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A 50 year review of basic and applied research in radiant heating and cooling systems for the built environment

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A B S T R A C T

The radiant heating and cooling (RHC) system has been gaining much popularity due to high thermal comfort, reduced energy consumption, quiet operation, space saving, and so on. For this reason, there have been numerous studies on the RHC system to evaluate the thermal performance of the system and to implement the system for practical applications. This study conducted a literature review on the basic and applied research in RHC systems for the built environment. The objective of this review is to find out the research trend of the RHC system, to discover main issues for the RHC system understanding, and to suggest further studies for the system development. In this study, a comprehensive review was conducted, in terms of thermal comfort, thermal analysis including heat transfer model, heating/cooling capacity, CFD analysis, energy simulation, system configuration and control strategies. The results showed that the RHC system has been continuously developed, modified and improved to achieve better thermal comfort and energy efficiency. Based on the review results, several topics for future studies were suggested, which are required to overcome the limitations of the RHC system for extending its application to various building types, climate, and so on.

1. Introduction

In order to provide the comfortable indoor environment, various heating and cooling systems condition the space through radiant and/or convective heat transfer. Radiant heating and cooling (hereinafter RHC) system utilizes the surrounding surfaces as heating and/or cooling sources, at which heat exchange is occurred by radiant and convective heat transfer. In general, RHC system can be defined as a system that radiant heat transfer covers more than 50% of heat exchange within a conditioned space [1]. In a building with the radiant heating system, the more favorable radiation exchange between the occupants and the radiant surfaces allows the air temperature to be a little lower while maintaining comfort conditions, thus reducing heat losses from the building, and this can be significant in mild climates [2]. Thus, the radiant heating system can maintain room air temperature be lower than the conventional all-air systems, while achieving the equivalent thermal comfort. When it comes to radiant cooling systems, the heat is removed from occupants by radiant heat transfer from cool surfaces which makes it possible to maintain the room air temperature be relatively higher than conventional all-air systems.

There are many variations of the RHC systems, which can be classified according to the position of radiant surfaces, integration with building structure, thermal medium, and so on. From the viewpoint of the position of radiant surfaces, the RHC systems were designated as ceiling radiant cooling [3], floor heating systems [4], radiant floor cooling system [5], cooling ceiling [6], and radiant cooling ceiling system [7]. Focusing on the integration with building structures, when the pipe is embedded into the structure elements, e.g. slab, the RHC systems were called as thermo active building systems [8], thermally activated building components [9], concrete core cooling slab [9], thermally activated building systems [10], in-slab heating floor [11], and radiant slab cooling [12]. There were other variations that use radiant surface separated from structural elements, such as surface radiant systems [9], ceiling radiant cooling panel [13], radiant cooling panel [14], radiant chilled panel systems [15], and so on. Considering that the RHC systems

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generally utilize water as thermal medium, they were also defined as water-based floor heating [16], hydronic heating radiant ceiling [17], hydronic radiant cooling system [18], and water-based surface embedded heating and cooling systems [19]. In addition, the RHC systems can be defined as low temperature heating [20] or high temperature cooling systems [21], as they can operate with the water temperature closer to the desired room temperature, because of relatively large heat transfer areas. Although the RHC systems are referred to in various names, they can be broadly classified into 'heating' and 'cooling' systems as tabulated in Table 1.

Conventional air conditioning systems, or all-air systems only depend on the convective heat transfer for heating or cooling, and they should warm or cool the entire room air, resulting in high energy consumption and increased fan power [18]. In addition, the large amount of air circulation in a conditioned room is likely to cause annoying noise and thermal discomfort due to cold draught. Compared with all-air systems, the RHC systems generally utilize the water as thermal media, which has much higher thermal capacity than air. Consequently, much less energy is consumed to heat or cool the conditioned room because relatively low pumping energy is required. The high operation temperature of radiant cooling systems enables a chiller to operate at high efficiency, which leads to the significant reduction in primary energy consumption. Moreover, it is possible to adopt renewable energy as heat sources of the RHC systems, because renewable energy, such as geothermal or solar energy, can efficiently provide water in suitable temperature for low temperature heating or high temperature cooling. In addition, the RHC systems are suitable to utilize building thermal mass, which can not only reduce peak time energy consumption but also attenuate much fluctuations of room air temperature.

