Building Simulation 2009

Eleventh International IBPSA Conference
Glasgow, Scotland
July 27-30, 2009

COMMISSIONING CASE STUDY OF A COOLING CEILING SYSTEM

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ABSTRACT

As a part of commissioning case study, the cooling ceiling system of a commercial building in Brussels is experimentally evaluated by means of a functional test procedure and a detailed thermal model of this system. This one has to be used in situ, as diagnosis tool in commissioning process in order to determine the main parameters of the cooling ceiling systems. Due to the extended glazing surface of the building, the problem is the overheating of zones submitted to the expected solar heat gains. The subsystems considered for commissioning process include the fenestration, ventilation and cooling ceiling system. The interaction and individual operation conditions of each system are evaluated. A Functional Performance Testing guide (FPT) for cooling ceiling commissioning process is proposed.

NOMENCLATURE

c	Specific heat [J/kg-K]
C	Constant [-]
D	Diameter [m]
H	Height [m]
L	Length [m]
$\dot{M}$	Mass flow rate [kg/s]
$\dot{Q}$	Heat flow [W]
t	Temperature [°C]
ΔT	Temperature difference [K]
ΔP	Pressure difference [Pa]
W	Width [m]
w	Distance between tubes [m]

Subscripts

a	Air
c	Ceiling
cc	Cooling ceiling
g	Glazing
i	Internal
e	External
meas	Measured
n	Constant
p	Pressure, panel
res	Resultant
su	Supply
s	surface
t	Tube
void	Air cavity on top of the cooling ceiling
w	Water or wall.
win	Window

INTRODUCTION

The cooling system consists in a radiant surface connected with a closed circuit containing chilled water. While the primary air distribution is used to fulfill the ventilation requirements, the secondary water distribution system provides thermal conditioning to the building. Cooling ceiling systems significantly reduce the amount of air transported through the buildings as ventilation is provided usually by displacement or mixing ventilation systems (often only about 20% of the normal all-air system air flow rates (Conroy et al. 2005)). This results in the reduction of the fan size and energy consumption and ductwork cross-sectional dimensions (Feustel and Stetiu 1995).

The original misgivings towards water piping in ceiling directly above the workplace, with attendant fears of possible leakage, condensation risk, high pressure drop, deficient thermal contact, radiant asymmetry etc. have generally given way to a high level of acceptance. It is important to remark, however, that the commissioning process is especially important in this system for detection of a possible malfunction and for its diagnosis.

Considering the large surface available for heat exchange, the water temperature is only slightly lower than the room temperature; this small difference allows the use of either heat pump with very high coefficient of performance (COP), or alternative cooling sources. Today there is a widespread interest in extending the range of application to heating, in order to save on investment costs on one hand, and on the other one to avoid the use of static heaters under or in front of glass facades, which are often undesirable for architectural reasons.

A detailed model for different types of cooling ceiling system (developed and validated on the basis of the experimental data) (Fonseca et al., 2009) was used in a commissioning case study presented here as example. The theoretical approach used in the model gives to the user an appropriate tool for diagnosis in commissioning processes, based solely on geometrical characteristics and operating condition measurements.

BUILDING DESCRIPTION AND CONDITION

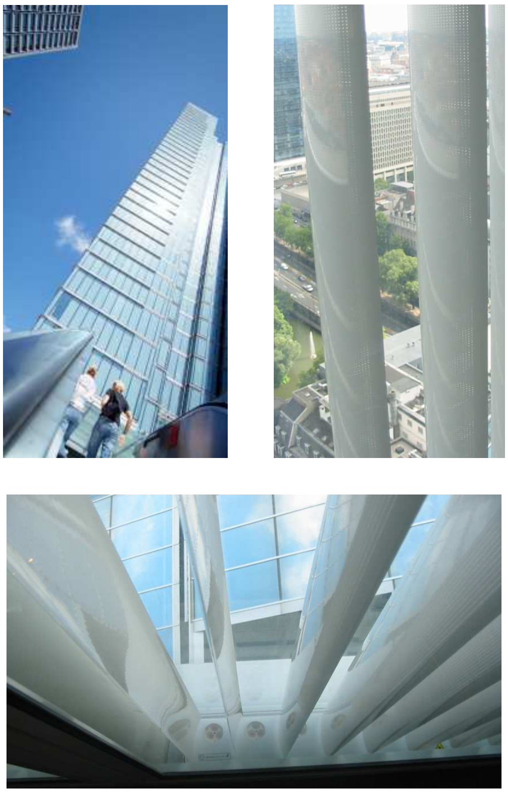

Figure 1: Building details.

