Building Simulation 2003

*Eighth International IBPSA Conference*
**Eindhoven, Netherlands**
**August 11-14, 2003**

# MODELLING AND SIMULATION OF A ROOM WITH A RADIANT COOLING CEILING

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## ABSTRACT

This paper describes modelling and simulation of a space with radiant cooling ceiling (CC). The computer model represents a test chamber, which is located in a laboratory of the Department of Environmental Engineering in Prague. The simulation results were obtained with the ESP-r software. These results will be used for comparison with experimental data.

The main goal is to determine conditions of thermal comfort of occupants in a room with cooling ceiling and various heat gains. The paper also presents the influence of the room height on thermal comfort.

## LITERATURE REVIEW

Several authors discuss thermal comfort in spaces with a radiant cooling ceiling. Kulpmann (1993) presented experimental results of thermal comfort and air quality in a room with this system. The paper presents thermal gradients in such conditioned space, for various heat gains conditions.

Loveday (1998, 2003) performed experimental measurements of thermal comfort on human subjects in a room with cooling ceiling and displacement ventilation. It is shown that Fanger's thermal comfort model according to ISO 7730 may be used, without modification for thermal comfort predictions of sedentary workers in offices equipped with such systems.

A few papers published in conference proceedings and scientific journals describe computer modelling of the system with cooling ceiling. Some examples are given below.

Imanari (1999) describes the experimental investigation of thermal comfort and the numerical simulation of energy consumption. The purpose of his study was to investigate various characteristics of the radiant ceiling panel system and its practical applications.

Alamdari (1998) presents the room air distribution and thermal environment of combined displacement ventilation and cooled ceiling systems. A field flow model based on computational fluid dynamics (CFD) was used to simulate comparative environmental performance of displacement ventilation with and without cooling ceiling.

Brohus (1998) describes the effect of radiant cooling ceiling on indoor air quality in a room with displacement ventilation, using CFD. The main goal of his effort was to examine the changes in concentration and temperature field in the room with cooling ceiling.

Miyanaga (1998) created a detailed 3D model of a room with cooling ceiling. He intended to make a computer analysis of thermal sensation in such a room.

Miriel (2002) developed a simulation model with the simulation program TRNSYS, using the experimental study of the performance, thermal comfort and energy consumptions results for the code verification.

Also Niu (1994) deals with computer modelling of a space with a cooling ceiling system. He describes the effect of this system on indoor air quality. Niu analysed the thermal comfort and concentration distribution in such a space on the basis of a computer model. He compared the CC system with another air-conditioning systems in the light of energy consumption.

## PROBLEM ANALYSIS

The problem underlying the current paper was to investigate indoor climate and thermal comfort in a space cooled by a radiant cooling ceiling. The main goal of our study is to examine the relation between thermal comfort for various activity levels and thermal conditions in such space and how mean radiant temperature (MRT) is influenced by the height of the room.

In practice, radiation heat transfer between the human body and surroundings is preferred to convection heat transfer in the light of thermal comfort. The influence of the surface temperature on thermal comfort is positive, therefore it is possible to keep a higher indoor air temperature in a given space to achieve the same thermal comfort compared with convective systems (Ferstl 1999).

Moreover, a system with cooling ceiling potentially has lower energy consumption than a convective system.

The operative temperature $t_o$ is the evaluative criterion for thermal comfort in spaces with cooling ceiling. The operative temperature depends on air temperature, mean radiant temperature and air velocity. From these quantities the thermal comfort in conditioned spaces can be predicted by using the PMV (predicted mean vote) / PPD (predicted percentage dissatisfied) index according to ISO Standard 7730. The comfort range of thermal comfort is normally considered as $-0.5 < PMV < 0.5$ corresponding to $PPD < 10\%$.

In a space with radiant cooling ceiling the height of the room may influence thermal comfort in the occupied zone. Convection and radiation ratio changes with changing height of the room. The radiation ratio change affects MRT and thus conditions thermal comfort in the occupied zone. We can assume that the radiation effect of the cooling ceiling will decrease when the room gets higher.

The main problem in the computer modelling of a space with cooling ceiling in ESP-r is modelling of the radiant surface. There is no option in this software to force the surface temperature. In ESP-r the radiant surface is defined as an actuator location with corresponding cooling capacity.

Manual calculation of MRT is very complicated and not suitable for practical usage since the angle factors which weigh the influence of surrounding surfaces are difficult to determine. On the contrary, computer-based calculation is prepared to do this automatically and could be particularly useful when seeking multiple solutions for a problem under optional conditions.

