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Ceiling water panel heating – cooling systems. Experimental and simulated study of the performances

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Abstract

The ceiling water panel technique is mainly used to provide cooling. As for the floor water panel system, it can provide heating in winter and cooling in summer. Ceiling water panels which are incorporated into false ceilings are made of steel or copper pipes with rigid diffusion fins generally in aluminium. The materials used present a good thermal conductivity and a low thermal inertia.

The water panels diffuse or absorb heat by natural convection and radiation at the same time through the front side towards the room and through the backside towards the plenum. The diffusion fins being separated, there is a re – circulating air flow between these two zones (room and plenum) which also participates in thermal exchanges.

In order to get a better knowledge of the performances of this system when heating and when cooling, the Gaz de France research centre funded a test campaign in partnership with our laboratory located in Rennes (Western France). The test room which surface area is about 14 square meters was equipped with four ceiling water panels. The experimental study carried out during one summer and two winters enabled us to measure the heating and cooling performances of the radiant ceiling panels and to study the thermal comfort conditions. Simulation models were developed with the American simulation program TRNSYS and validated with the experimental results.

1 Introduction

It's only lately that, the HVAC equipment market has seen the introduction of ceiling water panels. Such a technique, rather unknown so far in France, is well developed in Scandinavian countries, Germany and Switzerland. As for the floor water heating system, this can provide heating in winter and cooling in summer. If the floor and the ceiling systems have similar heat transfer characteristics, they don't have the same thermal inertia. The floor has a strong thermal inertia while the ceiling has a rather low thermal inertia. In order to get a better knowledge of the performances and limits of this system, The Gaz de France Research Centre funded a test campaign in summer (1993) and in winter (1994-95) and (1995-96), in partnership with our laboratory and Espace HD (Habiter Demain), an organisation located in Rennes, which carries out research and promotion in the field of natural gas and domestic innovations.

Ceiling water panels which are incorporated into false ceilings, are made of copper pipes with rigid aluminium diffusion fins. The materials used, present a good thermal conductivity, a reduced water capacity and a low thermal inertia [3]. This system has the advantage to provide heating and cooling. It also improves thermal comfort, a major portion of the heat being transferred by radiation and by the reduction of air speed. Dimensions of these units, generally correspond to the standard dimensions of false ceilings which permits an easy installation.

2 Experimental installation

2.1 Test room and ceiling

The test room occupies one room in the T5 experimental house of Espace HD. The test room which surface area is about 14 square meters, has a low thermal inertia and a double glazed window facing West. The four ceiling water panels equipped with rigid separated fins (figure 1) are incorporated into the false-ceiling and cover only 63% of the available surface area that is to say 8.6 square meters.

Originally, this type of equipment does not include backside insulator. The house being on one level and in order to reduce heat losses through flat-roof, we have for the majority of the tests laid a 7 cm thick insulator on the back side of the ceiling water panels, as shown in figure 2. The water capacity of these panels is 2 l/m^2 with a mass of about 15 kg/m^2.

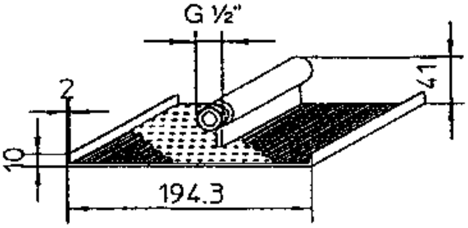

Figure 1: Water panel fins (dimensions in mm)

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2.2 Hydraulic and control systems

The water inlet temperature in the ceiling panels is controlled by a 3-way valve on the primary side of the exchanger. The opening of the valve is controlled in proportion of the difference between indoor air temperature and set - point temperature ($T1 - T1_{sp}$), figure 3. The same device controls the cooling but this second proportional action is controlled by a dew-point limitor in order to prevent condensation on the ceiling panel.

The production of hot and cold water is made by a system composed of two subsets powered by natural gas : an ammonia-water absorption unit for the production of cold water and a burner-smoke-exchanger for hot water. The four ceiling-water panels are connected in parallel and fed by a flat-plate exchanger, figure 4.

