Designing a ceiling radiant cooling system for different installation conditions

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Abstract. A ceiling radiant cooling system (CRCS) can provide comfortable environment with less energy consumption. It has been reported that the amount of heat removed by only radiant panels increases compared to one removed by only air handling units (AHUs) due to the existence of a plenum. However, few studies have focused on installation conditions of CRCS and surface temperature of radiant panels. Therefore, we proposed a new calculation flow to decide cooling system specifications, where we considered an impact of a plenum and the surface temperature of panels. In the conventional flow, the amount of heat covered by AHUs and the equipment capacity are determined by subtracting the assumed capacity of radiant panels from the load without radiant panels. On the other hand, in the proposed flow, the amount of heat covered by radiant panels and AHUs and the capacity of them are simultaneously calculated by using a thermal network model considering the impact of radiant panels on the wall surface temperature. In this study, we carried out case studies for different installation conditions of CRCS and examined the cooling loads and the equipment specifications. As a result, regardless of the laying area of radiant panels, the entire cooling load removed by both radiant panels and AHUs in the proposed flow was higher than that in the conventional flow. Furthermore, depending on installation conditions, we found that there is a possibility that the equipment capacity of AHUs is underestimated in the conventional flow. In addition, through the proposed flow, supply water temperature can be slightly raised when the heat capacity of the building is larger. This study will contribute to the establishment of the correct design method of CRCS. From now on, we need to study about the design of CRCS considering the energy-saving performance including heat source system.

1. Introduction

CRCS is attracting attention as one of technologies useful for realizing Zero Energy Building because of its energy saving performance and comfort. However, we can say that the determination flow of the equipment specifications has not been established. Previous study [1] has shown that cooling load for radiant systems is calculated the same way as for air systems in most cases. It is pointed out that the conventional thermal load calculation on the premise of convection air conditioning is not adequate when selecting the equipment suitable for CRCS. To be specific, in the case of CRCS, the thermal load on the entire room removed by the radiant panel increases due to heat flux from plenum space [2, 3]. The ability of the radiant panels changes due to the thermal load of the plenum [4]. Thus, in the conventional thermal load calculation, the influence of the plenum made by installing radiant panels is not taken into consideration. Furthermore, there are very few examples which incorporate
characteristics of radiant panels with temperature conditions different from general indoor surfaces into the thermal load calculation [5]. The design procedure for CRCS is described in the ASHRAE handbook [6]. This shows how to determine specifications of radiant panels that satisfies the design conditions. However, the determining method of the design condition, i.e. the thermal load, is not referenced in the design procedure. Therefore, in this research, we propose a new determination flow of equipment specification which considers the influence of the plenum due to the installation condition of radiant panels and the surface temperature of radiant panels. In order to clarify the difference from the conventional method, we compared and examined the thermal load and equipment specifications of CRCS.

2. Methodology

2.1. Simulation model

Figure 1 shows the isometrics, ceiling plan and sectional view of the target building. The panel is installed into the building model of Cases 600 and 900 presented in the thermal load calculation test of ASHRAE standard 140-2011 [7], and the room is divided into two chambers: a room and plenum chamber. The materials of the wall and floor are different between Cases 600 and 900. The heat capacity of Case 600 is small and that of Case 900 is large.

![Figure 1. Case study model.](image)

2.2. Calculation method of thermal load and panels’ equipment specifications

Previous study shows that radiant systems should be modeled using a dynamic simulation tool that uses either heat balance model or thermal network model to accurately conduct cooling load calculation [8]. So, we used the thermal network program [9] for the thermal load calculation in the proposed flow. First, we created a thermal network model, which consists of nodes and thermal resistances connecting each node (Figure 2), of the target building and set a value of parameters such as heat capacity and thermal resistance of nodes of the model. Room temperature and room-side surface temperature of panels were controlled. We executed the calculation after defining conditions such as weather data, internal heat generation and calculation interval.