## EXPERIMENTAL SET-UP

The experiments were carried out in an existing test chamber with a floor space of 4.2 by 3.6 m and room height of 2.7 m (Figure 1). The radiant cooling ceiling with dimension of 3.0 m by 2.8 m is placed symmetrically into the chamber. In the model no heat exchange through the wall is assumed since the real test chamber is placed in a bigger air-conditioned enclosure providing required ambient conditions. The surrounding air was conditioned to provide minimal heat flux between both spaces; i.e. the temperature of the surrounding air was adjusted identically to air temperature in the test chamber. Moreover, all chamber surfaces are very well heat insulated to minimize heat loss.

The test chamber is ventilated by the minimum required amount of air for two persons (90 $m^3/h$). This value corresponds with the Czech standard for minimum fresh air requirements, which is, incidentally, more than the value according to Ashrae Standard 62 (28.8 $m^3/h$ per person).

The exhaust and supply air openings (0.3 x 0.2 m) are installed symmetrically on the front wall (Figure 1). Opposite these openings is a model of the window on the back wall. The model of the window with dimension of 1.9 m by 1.6 m is placed symmetrically on the wall. The construction of the window was specified with similar thermal conditions as in a real model.

Figure 1 shows the test chamber, which is currently set-up to represent displacement ventilation system. Isothermal supply of air is assumed in the computer simulations; therefore there is almost no influence on the temperature distribution in the test chamber. This air supply system also minimizes the local airflow effects on the ceiling and the window.

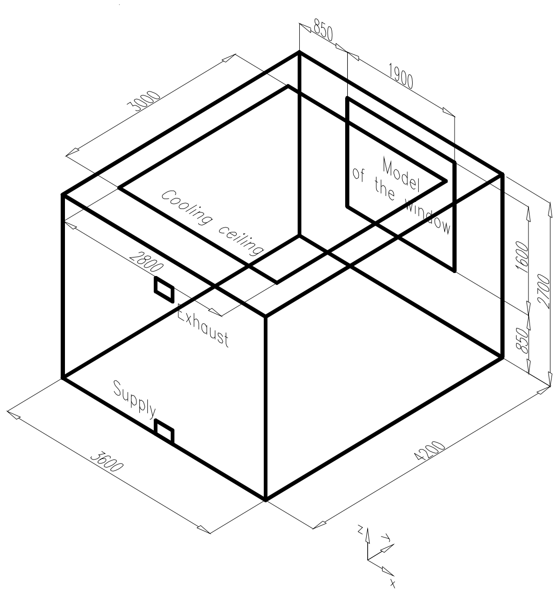


***Figure 1:*** *Schematic drawing of the real test chamber*

Internal heat gains representing occupants, lighting and equipment were introduced. The window model was modelled as internal heat gain too. In the real test chamber the window represents shaded window without direct solar heat gains. The total heat gain of the test chamber is 44 $W/m^2$.

## COMPUTER MODEL

In the computer model, the cooling ceiling is defined as a cooling capacity located in the ceiling. It is controlled with an ON/OFF law. During the calculations the cooling load was equal to the internal heat gains. The cooling of the space starts at 6am and ends at 8pm. The same applies for the heat gains.

The thermal conditions of the ambient air were defined as static boundary conditions with temperature of air equal to required indoor air temperature.

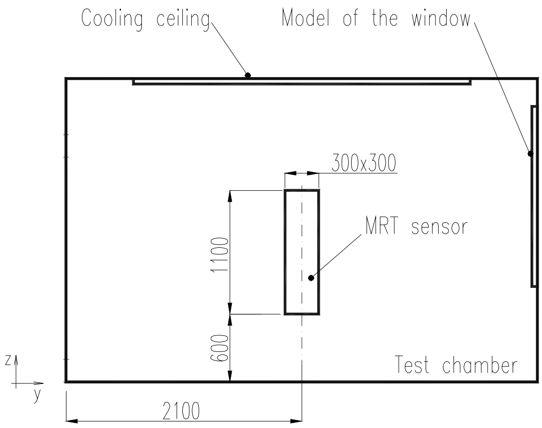


***Figure 2:*** *Location of MRT sensor (x = 1.8m)*

The air temperature was controlled in the simulation model of chamber. The indoor air temperature within the zone is everywhere the same. The mean radiant sensor was placed in the occupied zone and was used for thermal comfort evaluation. The sensor with dimensions 0.3x0.3x1.1 m (human body) is situated in the centre of the room, 0.6 m above the floor as shown in Figure 2.

## SIMULATION AND RESULTS

In view of the fact that there are minimum external heat gains / losses in this case, the simulation was run for a two-day period only. The results of the course of the indoor air temperature ($t_i$) and the mean radiant temperature (MRT) during these two days are shown in Figure 3. This particular simulation was for room height of 270 cm and indoor air temperature 26°C.