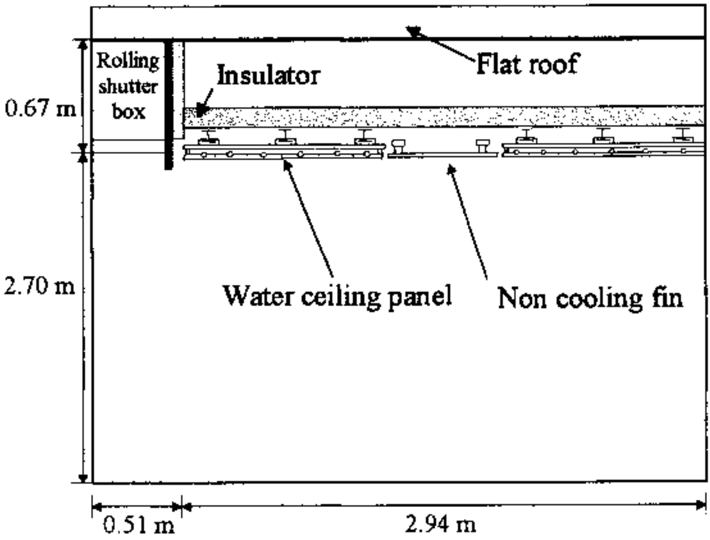

Figure 2: Ceiling water panel installation

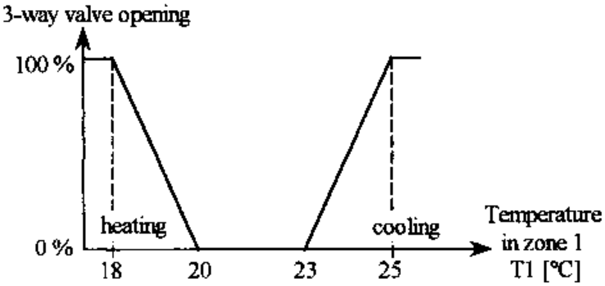

Figure 3: Controller action

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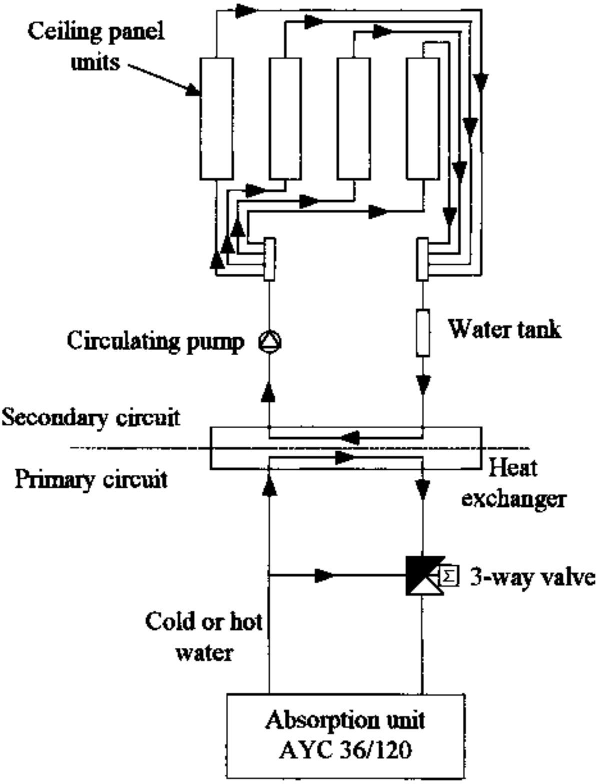

Figure 4: Hydraulic circuit

3 Performances

3.1 Sensors in test room

80 sensors (temperature sensors, flow – meters...) have been connected to a data acquisition system. The monitoring equipment could display a permanent report on the following data group:

- indoor an outdoor climatic conditions
- values of thermal comfort parameters
- thermal behaviour of the hydraulic components
- heating and cooling rate provided on each sides of exchanger.

During each test (4 to 6 days long), except outdoor climatic conditions, the conditions were constant :

- rolling shutters closed or open
- with or without internal heat gains
- 3 way valve controlled or fully open

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3.2 Cooling performances

When cooling, controlling the water temperature (minimal value close to 16°C) prevents any risk of condensation. The rate of cooling provided by the panels is rather low and varies from 30 to 60 W/m² [5]. In case of high internal gains, the ceiling water panels do not maintain the setpoint temperature. Yet, it provides a noticeable cooling of the test room. It should be noted that heat absorption consists of 2/3 radiation and 1/3 convection.
Figure 5 shows the evolution of indoor and outdoor temperatures with a ceiling water panel providing cooling since 9.30 AM. There is a 6 °C temperature differential between the test room and an adjacent reference room, also facing West.

