Energy and Buildings 86 (2015) 58–65

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Field evaluation of performance of radiant heating/cooling ceiling panel system

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ARTICLE INFO

Article history:
Received 19 November 2013
Received in revised form 12 August 2014
Accepted 15 September 2014
Available online 13 October 2014

Keywords:
Radiant heating/cooling ceiling
Overall heat transfer coefficient
Heat flux
Heat use coefficient
In situ

ABSTRACT

As in many other countries in the world, Japan has witnessed an increased focus on low-energy buildings. For testing different engineering solutions for energy-efficient buildings, a low-energy building was built at the University of Tokyo as an experimental pilot project. In this building, a radiant heating/cooling ceiling panel system is used. However, no standard exists for the in situ performance evaluation of radiant heating/cooling ceiling systems; furthermore, no published database is available for comparison. Thus, this study aims to not only clarify the system performance but also to share our experience and our results for them to serve as a reference for other similar projects. Here, the system performance in relation to its heating/cooling capacity and thermal comfort has been evaluated. The heat transfer coefficient from water to room was 3.7 W/(m^2 K) and 4.8 W/(m^2 K) for heating and cooling cases, respectively. The upward heat flux from the panels was found to be as large as 30–40% of the water heating/cooling capacity; this would translate into heat loss in certain operating modes. Several proposals for reducing the upward heat flux were discussed. The measurements also showed that a category B thermal environment was obtained using the radiant ceiling heating/cooling system.

1. Introduction

Water-based radiant heating/cooling systems can achieve high energy efficiency because of reduced distribution losses and the possibility of using low- and high-temperature water for heating and cooling, respectively. As a result, the coefficient of performance of the heat supply equipment can increase [1–4].

As in many other countries in the world, Japan has witnessed an increased focus on low-energy buildings. For testing different engineering solutions for energy-efficient buildings, a low-energy building (21KOMCEE) was built at the University of Tokyo as an experimental pilot project [5]. In this building, a radiant heating/cooling ceiling panel system is used. Currently, the performance of the building's heating/cooling system in relation to its heating/cooling capacity and thermal comfort has been evaluated. This is also the first step toward our goal of making this project a zero energy building.

The heating/cooling capacity strongly depends on heat transfer coefficients. Therefore, many studies have focused on evaluating and enhancing the heat transfer coefficients [6–9]. However, previous studies have mostly focused on the heat transfer coefficients between radiant surfaces and the room, whereas the energy consumption of the supply system has not been considered. Thus, insufficient data is available for a comprehensive evaluation of low-energy buildings, because the cool/warm water temperature is one of the parameters that directly affect the coefficient of performance of heat supply equipment.

Furthermore, design and rating guides presently provide only evaluation methods and reference values based on idealized steady-state conditions. In addition, most studies employed test chambers and computer modeling [1,3,6,10–16]. However, the performance of an in-situ system is usually not the same as that tested in a laboratory or calculated using computer models because it is exposed to a dynamic environment. Meanwhile, in situ values of the system are necessary for improving the system performance and achieving a low-energy building.

However, no standard exists for the in situ performance evaluation of a radiant heating/cooling ceiling system; furthermore, no published database is available for comparison. Thus, this study aims not only to clarify the system performance but also to share our experience and publish our results for them to serve as a reference for other similar projects.

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http://dx.doi.org/10.1016/j.enbuild.2014.09.070
0378-7788/

Nomenclature

θ_s	mean surface temperature of the radiant panels [°C]
θ_u	mean temperature of the plenum space [°C]
θ_o	operative temperature measured in the middle of the room at 0.7 m above the floor [°C]
θ_w	mean heating/cooling water temperature [°C]
q_w	heating/cooling capacity of the water [W/m^2]
q_1	heat flux from the water to the room[W/m^2]
q_2	heat flux from the water to the plenum [W/m^2]
$q_{1,meas}$	measurement heat flux[W/m^2]
$q_{1,calc}$	calculated heat flux[W/m^2]
$\theta_{w,in}$	supply water temperature [°C]
$\theta_{w,out}$	return water temperature [°C]
m	water flow rate [m^3/h]
ρ	water density [kg/m^3]
c	specific heat capacity of the water [kJ/(kgK)]
R_{ws}	thermal resistance between the fluid and the panel surface [m^{2}K/W]
R_{so}	thermal resistance from the panel surface to the room [m^{2}K/W]
R_{su}	thermal resistance from the panel surface to the plenum [m^{2}K/W]
R_{wo}	thermal resistance between the water and the room [m^{2}K/W]
R_{wu}	thermal resistances between the water and the plenum [m^{2}K/W]
U_{wo}	overall heat transfer coefficient from the water to the room [W/(m^{2}K)]
U_{wu}	overall heat transfer coefficient from the water to the plenum [W/(m^{2}K)]
U_{so}	heat transfer coefficient between the radiant surface and the room [W/(m^{2}K)]

Here, the water temperature is considered, and the overall heat transfer coefficients from water to the room and from water to the plenum are analyzed to evaluate the in situ performance of the radiant panel system. The potential upward heat loss from the panels is clarified as well.