The cooling starts later than the effect of heat gains is present. The consequence is that the indoor air temperature increases at the beginning of characteristic interval. After that a rapid decrease in air temperature is visible.

Oscillation of $t_i$ and MRT values at the end of the characteristic interval is caused by the assumed control procedure.

During the night, when the room is not occupied and the cooling system is not active, the indoor air temperature becomes equal to the mean radiant temperature.

The cooling capacity of the ceiling does not exactly match to the heat gain. Consequently, the indoor air temperature and mean radiant temperature increase during the characteristic interval of 7am – 8pm.

It was necessary to choose a specific interval from the cooling time for evaluation of the results. This specific interval was selected from 6pm till 7pm for all evaluated data. During the specific interval the steady state of set indoor air temperature was achieved.

## THERMAL COMFORT EVALUATION

The simulation model is made for a constant cooling load and constant heat gains. The room height was set to 270 cm. The required air temperature during the day was set to 23 – 28°C from 6am till 8pm.

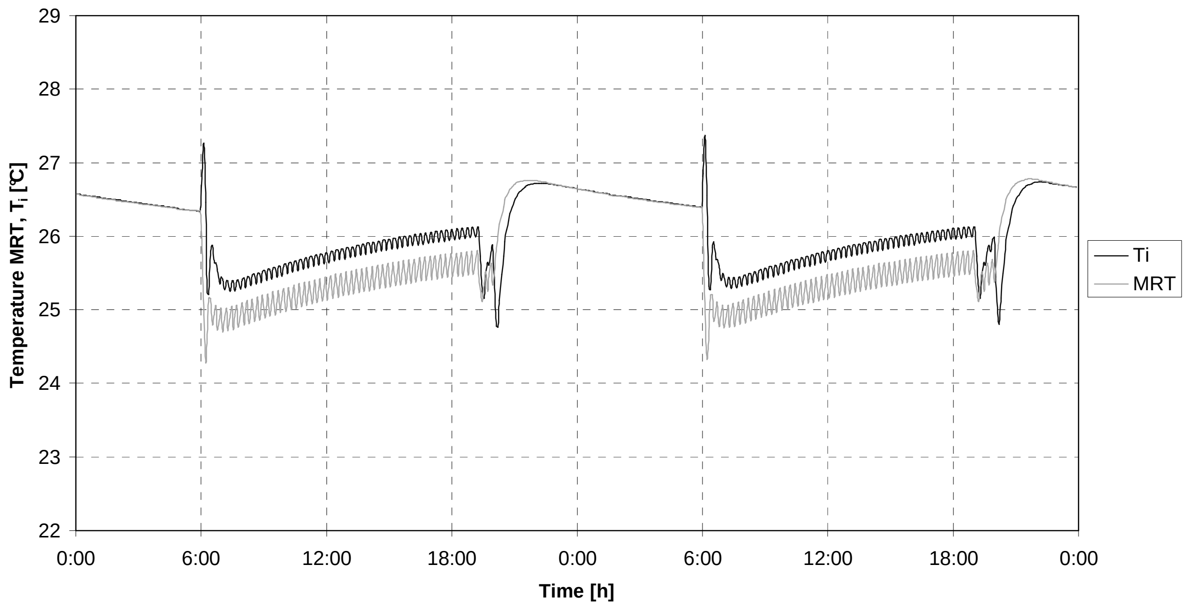


***Figure 3:*** *Mean radiant temperature (MRT) and indoor air temperature $t_i$ in the middle of the test chamber. The chamber (h = 270cm) is cooled from 6am till 8pm, the required air temperature is 26°C.*

When the constant cooling load is kept, the surface temperature of cooling ceiling for higher air temperatures increases. Thereby the mean radiant temperature MRT increases.

| *Activity* | *q [W/m$^2$]* |
|---|---|
| Reading, seated | 58 |
| Typing | 64 |
| Filing, seated | 70 |
| Standing, light work | 93 |
| Standing, middle work | 116 |

***Table 1:*** *Metabolic heat generation for various activity levels*

The results of the thermal comfort predictions are shown in Figure 4 and 5. The PMV and PPD indices were evaluated for various activities according to Table 1. The air velocity was chosen as 0.1 m/s and the clothing insulation as 0.7 clo.

The average value of PMV and PPD index were evaluated during the steady state situation i.e. between 6pm and 7pm. The results of the simulations for various activity levels show the range of thermal comfort (-0.5 < PMV < 0.5) in such a space with radiant cooling ceiling (Figure 4). The PPD index is presented in Figure 5.