The building considered in this study has a total of 38 floors with a floor area of 87200 m^2. The façade is composed by 6,000 windows. The internal walls are made in security glazing. Some details of façade and windows are presented in Figure 1.

The glazing is composed of an external double glazed unit and an internal single pane of clear glass. The cavity between the two skins is ventilated with return room air, which is extracted from the room at the base of the glazing and rejected to the ventilation system from the top. The principle is to position the shading devices between two layers of glazing, capturing the irradiated energy within the cavity. The energy can be expelled in periods with high gains and cooling demands or recovered in periods with heating demands.

Cooling ceiling description

The cooling ceiling system of the selected office is composed by cooling mats consisting of numerous thin capillary tubes (D_e=3.4 mm and D_i =2.3 mm) made in polyethylene that are placed on top of the perforated metal ceiling panels (Figure 2).

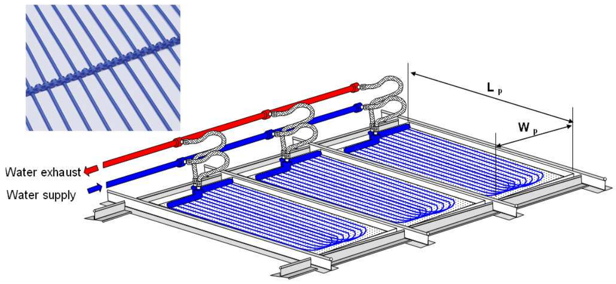

Figure 2 View of Synthetic capillary tube mats cooling ceiling.

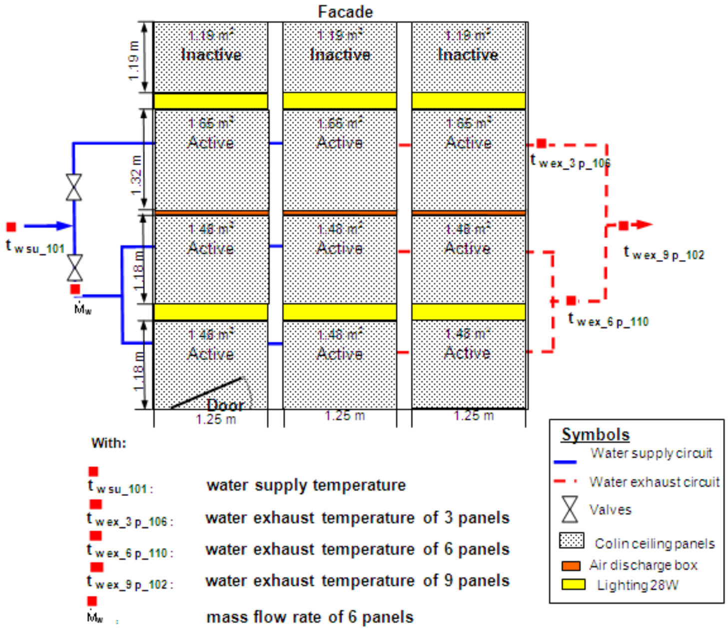

Figure 3: Schematic view of the cooling ceiling.

The distance between the individual small tubes (10 mm) through which chilled water flows is small enough to ensure that a homogeneous temperature is produced on the bottom side of the ceiling. The capillary tube mats have a "**U**" configuration with glass-wool thermal and sound insulation above the mats. Ventilation and lighting systems are integrated into the cooling ceiling panels (Figure 3).

MEASUREMENTS

Measurements are performed according to ANSI/ASHRAE Standard 41.1-1986 (RA 91) and ASHRAE. ANSI/ASHRAE Standard 41.2-1987 (RA92). The method used here for uncertainty analysis is based on the ASHRAE Guideline 2-2005*;* instrumental accuracies are given for a confidence level of 95%.