2. Basic theory

Fig. 1 shows the cross section of the testing room with a suspended ceiling. The height of the room is 2.85 m and the height of the ceiling plenum is 1.15 m. In this figure, θ_s is the mean surface temperature of the radiant panels; θ_u, the mean air temperature of the plenum; θ_o, the room's operative temperature as measured in its middle at a height of 0.7 m above the floor; θ_w, the mean heating/cooling water temperature; q_w, the heating/cooling capacity of water [W/m^2]; q_1, the heat flux from the water to the room [W/m^2]; and q_2, the heat flux from the water to the plenum [W/m^2].

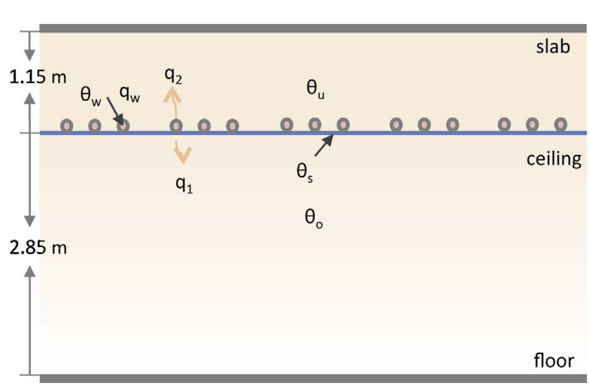

Fig. 1. Cross section of testing rooms.

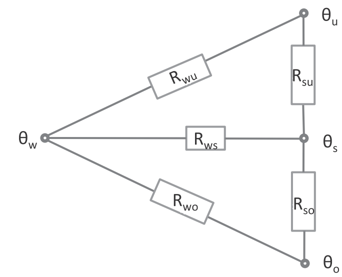

Fig. 2. Resistance model for radiant panel.

This study aims to evaluate the in situ performance of the system, including the overall heat transfer coefficient from the water to the room U_{wo} and from the water to the plenum U_{wu}, and to analyze the heat loss. Because no standard exists for the evaluation of in situ radiant heating/cooling ceiling panel systems, we create a resistance model for the radiant ceiling according to ISO 11855-2 [13] and EN 14240 [14]. This model is shown in Fig. 2, and it is governed by the following equations:

$$\theta_w = \frac{\left(\theta_{w,\mathrm{in}} + \theta_{w,\mathrm{out}}\right)}{2} \tag{1}$$

$$U_{\mathrm{wo}} = \frac{q_1}{\left(\theta_w - \theta_o\right)} \tag{2}$$

$$U_{\mathrm{wu}} = \frac{q_2}{\left(\theta_w - \theta_u\right)} \tag{3}$$

$$q_2 = q_w - q_1 \tag{4}$$

$$q_w = \frac{\rho c m\ \left(\theta_{w,\mathrm{in}} - \theta_{w,\mathrm{out}}\right)}{A_p} \tag{5}$$

$$R_{\mathrm{wo}} = \frac{1}{U_{\mathrm{wo}}} \tag{6}$$

$$R_{\mathrm{wu}} = \frac{1}{U_{\mathrm{wu}}} \tag{7}$$

here $\theta_{w,\mathrm{in}}$ and $\theta_{w,\mathrm{out}}$ are the supply and return water temperatures, respectively [°C]; m is the water flow rate [l/s]; ρ and c are the water density [kg/m^3] and specific heat capacity of water [kJ/(kg K)], respectively; A_p is the area of the panels [m^2]; R_{ws} is the thermal resistance between the fluid and the radiant panel surface; R_{so} and R_{su} are the thermal resistances from the panel surface to the room and the plenum, respectively; and R_{wo} and R_{wu} are the thermal resistances between the water and the room and between the water and the plenum, respectively. The unit of thermal resistance is [m^2 K/W].

To verify the accuracy of the measurements, we followed ISO 11855-2 [13]. The ISO 11855 series is applicable to water-based embedded surface heating and cooling systems in residential, commercial, and industrial buildings, and it is applicable to systems integrated into the wall, floor, or ceiling construction without any open air gaps because the heat transfer coefficient between the radiant surface and the room is not related to the structure of the radiant body. The recommended heat transfer coefficient can be used as a reference value for our study. This standard recommends theoretical models for calculating the heat flux between the ceiling and the room as

$$q_1 = U_{so}\left(\theta_s - \theta_o\right) \tag{8}$$

here U_{so} is the heat transfer coefficient between the radiant surface and the room, which combines convection and radiation. Its value