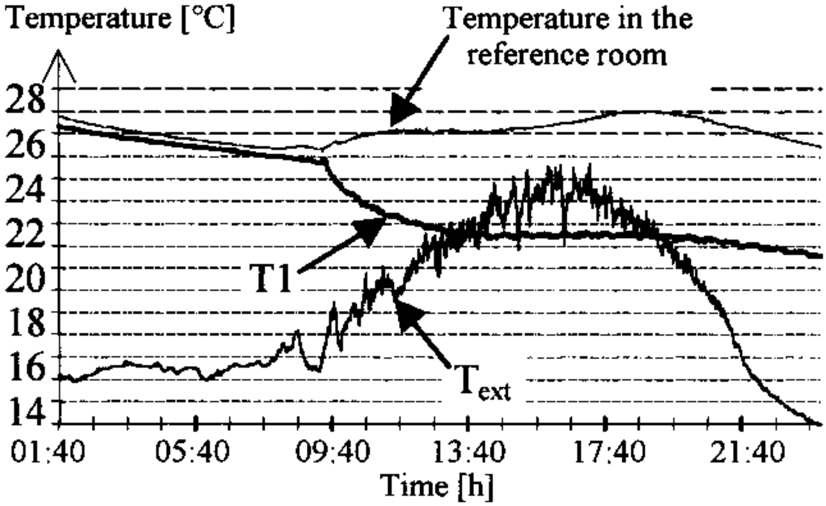

Figure 5: Inside and outside temperatures (June, 29th 1994)

3.3 Heating performances

When providing heating, the total heat transfer varies, in normal conditions, between 40 and 80 W/m² and consists of 80 % radiation and 20 % natural convection. Figure 6 shows for one day, the variations of ceiling surface temperature and indoor air temperature with internal gains (office building) from 8 am to 6 pm. Those internal gains which represent approximately 500 W (one person, one PC) produce another rise in indoor temperature from 8 am. The set - point temperature being 20 °C, the 3 way valve closes slowly after 8 am. During these tests, the shutters were open from 8 am until 7 pm and the outdoor temperature remained more or less unchanged, that is to say close to 4 °C.

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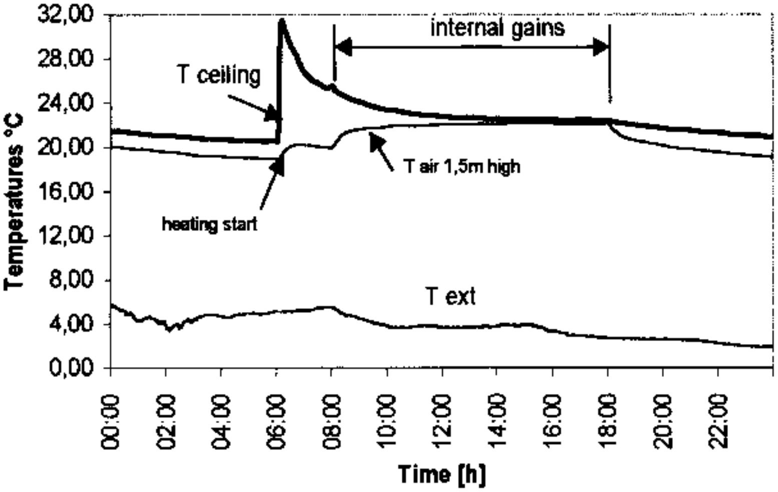

Figure 6 : Inside, outside and ceiling temperatures in heating

3.4 Indoor air temperature profiles

For these two tests, the average ceiling surface were respectively of 25.9 °C (test 1) and of 35.7 °C (test 2). We can notice that on figure 7, temperature decreases strongly between 2.50 m and 1.80 m. Taken as a whole, the level of thermal comfort for these two tests is very good with for the global sensation a predicted percentage of dissatisfied (PPD) close to 6 %, despite a high value of the ceiling's surface temperature during test 2 [4].

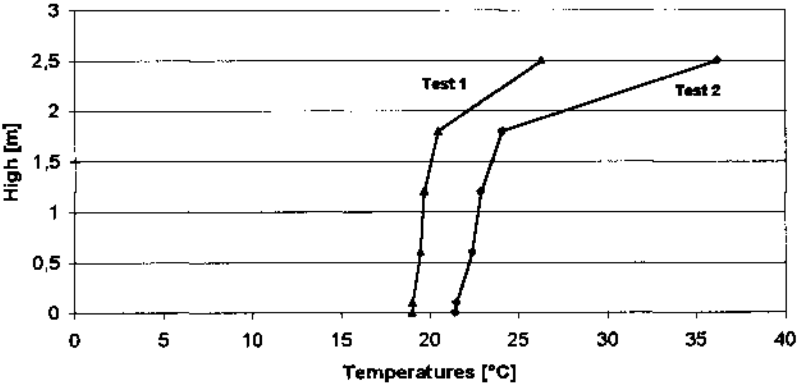

Figure 7 : inside air temperature profiles

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4 Simulation model with the TRNSYS program

4.1 Simulation model of the ceiling

A simulation model of ceiling water panels was developed with the TRNSYS American program [2]. This equipment model is connected to different components of the hydraulic system and to control devices.