For the calculation of the equipment specifications, performance prediction method for ceiling radiant cooling panel [4] was used. We calculated supply water temperature using room temperature, room-side surface temperature of panels, the amount of flowing supply water, room-side load ratio of panels (room-side load removed by panels / entire load removed by panels) as input conditions.
2.3. Validation of thermal network model

We conducted the thermal load calculation test of ASHRAE standard 140-2011 for Cases 600 and 900, and the validity of the building model made by the thermal network program was confirmed. To compare with other simulation tools, weather data was used from Denver, Colorado, USA. The thermal load calculation test was carried out under the calculation period of 1 year, the calculation interval was 60 minutes, and the air conditioning time was 24 hours. Figure 3(a) shows the annual accumulated load, and figure 3(b) shows the simulation result of the annual maximum load. The data of the orange label (“Our model”) is the thermal network program used in this study. Figures 4(a) and 4(b) are graphs of cooling and heating loads when 24 hours air conditioning is performed on Cases 600 and 900 on the representative date (January 4th). The room temperature was set to 20°C in heating and 27°C in cooling, and it was set to be a dead zone where no air conditioning is performed in the case of 20°C to 27°C. We can conclude that the validity of modeling the building by the thermal network program has been confirmed since the results are relatively close to those of other tools in figures 3 and 4.
2.4. Determination flow of equipment specifications for CRCS

Conventionally, equipment specifications for CRCS are determined in the following flow. 1) After determining the laying area of radiant panels, the panel capacity and specifications are determined by the capability diagram of the panel specified in EN 14240 [10], and the thermal load to be removed by panels. 2) The thermal load to be removed by the air conditioner such as AHUs is calculated by deducting this panel capacity from the thermal load of room, and the equipment is selected. Figure 5(a) shows the flow chart of this procedure.

On the other hand, the determination flow of equipment specifications proposed in this paper is shown in figure 5(b). In the proposed flow, there is a feature that we determine the equipment specifications of radiant panels after calculating the thermal load taking into consideration the influence of the plenum due to the installation condition of radiant panels and the surface temperature of radiant panels. Specifically, it is determined whether the target indoor thermal environment such as operative temperature can be achieved and whether the supply water temperature does not become equal to or lower than the dew point temperature of the room air so that condensation may not occur. The surface temperature of panels, the laying area of panels, supply water temperature and setting temperature of room air are determined by iterative calculation.

![Figure 5](image_url)

**Figure 5.** The (a) conventional and (b) proposed determination flow of equipment specifications.

| Table 1: Variable definition. |
|-------------------------------|
| **OT** | Operative temperature |
| **RH** | Relative humidity |
| **MRT** | Mean radiant temperature |
| **S_p** | The laying area of panels |
| **θ_{ra}** | Room temperature |
| **θ_{rs}** | Room-side surface temperature of panels |
| **θ_{DEW}** | Dew point temperature |
| **θ_{w,0}** | Supply water temperature |
3. Case study

3.1. Simulation conditions
We used Extended AMeDAS Weather Data (Sampling Period: 1991-2000) [11] and set the area to Tokyo. The simulation period was set to July 1st – 31st. The air conditioning operation time was set to 8:00 – 18:00. The calculation interval was 5 minutes.

3.2. Trial of determination flow of equipment specifications
We conducted case study using the building model shown in figure 1 and determined the equipment specifications of CRCS by the conventional flow and the proposed flow. We considered the cases where the laying rate of radiant panels was 40%, 60%, and 80% both in Cases 600 and 900. The results are shown below.

The design process by the proposed flow is shown concretely. As an example, we will discuss the condition of the laying ratio of panels 40% in Case 600. Figure 6(a) is a graph showing $OT$ and $MRT$ when $\theta_{ra}$ is controlled at 27.5°C and $\theta_{rs}$ at 22°C. Figure 6(b) is a graph of thermal load. Regarding to the thermal load, since it became the maximum at 12:00 on July 19th excluding the moment when the air conditioning rose during the calculation period, the thermal load at this time was set to the thermal load for determining the equipment specifications. The target value was regarded to be satisfied if $OT$ at this time was equal to 27.0°C or lower. According to the graph of $OT$ determined by the thermal load calculation (Figure 6(a)), the target value of $OT$ (=27.0°C) is not satisfied at the time of generating the thermal load for determining the equipment specifications (at 12:00). Although the target value of $OT$ was satisfied when $\theta_{rs}$ decreased to 18°C, $\theta_{w,0}$ (=10.1°C) was lower than (=16.2°C) at this time. So, we lowered the set value of $\theta_{ra}$ and calculated the thermal load again. After this operation was repeated, the target value of $OT$ was finally satisfied at $\theta_{ra}$ of 26.5°C and $\theta_{rs}$ of 22°C (Figures 7(a) and 7(b)). Furthermore $\theta_{w,0}$ determined by the calculation of equipment specifications where $Q_w$ and $\beta$ were used as input conditions was higher than $\theta_{DEW}$, so the equipment specifications of panels were determined.