For the temperatures one considers two sources of uncertainty: one coming from the thermocouple tolerance (±0,5 K) and other coming from the data acquisition system (±0,3 K). Thus, there is obtained an overall absolute uncertainty of ±0,6 K (the relative uncertainty is smaller). The air flow rate is measured according to international standard ISO 5167 (1991). Thus, the cooling effect of air discharged into the chamber is evaluated with an uncertainty of ± 3.5 %.

In order to develop a performance testing of the cooling ceiling system, the following measurements must be made during the commissioning process (Figure 3 y 4) (office without occupation and summer mode of the facade):

$t_{w, su}$, $t_{w, ex}$:Supply and exhaust water temperature, °C .
$\dot{M}_W$: Water mass flow rate, kg/s.
$t_{res, room}$, $t_{a, room}$: Resultant and air temperature, °C.
$t_{a, void}$: Void air temperature, °C.
L_p, L_{room} : Panel and room length, m.
W_p, W_{room} : Panel and room width, m.
$H_{room,}$: Room height, m.
$t_{c\,s\,average}$: Ceiling surface average temperature °C.

The steady state model allows to verify the main cooling ceiling performance. The test consists in measuring these variables defined as model inputs and calculates the cooling ceiling capacity, ceiling surface average temperature and water exhaust temperature.

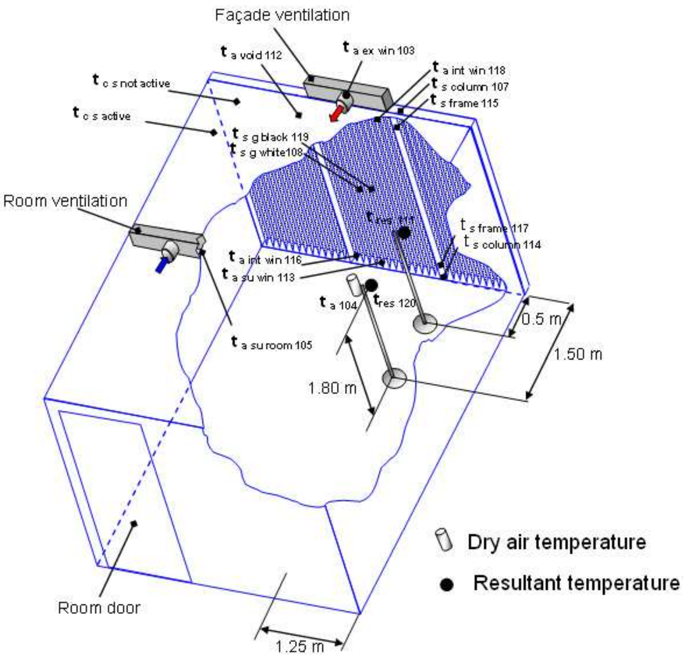

Figure 4 Sensors positions into the room.

In order to evaluate the fenestration and ventilation systems, the surface and air temperatures in different points of the room must be measured. Sensor positions are showed in Figure 4.

Cooling ceiling commissioning results

At the first visual inspection of the system, it was observed that the cooling ceiling panels close to the facade were inactive and 4 of the 9 active panels were installed with shorter capillary mats (due to installation errors), witch implies a reduction of the active cooling surface. Figure 3 shows a schematic view of the studied cooling ceiling system.

The nominal water mass flow rate and pressure drop for the operation condition must be 0.053 kg/s and 0.6 kPa respectively (according to manufacturer documentation); however the mass flow rate measured is around 3.15 times higher. This does not represent an influence on cooling emission, nevertheless the pressure drop of the system increases to 1.65 kPa. The pressure loss is important in this case, because pumping energy consumption is not negligible and the COP can be improved if choosing correctly the water flow rate and minimizing pressure drops for commissioning process.

Average results of measurements for May 13th (Hannay 2008) from 11 h to 13 h are summarized in Table 1 and 2. It is observed a strong overheating of the façade (air, glazing and frame windows) considering that measurements were performed during middle season. The average outdoor temperature and solar radiation intensity incident on the glass façade during the time period of the measurements presented in Table 1 and 2 are 28.4°C and 240 W/m^2.