The thermal insulator placed on the back-side of the ceiling's devices, makes a 20 cm thick space or plenum. The rigid fins of the ceiling makes the separation between the test room (zone 1) and the plenum (zone 2).

The total heat transfer by natural convection and radiation (P_{exch}) is made at the same time through the front-side towards the test room and through the back-side towards this plenum limited on the top by the insulator, figure 8. On the other hand, through the separated fins of the ceiling, an air flow comes between these two zones.

These two volumes are described in the multizone building model of the TRNSYS library and the water ceiling panel heating-cooling system is the partition. The inputs of the ceiling model correspond to the values of the ceiling water inlet temperatures, air temperatures and walls temperatures of zones 1 and 2. The average ceiling water temperature is calculated on the basis of the ceiling energy balance, eqn (1) where C is the thermal capacitance of ceiling panel and P_{del} the rate of energy delivered by the water flow.

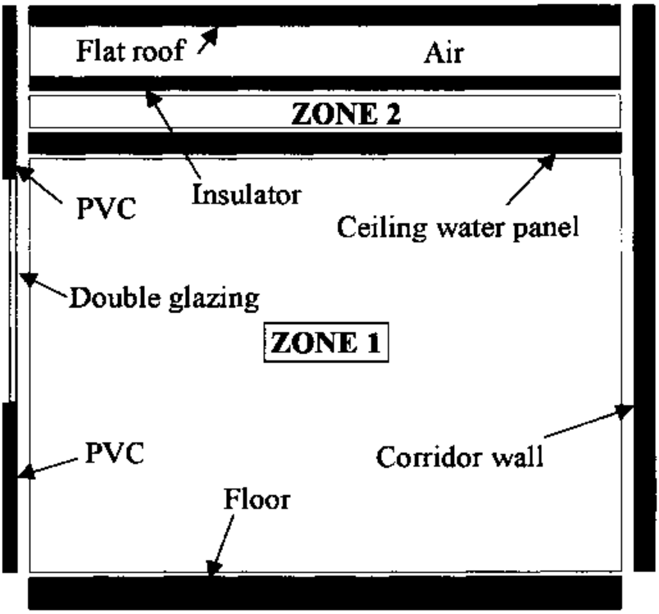

Figure 8: zones and walls for the test room modeling

$$C\,\frac{dT_{w,m}}{dt} = P_{del} - P_{exch} \qquad (1)$$

When the water flow circulating is not nil and by using a formula with finite differences, we get the expression of the ceiling's water outlet temperature at the timestep n + 1, $T_{w,o}^{n+1}$, eqn (2), knowing the value of the water inlet temperature at the same timestep $T_{w,i}^{n+1}$ and the values at the previous simulation timestep of the mean water temperature of ceiling panel $T_{w,m}^{n}$ and of P_{exch}^{n}. In the equation 2, qm is the water flow rate, c the water specific heat and Δt the simulation time step.

$$T_{w,o}^{n+1} = \frac{T_{w,i}^{n+1}(2\ \ \Delta t\ (q_m c)_w - C) + 2\ \ \Delta t\ P_{exch}^{n} + 2CT_{w,m}^{n}}{C + 2\ \ \Delta t.(q_m c)_w} \qquad (2)$$

The calculation of the ceiling's surface temperature $T_{ceiling}$ includes the global heat transfer coefficient K, eqn (3). As a result of the interconnection between the models representing the ceiling and the room, this temperature of the ceiling calculated at the timestep n + 1 is one of the inputs of the multizone model representing the test room.

$$T_{ceiling}^{n+1} = \frac{P_{exch}^{n}}{K} + T_{w,m}^{n+1} \qquad (3)$$

4.2 Simulations with TRNSYS - Experimental validation of ceiling water panel model

4.2.1 Testing conditions

In order to delete initialization period during simulation process, long-lasting sequences (more than 24 hours) are required. The following procedure had to be carried out in order to validate the various models of the system :

- experimental validation of the single test room model without operating ceiling panel units;
- experimental validation of heat transfer coefficients of the heating/cooling systems using measured ceiling temperatures;
- experimental validation of heating/cooling systems for the two-unit model (test room + ceiling panel) using inlet water temperatures recorded during tests as input data;
- experimental validation of heating/cooling systems for the global model (room + ceiling panel + hydraulic system + exchanger) using water temperature measured at the primary side of the exchanger as data file.