Figure 6. (a) Each temperature change and (b) thermal load when $\theta_{ra}$ is controlled at 27.5°C and $\theta_{rs}$ at 22°C.
Next, trial of the conventional flow is conducted under the same Case 600 with the laying rate of 40%. In this study, the thermal network program was used also in the conventional flow. Only $\theta_{ra}$ of 26.5°C was set coordinating with the conditions of the proposed flow to obtain the thermal load of the room (Figures 8(a) and 8(b)). The capability of panels was obtained in the capability diagram of the panel by assuming $\theta_{w,0}$ of 16°C, which is generally supposed to be the minimum condition where condensation does not occur, and assuming the temperature difference of the cold water in inlet and outlet to be 2°C. Then the load of panels was calculated by multiplied by the laying area of panels.

4. Results
In the other cases similarly, the thermal load for determining equipment specifications was obtained (Figure 9). In addition, set values of $\theta_{ra}$ and $\theta_{rs}$, $OT$ at the time when the thermal load for determining equipment specifications generated, and $\theta_{w,0}$ were also determined (Table 2).
Figure 9. The breakdown of the thermal loads to decide equipment specification (Numerical values are the loads of AHUs).

| Case | Case600 | Case900 |
|------|---------|---------|
| Laying rate of panels | Small | Large | Small | Large | Large |
| 40% | 60% | 80% | 40% | 60% | 80% |
| $\theta_{rs}$ [$^\circ$C] | 26.5 | 27 | 28 | 26.5 | 27 | 28 |
| $\theta_{ra}$ [$^\circ$C] | 22 | 21.5 | 21.5 | 21.5 | 21.5 | 21.5 |
| OT [$^\circ$C] | 26.99 | 26.90 | 26.66 | 26.94 | 26.97 | 26.93 |
| $\theta_{w,0}$ [$^\circ$C] | 18.18 | 17.11 | 16.65 | 17.32 | 17.17 | 16.75 |
| Proposed | | | | | | |
| Conventional | | | | | | |
| OT [$^\circ$C] | 29.29 | 29.72 | 30.62 | 29.08 | 29.48 | 30.33 |
| $\theta_{w,0}$ [$^\circ$C] | 16 | 16 | 17.40 | 16 | 16 | 18.25 |

5. Discussion

Figure 9 shows that the thermal load was larger in the proposed flow than in the conventional flow regardless of the laying rate of panels. This is thought to be due to differences of thermal environment conditions depending on whether $\theta_{rs}$ is controlled or not, and the thermal load of the plenum. As the laying rate increased, the entire thermal load in the conventional flow decreased, but that in the proposed flow increased. Looking at the breakdown of the thermal load, the panel was able to remove the entire thermal load with laying rate of 80%. The numerical values of the load of AHUs in the conventional flow shows that the thermal load to be removed by AHUs is underestimated when the laying rate is 60% in Case 900. Although the setting of $\theta_{ra}$ and $\theta_{rs}$ in Cases 600 and 900 was equal for both the laying rates of 60% and 80%, $\theta_{w,0}$ can be slightly raised when the heat capacity is larger. Thus, the proposed flow makes it possible to design an appropriate equipment capacity.

6. Conclusion and implications

In this paper, we proposed the determination flow of equipment specifications for CRCS and showed the results of trial in both proposed and conventional flow. It was founded that the thermal environment can be controlled as intended by taking the surface temperature of panels into consideration in the proposed flow. In addition, this study points out that there is a possibility that both
radiant panels and AHUs may be under-designed in the conventional flow. Although the usefulness of the proposed flow has been shown from the above, it is necessary to be verified by more practical building model since it is limited to a simple building model. Furthermore, future research should focus on devising the determination flow of equipment specifications for CRCS which consider the energy-saving performance including both air conditioning and heat source system.

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