In terms of indoor environment quality, the radiant heat transfer can contribute to improved thermal comfort by preventing cold draught as well as mitigating the air-borne noise from the system operation. The radiant cooling system can be more comfortable than conventional air cooling systems due to smaller vertical temperature gradient, less air movements and reduced local discomfort for occupants during long stays in cooled room environment [6]. When considering enhanced thermal comfort can be accomplished from individual controls, the RHC systems are reasonable alternatives because they provide a simple and effective zone control [22]. Apart from thermal comfort, the RHC systems are better in space saving and noise elimination than conventional system due to its energy transfer mainly by radiation [23]. Regarding indoor air quality, radiant heating systems result in less transportation of dust compared to convective heating systems [24]. Radiant cooling systems can provide a high level of indoor air quality, because they separate the tasks of ventilation and space conditioning by using the primary air distribution to fulfill the ventilation requirements and the secondary water distribution system to cool the space. In general, this separation reduces the amount of air transported through buildings significantly, as the ventilation is provided by outside air systems without the recirculating air fraction [18].

With these merits of the RHC system, its popularity has been increasing over last several decades, and lots of researches have been conducted in order to investigate and improve the performance of the systems. In addition to the traditional radiant heating systems, e.g. Korean Ondol [25], Chinese Kang [26], and Roman Hypocaust [27], various radiant heating and cooling systems are currently applied to residential buildings, office, school, museum, even airport terminal building [28]. The RHC systems are implemented as alternative HVAC systems for zero energy buildings or low carbon emission buildings, because they can harmonize with passive design (e.g. thermal mass) [29] and incorporate with renewable energy systems [30–32].

As mentioned earlier, the RHC systems utilize building elements as heating or cooling surface, therefore both aspects of building physics and system characteristics need to be taken into account, in order to fully understand the indoor environment and energy performance of a building equipped with the RHC system. In this regard, a wide spectrum of research topics on the RHC systems has been investigated over last fifty years. Starting with the fundamental study on the thermal comfort in radiant environments, there have been studies on simulation models to analyze the thermal comfort, complicated heat transfer mechanism, energy saving potentials, system configuration, control strategies and so on. The objective of this study is to overview the trend of application and research of the RHC systems, and to find out meaningful issues in terms of comfort, heat transfer analysis model, heating/cooling capacity, CFD analysis, energy simulation, system configuration and control. Based on the review results, the authors

Table 1
Classification of the RHC system and appellation in the literature review.

	Heating	Cooling
Ceiling	- Hydronic heating radiant ceiling [17] - Radiant heating ceiling panel system [94]	- Ceiling radiant cooling [3] - Cooling ceiling [6] - Radiant cooling ceiling system [7] - Ceiling radiant cooling panel [13] - Radiant cooling panel [14,96] - Radiant chilled panel systems [15] - Chilled ceiling systems [23,98] - Suspended metal ceiling radiant panel [95]
Floor	- Radiant floor heating systems [4,132] - Embedded floor heating system [15] - Water-based floor heating [16] - Underfloor heating [124]	- Radiant floor cooling system [5,101,120,136] - Cooled radiant floor [87,99]
Building structure	- In-slab heating floor [11]	- Concrete core cooling slab [9] - Radiant slab cooling [12] - Radiant slab system [110] - Thermally activated building surfaces [112]
	- Thermo active building systems (for both heating and cooling) [8,113] - Thermally activated building components (for both heating and cooling) [9] - Thermally activated building systems (for both heating and cooling) [10,114,145] - Hollow core concrete floor system (for both heating and cooling) [48] - Active hollow core slabs (for both heating and cooling) [74]	