Table 1 Commissioning process: Cooling ceiling average results of measurements

Sub system	variable	result
Cooling ceiling 6 panels	$t_{w, su}$	14.7 °C
	$t_{w, ex}$	**15.9 °C**
	$\dot{M}_W$	0.183
	$t_{res, room\ 120\ (1.5\ m)}$	26.2 °C
	$t_{res, room\ 111\ (0.5\ m)}$	**28.5°C**
	$t_{a, room\ (1.5\ m)}$	25.5 °C
	$t_{a, void}$	25.2°C
	$t_{c\ average}$	**18.7** °C
	L_p	1.25 m
	W_p	1.18 m
	L_{room}	5.15 m
	W_{room}	4 m
	H_{oom}	2.58 m

The experimental data provided by the manufacturer can be used in order to identify the model parameters (First parameter identification: thermal contact resistance and convective thermal coefficient). If the cooling ceiling model (validated previously for "U" mats configuration on top of perforated panel with upward insulation) is used with the results presented at Table 1 and the reference temperature at 1.5 m from the façade, the commissioning results can be observed at the model diagram in Figure 5. The comparison between calculated and measured values selected for commissioning process is presented in Table 3.

Table 2: Commissioning process: Façade and ventilation system average results of measurements.

Sub system	variable	result
Façade	$t_{s\ column\ 107}$	41.7 °C
	$t_{s\ frame\ 115}$	46.4 °C
	$t_{s\ frame\ 117}$	32.9 °C
	$t_{s\ column\ 114}$	28.2 °C
	$t_{a\ int\ win\ 118}$	**44.8 °C**
	$t_{a\ int\ win\ 116}$	36.6 °C
	$t_{c\ s\ not\ active}$	28.9 °C
	$t_{s\ g\ black\ 119}$	**35.1 °C**
	$t_{s\ g\ white108}$	**35.5 °C**
	$t_{a\ su\ win\ 113}$	25.7 °C
	$t_{a\ ex\ win\ 103}$	**44.9 °C**
Ventilation system	$t_{a\ su\ room\ 105}$	16.8 °C
	Supply air overpressure principal duct	+13 Pa
	Return air depression principal duct	-64 Pa
	Return air depression window exhaust	-4 Pa

Table 3 Cooling ceiling measurement and calculated values results

Variable	Measured value	Model results
$t_{c\ s\ average}$	18.7 °C ± 0.5°C	19.5°C
$t_{w\ ex}$	15.9 °C ± 0.25°C	16°C
$\dot{Q}_{system}$	919 W± 270 W	1020 W

It can be observed that the cooling emission of the system fits into the expected range (according to the As-Built files). However, for the case study presented here, the cooling ceiling capacity is insufficient to fulfil the comfort conditions expected by the occupants, considering the overheating of the façade and the very low thermal inertia of the building.

The possible solutions of the problem could be to consider the activation of the cooling ceiling panels close to the façade (considering the thermal load concentration in this zone) and also the use of an additional mobile shading device, transparent to visible light, but opaque to infra-red radiation in order to reduce the overheating of the occupancy zone. A global dynamic model of the cooling ceiling and its environment (ceiling and ventilation systems, internal load distribution and building envelope) must be used in order to evaluate the global system performance.