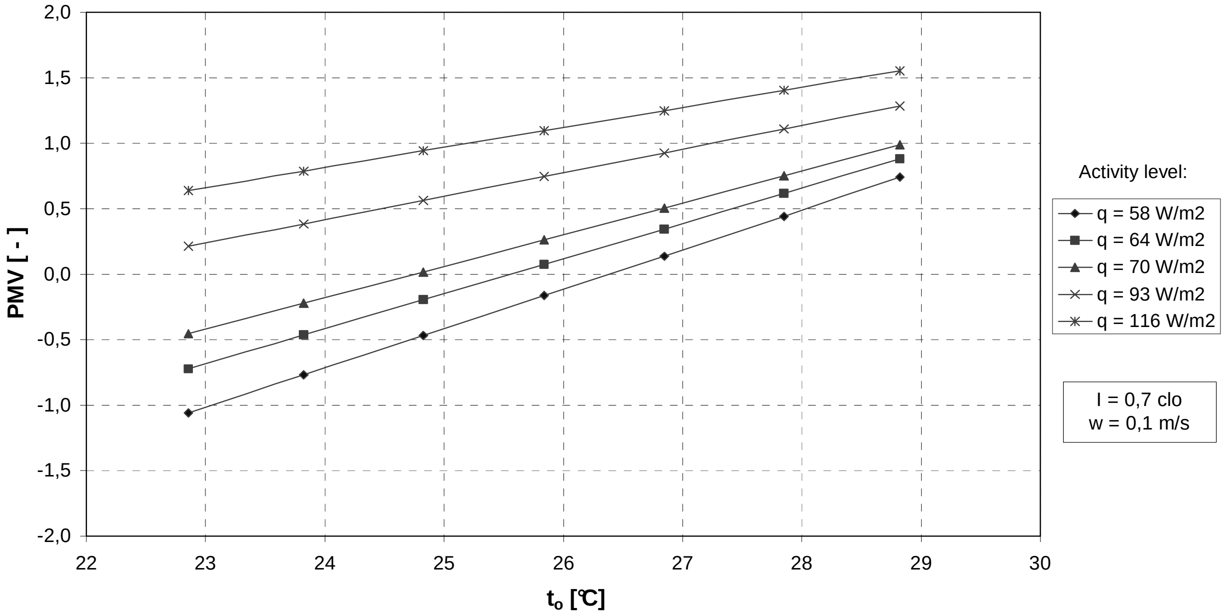


***Figure 4:*** *PMV index for various operative temperatures and activities*

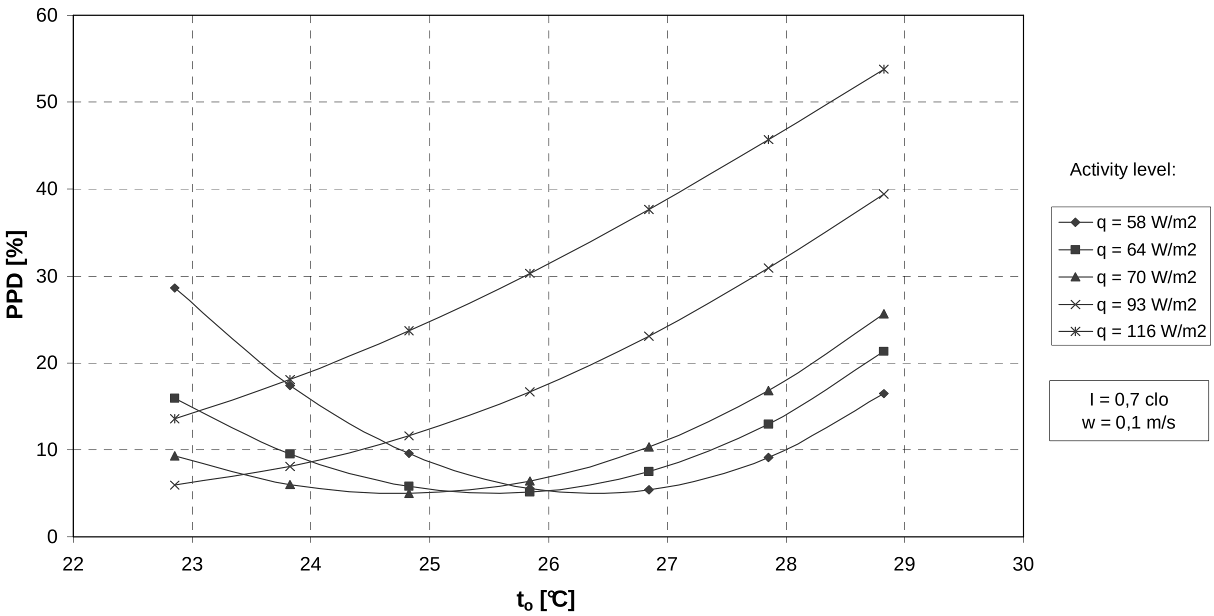


***Figure 5:*** *PPD index for various operative and activities*

In consequence increased of cooling ceiling temperature, the MRT temperature is growing too, which means that also thermal comfort is influenced. When the indoor air temperature increases up to 28°C, the temperature of cooling ceiling is high and the MRT grows. Due to this effect, the PMV index deteriorates which means discomfort.

The PPD index for various activities is shown in Figure 5. We can see for which air temperatures the minimal PPD index rises in such a space.

Miyanaga (1998) presents in his paper dependence of PMV index on operative temperature $t_o$. Extras simulation was made for the activity level 1 met (58 W/m$^2$) and clothing insulation value 0.5 clo to compare the results. Comparison of the results is shown in Figure 6.

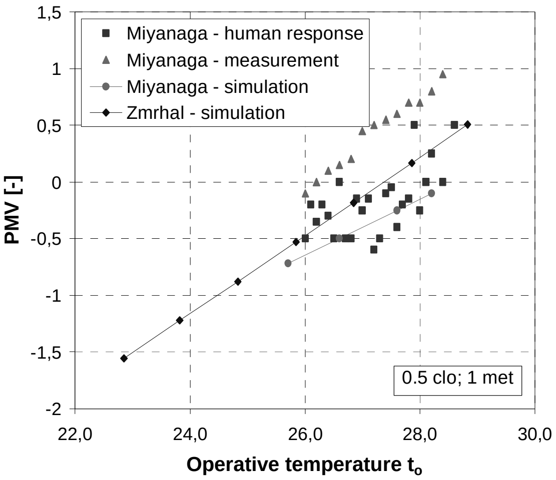


***Figure 6:*** *Results comparison*

THE EFFECT OF ROOM HEIGHT

During the simulation of the chamber with indoor air temperature 26°C the height of the room was gradually changed by step of 10 cm from 2.4 m up to 4 m. The results of the simulations are shown in Figure 7. The effect of a room height on mean radiant temperature (thermal comfort) is displayed. MRT sensor is always placed on the same position according to Figure 2.

The data *MRT = f(h)* (Figure 7) were obtained from simulations similar to those in Figure 3. The simulations were repeated for various room heights and the effect of room height was evaluated during specific interval (6pm - 7pm).