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4.2.2 Cooling System Validation

This experimental validation relies on tests performed during one week in July. During the simulation, ceiling panel cooling system was in operation from 6.00 am to 7.00 pm, rolling shutters were raised from 8.00 am to 11.00 pm, so that coefficient K on the picture window would be different during the day or the night, and thermal sensible gains of approximately 500 W were delivered to the test room. All these conditions did not change during the 6-days testing period. Figure 9 shows that simulated ceiling surface temperatures ($T_{ceiling\ sim}$) agree with experimental measurements ($T_{ceiling\ exp}$) when natural convection heat transfer coefficients are 3 $W.m^{-2}.K^{-1}$ at the front-side and 0.8 $W.m^{-2}.K^{-1}$ at the backside of the panel respectively, air flow being 10 $kg_{dry\ air}.h^{-1}$. Nevertheless test room temperature may reach 27°C at the end of the day, even if cooling ceiling panel surface temperature remains under 20°C all day long. This overheating is due to internal gains and direct solar gains delivered by the West-facing picture window.

4.2.3 Heating System Validation

This experimental validation relies on tests performed during 3 consecutive days of March. The ceiling panel operated with fully opened 3-way valve from 8.00 am to 4.00 pm. No additional thermal gain was delivered and rolling shutters were raised from 8.00 am to 8.00 pm. Direct solar gains were limited due to stores installed in the test room.

Graph of figure 10 illustrates the simulated evolution of indoor temperature T_{1sim} obtained with convection coefficients of 1.25 $W.m^{-2}.K^{-1}$ at the front-side and 1.75 $W.m^{-2}.K^{-1}$ at the backside of the panel respectively. The evolution of simulated temperature is in accordance with experimental temperature T_{1exp}. These corresponding values lead to the conclusion that the ceiling panel simulation model perfectly met the test requirements. Furthermore, as far as emissions are concerned, similar targets were reached.

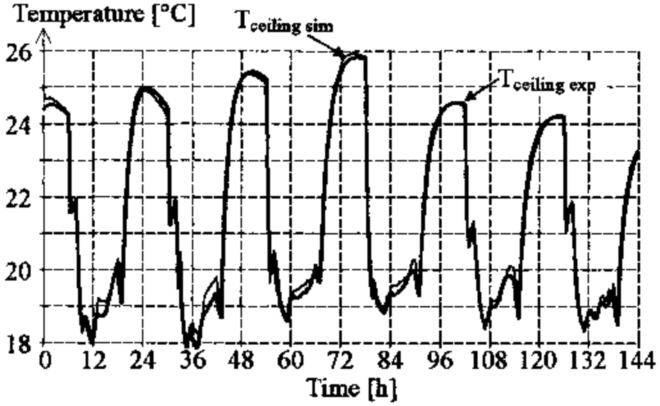

Figure 9: Real and simulated ceiling temperature with cooling in July

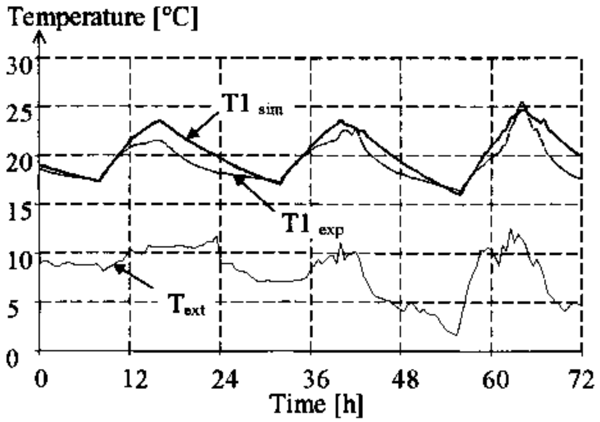

Figure 10: Real and simulated ceiling temperature with heating in March

5 Conclusions

The water ceiling radiant panel heating and cooling system is well suited to houses, office buildings or hospitals. But, the heating and cooling loads of these buildings must be low. Experimental performances of this system are :

- 40 to 100 W/m^2 in heating mode
- 25 to 60 W/m^2 in cooling mode.

Defining the TRNSYS simulation model of a ceiling panel heating/cooling system equipped with separated fins was quite difficult.. Therefore convection heat transfer coefficients and re-circulation airflow rate through ceiling separated fins could not be easily measured. The results of the TRNSYS ceiling water panel model with constant heat transfer coefficients are satisfying.

Furthermore, TRNSYS multizone building model only gives a single air temperature per zone, which are not sufficient data to enable an evaluation of thermal comfort. TRNSYS program could provide neither information on air movements in the room.

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