diagram of the proposed MCRCP is shown in Figure 7 [74]. Lan Ding *et al.,* [74] claims that the conventional serpentine flow design with a large panel area will limit the cooling capacity of the RCP. The advantage of MCRCP design is that it can give a significant improvement on the cooling capacity of the MCRCP by increasing the surface area of the panel which cannot be achieved by the conventional serpentine flow RCP [74]. For the same ceiling coverage ratio, increasing the surface area of MCRCP can greatly increase the maximum permissible cooling capacity [74].

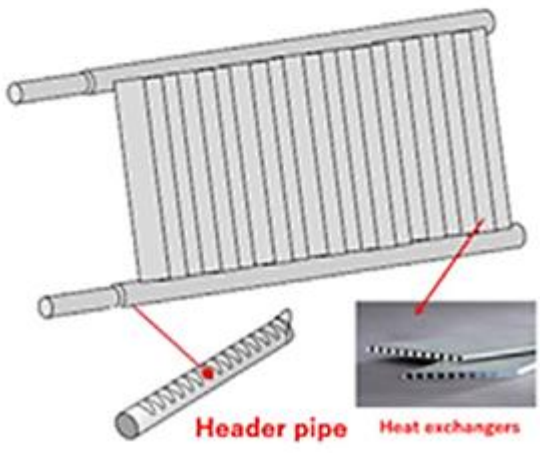

Fig. 7. Schematic diagram of MCRCP [74]

Based on the findings of Mohamed Mosa *et al.,* [66] and Lan Ding *et al.,* [74], the aspect ratio of the RCP can give a significant impact on the cooling performance of the RCP. Different aspect ratio is needed for different design of RCP in order to gain the maximum cooling performance from the RCP. Therefore, the aspect ratio of the RCP is an important factor that should be taken into consideration when designing new RCP flow configurations. A summary of flow design is shown in Table 2.

Table 2
Summary of research findings on the RCP with different flow configurations

RCP with Different Flow Configurations	Definitions	Findings
Serpentine Flow	• A single pipe of fixed diameter is bent into an S-shaped and positioned parallel to each other to create the serpentine layout.	• A serpentine flow with smaller aspect ratio has a more uniform panel temperature but the plate temperature is hotter than a higher aspect ratio panel.
Canopy-to-Canopy Flow	• A canopy-to-canopy design is taken from a tree structure design. • Cooling fluid enters the inlet and then flows into equally spaced pipes that are parallel with each other before merging back into the outlet pipe.	• The cooling performance of a canopy-to-canopy flow design is not affected by the panel aspect ratio.
Multi Segmented Mini-Channel Flow	• Have header pipe with a mini channel that flows into the multi segmented heat exchangers. • The angle between the inclined segment and header pipe can be manipulated.	• The cooling capacity of the MCRCP increases when the aspect ratio of the panel increases. • Further increasing the aspect ratio of the panel after a peak cooling performance have been obtained will result in decreasing cooling capacity of the MCRCP.

4. Results Parameters to Determine the Heating and Cooling Capacity of Radiant Panel

Rhee *et al.,* [6] proposed that heat transfer at each element of the radiant cooling and heating system are important criteria in determining the cooling and heating capacity of the radiant system. The heat transfer in the system depends on the heat exchange between the occupied space and the radiant surface. Besides that, it also depends on the heat conduction between the panel surface and the panel's pipe as well as the flow dynamics of water inside the pipe. Therefore, important parameters can be determined by understanding the heat exchange that occurs in the system. One of the parameters is the coefficient of convective and radiant heat exchange. Based on Rhee *et al.,* [6], the radiant heat transfer coefficient is generally about 5.5 W/(m^{2}K), while the convective heat transfer coefficient is between 0.3 and 6.5 W/(m^{2}K). The coefficient of both convective and radiant heat exchange have a direct proportionality to the heating or cooling capacity of the radiant panel. On the other hand, parameters such as the surface material, piping system, pipe spacing, mass flow rate of water, supply water temperature and return water temperature are also important and should be taken into account when designing a radiant heating or cooling system.

5. Conclusion

Finally, it can be concluded that the efficiency of the radiant cooling panel can be enhanced with the proper investigation of flow configurations. From this article, the aspect ratio and flow configurations of the radiant cooling panel can give a significant impact on its performance in terms of temperature distribution and pressure drop. Pressure drop is highly related to pumping power and with lesser pressure drop, smaller pumping power can be achieved that will increase the energy-saving potential of the panel. Based on the review results, conventional serpentine flow configuration does not bring out the best cooling performance of the radiant cooling panel. Instead, canopy-to-canopy flow configuration gives a better cooling performance that results in a higher cooling capacity with lesser pumping power. Based on this comparison, it is suggested that increasing the number and location of pipe inlets and outlets as well as the compactness of the pipe arrangement has the potential on improving the cooling performance.

The design of a radiant cooling panel should provide satisfactory indoor cooling performance. In order to achieve this, it is recommended that different design groups and flow configurations of the radiant cooling panel should be explored and investigated in the search for a better panel design and flow configurations.

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