The data ( *MRT = f(h)* ) dispersion is probably caused by MRT evaluation for all room heights at the end of daily round.

On the assumption that the cooling load and heat gains are constant, Figure 7 confirms the expected course of MRT, which gradually increases with higher room height. When the room is higher, the heat transferred by radiation to the cooling ceiling from a larger surface of the surrounding walls grows and consequently the surface temperature of the surrounding walls will be higher and thus the mean radiant temperature increases.

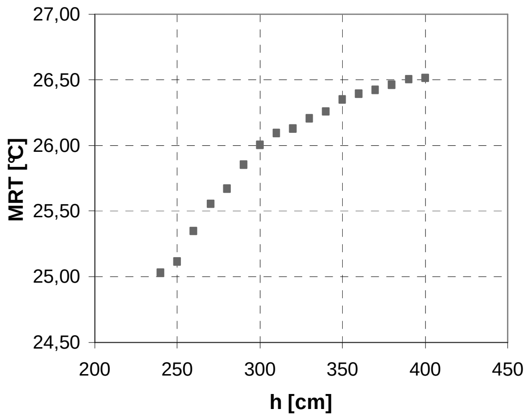


***Figure 7:*** *The effect of room height on MRT ($t_i$=26°C)*

## CONCLUSION

A computer model was set up representing a real test chamber. The average value of PMV and PPD index were predicted. The effect of room height on mean radiant temperature (thermal comfort) is shown. The following conclusions can be made:

1. The simulation results show the course of indoor air temperature ($t_i$) and mean radiant temperature (MRT) in a space with radiant cooling ceiling in two-day terms.
2. The results show the tendency of thermal comfort in a room with radiant cooling ceiling in dependence on operative temperature and activity level.
3. System with radiant cooling ceiling is acceptable for light office work in particular as the comfort index PMV and PPD results show.
4. Thermal comfort simulation results are in good agreement with published values.
5. The room height effect on MRT confirms the expected course of MRT, which gradually increases with room height.
6. The cooling ceiling system is more effective in the low rooms.

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