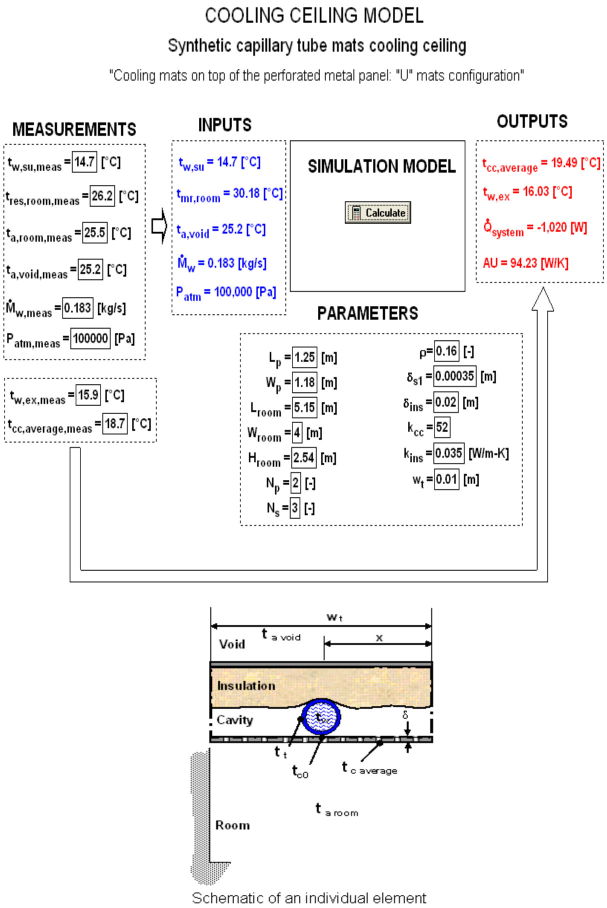

Figure 5: Block diagram of the cooling ceiling model (EES software): Commissioning results.

COOLING CEILING FUNCTIONAL PERFORANCE TESTING GUIDE

The functional performance testing guide (FPT) is devoted to the detection of a possible malfunction and to its diagnosis. The test can be "active" or "passive", according to the way of analyzing the component behaviour: with or without artificial perturbation. Active tests are mostly applied in initial commissioning, i.e. at the end of the building construction phase. Later in the Building Life Cycle, i.e. in re-, retro- and on-going commissioning, a "passive" approach is usually preferred, in order to preserve health and comfort conditions inside all the building occupancy zones (IEA Annex 40 2003).

The FPT is just one part of the whole Commissioning process. It has only to be started on the basis of strict specification, given in the Design Documents; the test results and interpretation must be incorporated into the As-built Records. Information and testing procedures are viewed from a system perspective, rather than a component perspective. This is especially critical for functional performance testing and for the overall success of the system. The FPT of HVAC system means to verify that the equipment, subsystem and total system work with in harmony (including the stability and durability) to show the final function of the building air-conditioning

In the frame of the program "Commissioning of Building and HVAC systems for improve energy performance Annex 40" of the International Energy Agency, some FPTs are presented. However there is no specific information about cooling systems.

Looking at the related literature, some case studies about this system are presented (AuditAC 2006, EIA 2003) in which its influence on building commissioning is usually simplified. Therefore a FTP for cooling ceiling systems is proposed here after as tool for diagnosis in commissioning processes.

Functional Performance Test presentation

Operating principles

Basic and working principle:

They are usually mounted in the false ceiling or embedded into the ceiling and are designed to cover the sensible cooling load of the room. As the cooling elements are part of the room architecture they are supposed to operate only in dry regime. Consequently the latent (moisture) load of the room has to be controlled by an auxiliary ventilation system, which is also designed to provide air renewal for hygienic requirements. Therefore, the water supply temperature in the ceiling must exceed the dewpoint corresponding to the setpoint of indoor humidity ratio. When natural ventilation of the room is allowed, the limitation will be related to the outdoor dewpoint (Ternoveanu et al 1999).

Expected performances:

The ceiling cooling power must be sufficient to maintain the setpoint for room temperature which is the comfort temperature corresponding to the activity and clothing level of occupants. Depending on the type of ceiling/assembly configuration, cooling capacities from 75 to 110 W/m² can be obtained.

The water temperature should be the minimum from condensation condition (0.5 K above the indoor or outdoor dew point). The indoor dew point must be controlled by an air conditioning system. If the windows are opening, they must be equipped with automatic cut-off of the water pumps.

The mean temperature difference between water and room air (resultant) should vary between 6~12 K, with absolute values of 13-18 °C for water and 24~26 °C for air. The lower difference corresponds to a minimal cooling power available while the upper limit corresponds to maximum acceptable room air velocity and temperature, and the surface temperature to avoid condensation risk.

The water flow rate should be the lowest value still sufficient to maintain a turbulent flow on water side and a reasonable water temperature drop across the ceiling (2~3 K).

The water circuit should be designed to favor parallel flow and minimize pressure drops. A special attention is to be paid to installation phase of pipes connections and bends in order to allow equal flow rate in parallel circuits and avoid exaggerated local pressure drops.

The slot diffuser should be located between the ceiling panels and above the occupancy zone. The air flow should be blown horizontally along the ceiling surface (increase of heat transfer coefficient and avoid jet fall in occupancy zone due to "Coanda effect") (Behhe M. 1999).

The contact quality (bonds between water pipes and ceiling panels) is crucial for cooling effectiveness. It is proved that identical ceiling modules (as design) can provide completely different results only due to a bad contact quality.

The thermal and sound insulation of the room ceiling void is recommended (in some cases required) and direct contact between ceiling elements and room surfaces is prohibited (cold bridges).

The free air circulation between rooms ceiling voids is allowed only if both rooms are equipped with the same cooling ceiling system and have identical destination (office room for example).

The ventilation system should ensure an over pressure for the rooms equipped with cooling ceilings in order to guarantee the air tightness (parasitic air flow from adjacent enclosures may disturb indoor convective flow).

The air velocity pattern at the occupancy zone must fulfill the comfort requirements. This means a maximum accepted average velocity in the range of 0.15-0.2 m/s with peak values limited at 0.25-0.3 m/s and a maximal allowed vertical temperature gradient of 2-3 K on the total height of the room.

Calculation methods and simulation models (used in the design):

The thermal model used here, allows to calculate the cooling ceiling capacity, ceiling surface average temperature and water exhaust temperature. A general evaluation of cooling ceiling performance can be achieved by the empirical equation giving the relationship between cooling power and temperature difference ($\Delta T = t_{res\ room} - t_{w\ average}$) as:

$$\dot{q} = C \Delta T^{n} \ [\mathrm{W/m^2}] \quad (1)$$

C and *n* for a particular system may be either experimentally determined or calculated from design material given in the literature. In either case, sufficient data or calculation points must be gathered to cover the entire operational design range.

Interaction with other (sub) systems:

The cooling ceiling systems must be evaluated in parallel with the ventilation and fenestration system.

Manufacturers Data

Cooling ceiling manufacturers publish technical sheets and performances data sheets, including curves of the cooling ceiling (relationships among the different variables of the systems cooling capacity, pressure drop, surface temperature) and also maintenance information. These sheets are also supposed to be available in the As-Built Records.

Problems to be considered

The condensation risk: This is occurring on ceiling surface in the case of windows opening or accidental reduction of water temperature. The indoor dew point temperature must be permanently controlled during the functioning of cooling ceilings; therefore the ventilation system must be started before the cooling ceiling is set on. (The delay can be calculated in function of system parameters) so the temperature constraint is given by the indoor or outdoor dew point corresponding to ventilation steady-state regime.

Pressure drop: the choice of the water flow rate is practically defined by the turbulent flow condition and geometry of the cooling elements. In order to minimize the pumping energy consumption, the water velocity inside the pipes should correspond to the critical Reynolds value for turbulent regime ($Re_{cr}>2300$).

Noise problems: the noise level provided by cooling ceilings is practically negligible in comparison with other sources as ventilation outlets and computers. The values of the water velocity imposed by the pressure drop limitation can not generate noise due to flow. However in office buildings, when the same cooling ceiling system is supplying two or more rooms in parallel, one is supposed to check the noise propagation between rooms.

Contact thermal resistance: the contact conductance is practically depending on the quality of bonds between water pipes and ceiling support material. A poor quality of contact (due to manufacturing or installation) is directly influencing the heat transfer.

Ventilation system: the ventilation contribution is limited to cover only hygienical requirements, which corresponds to small flow rates.

Surfaces temperatures: The radiant temperature asymmetry between cooling ceiling system and room surfaces (especially with façade) must remain between the allowed values for thermal comfort requirements, which are 7 to 17 K for cool ceiling (ASHRAE 2005).

Insulation level of the void (towards upper floor): the fraction of the total cooling power lost through the ceiling towards roof or rooms located at next floor can be considered as useful cooling power if the upper floor is occupied but the cooling energy is not available instantaneously but accumulated and released progressively from the ceiling thermal storage.

Test specifications

Objectives and sequence of the test

The goal of this test is to verify if the installation has been made according to the specification described in the "design documents". In any case, this test verifies if the specification of the "design documents" are adapted to the actual needs of the building. The testing procedure is subdivided into 5 steps, each one aiming at checking some specific performances:

1st Step: Selection of a representative office

Verification of the thermal loads influences, Solar radiation, equipment etc, for a representative analysis of the system into the building.

2nd Step: Visual inspection

Verification of active cooling ceiling surface, hydronic connections and insulation state. Considering that the temperature gradient into the metal ceiling panels is usually lower than 1K, a simple IR thermometer can not be used in this case.

3rd Step: Sub system definition.

Verification of subsystems related with cooling ceiling operation: Fenestration and ventilation systems.

4th Step: Test in automatic stop

Verification of the system state in automatic stop to prevent condensation risk.

5th Step: Test of normal functioning

Verification of cooling ceiling performances.

Required material

- Temperature sensor (air, resultant and surface temperature measurements).
- Water flow counter.
- Portable humidity sensor.
- Portable air velocity sensor.
- Portable steam generator.
- Portable data acquisition system.
- Portable differential manometer
- Thermal imaging system

Time required for the test execution

It depends on the accuracy and also on the characteristics of the components involved in the test and on the control possibilities. If the building BEMS can be used, the system might be monitored and studied in real time (using the remote access by internet) reducing significantly the required time for the test. The control system can serve as a commissioning tool by making use of its ability to manipulate energy systems through interfaces such as actuators and switches.

Pre-requirements

In order to make this test, it is necessary that:

- The design documents are available
- The availability of measuring points in order to place the sensor, considering the reduced space into the ceiling void or façade.
- Calibrated sensors must be used.

Preparation phase

1. Technical information from manufactures should be available. Before applying the method described hereafter, it must be made a certain number of preliminary studies from documentation: Geometric and characteristic data of the cooling ceiling system and evaluation of expected performances.

2. Measuring instruments must be installed. As already shown, the position and the way in which measurements are taken and their individual accuracies play a significant role for cooling ceiling commissioning.

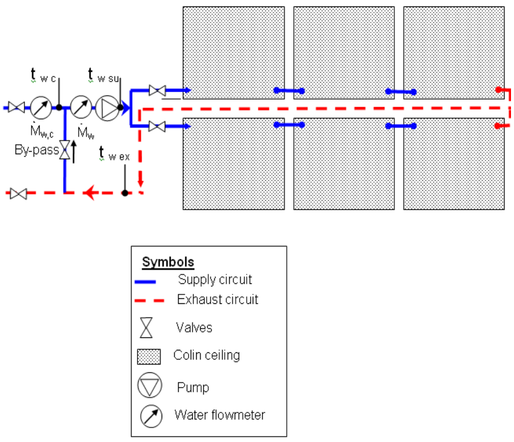

Figure 6: Water loop for cooling ceiling power measurement

Due to the high water flow rates imposed for this kind of systems (0.183 kg/s), the water temperature differences across the ceiling are small (1.2 K) thus a **great uncertainty** on direct cooling capacity is expected as the accuracy of the thermocouples is in the range of 0.2-0.3 K (Fissore and Fonseca 2007). It makes difficult the comparison of the experimental and calculated values for commissioning processes.

The accuracy of enthalpy flow rate definition (used for experimental verification of cooling ceiling performances) can be increased by measuring directly the water temperature difference and by using, during the functional test, a water loop as shown in Figure 6. This method allows an increase of the accuracy on enthalpy flow rate as the total flow rate across the ceiling is maintained constant; the water supply temperature is adjusted using the by-pass valve. Consequently the cooling capacity can be defined from a heat balance on the whole loop (water pump included) by using this time higher temperature differences (2 to 3 times) as the water flow rate is lower.

$$\dot{Q}_{system} = \dot{M}_{w,c} c_{p,w} \left(t_{w,ex} - t_{w,c}\right) - \dot{Q}_p \qquad \text{[W](2)}$$

Where:

$\dot{Q}_p$ is the electrical power dissipated by the water pump. [W].

The value of the water supply temperature in the ceiling can be recalculated by taking as reference Eq 2.

$$t^*_{w,su} = \left(1 - \frac{\dot{M}_{wc}}{\dot{M}_{wsu}}\right) t_{w,ex} + \frac{\dot{M}_{wc}}{\dot{M}_{wsu}} t_{wc} + \frac{\dot{Q}_p}{\dot{M}_{wsu} c_{pw}} \quad \text{[°C] (3)}$$

Execution phase

Physical checking: visual comparison of the cooling ceiling parameters with information given in the as-built files (geometry, active surface, water mass flow rate ...etc).

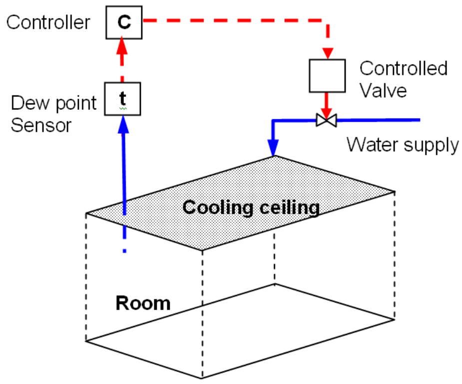

Figure 7: Scheme of ceilings control system.

First parameter identification: The experimental data provided by the manufacturer can be used in order to identify the model parameters (thermal contact resistance and the constant convective thermal coefficient).

Performance testing: The test consists in measuring the variables defined as model inputs and calculates the cooling ceiling capacity, ceiling surface average temperature and water exhaust temperature. The following measurements must be taken:

L_{p}, L_{room}	: Panel and room length, m
W_{p}, W_{room}	: Panel and room width, m
H_{room}, H_{void}	: Room and void height, m
t_{wc}, $t_{w,su}$, $t_{w,ex}$	: Control, supply and exhaust water temperature, °C.
$\Delta_{T,w}$	: Difference between water supply and exhaust temperatures, K

$\dot{M}_{w,c}$ $\dot{M}_{w}$	: Control and supply water mass flow rate, kg/s
$t_{res, room}$, $t_{a, room}$	: Resultant and air temperature, °C
$t_{a, void}$	: Void air temperature, °C
$t_{c\ average}$	:Surface ceiling average temperature °C.

Subsystem testing: The cooling ceiling behavior must be verified by coupling it with the corresponding structure of building (walls, internal loads and ventilation system), climate and functioning conditions. Therefore a simulation of the whole system must be performed by using a dynamic model (**the next step in this study**). The model inputs must be consider the geometry and materials of the system and building, the supply and exhaust water temperatures, mass flow rate, indoor and outdoor climatic conditions, and the following additional measurement:

$\Delta_{P,a}$	: Pressure differential for supply and return ventilation systems, Pa.
t_{s}	: Surface temperatures (walls, glazing, frame) °C.
$t_{a\ su}$, $t_{a\ ex}$	: Ventilation supply and exhaust air temperature, °C.

Comfort test: Air velocity and pattern from ventilation outlets, and representative air velocity and temperature pattern for the occupancy zone must be measured (in this case the measurements must be vertically placed at 10 cm and 110 cm from the floor at the occupancy zones).

CONCLUSIONS

A commissioning case study is presented in which the thermal modeling is applied as diagnosis tool of cooling ceiling systems. It was found that considering the reduced temperatures differences (characteristic of the system), the measurement uncertainty has a significant influence on the commissioning test results. A Functional Performance Testing (FPT) for cooling ceiling commissioning is proposed.

It is important to remark that spite the sophisticated BEMS and measurements system provided at the buildings, an inadequate installation, verification and management of the individual and global system performances (according to the As-Built files), produce usually the deterioration of components and global system conditions which implies an increase of energy consumption and sub-utilizing of the expensive monitoring system.

Commissioning test results show that the influence of heat sources distribution and surfaces temperatures inside the room, especially the façade, is considerable. Then, the applicability of a certain heat sources concentration which is closely related to the case studied (laboratory conditions should correspond to site conditions), and the cooling ceiling must be evaluated together with its designed environment and not as a separate HVAC equipment.

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