MULTICRITERION EVALUATION OF AN INTEGRATED SUSTAINABLE HEATING/COOLING SYSTEM IN CLIMATE CONDITIONS OF CENTRAL EUROPE

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ABSTRACT

The aim of this case study is to investigate an integrated heating/cooling system performance in central Europe climate conditions. The possibility of a reliable application of radiant low-temperature heating/ high-temperature cooling ceiling system with capillary mats is discussed. ESP-r, an energy performance simulation program, was used for this purpose. Three types of the buildings are taken into account: a residential building, an office building with small offices and an office building with open space offices. Each of them represents a different operating pattern. The discussion about the results is focused on heating/cooling energy consumption and thermal comfort. The third thing to stress is possible condensation on the ceiling surface during the cooling period.

KEYWORDS

Integrated heating-cooling system, thermal comfort, simulation programs, radiant cooling, ceiling radiant panel.

INTRODUCTION

Recent low-energy building heating and cooling design concept in climate conditions of Central Europe is based on minimizing energy consumption as one of the critical criterions in building design. The aim is to decrease total energy consumption and environmental pollution at the same time with preserving or improving indoor air quality.

Sustainable approach to a building and its energy system design, as next step after the low-energy approach, leads to evaluate besides the operational energy also energy embodied in the building and the system material (Kabele et al. 2006).

The typical need for climate conditions of Central Europe (Czech Republic) is space heating during heating period (approx 230 days a year). There were no active cooling systems considered in traditional buildings. Due to low internal gains, high thermal inertia and optimised glazing ratio this building could be operated without any active cooling. Current modern buildings in the Czech Republic, with high internal gains, high glazing ratio, low mass and well-insulated walls (U-value less than 0,3 W/m^2K) and windows (U-value less than 1,8 W/m^2K) are nowadays very often equiped with an active cooling system to follow the comfort requirements also in summer period. In many cases, in these buildings the cooling load finally exceeds the heating load.

Traditional approach to the technical solution of a heating/cooling system in such a buildings was to design two independent systems (i.e. radiator heating and split units cooling). One of the modern technical solutions, which could be considered as a sustainable one, is an integrated heating/cooling ceiling system. Capillary mats, embedded in the gypsum plaster layer of the ceiling structure are supplied by the heating/cooling water (four-pipe system). Ceiling surface transmits energy into the heated/cooled room via radiation and convection heat transfer modes. Comparing to a traditional system, this technical solution integrates two systems into one and reduces air change rate need to hygienic minimum. The strong point of this solution is a significant reduction of the used material or rather embodied energy in a heating, cooling and ventilating system (Roulet et al. 1999).

The main problem is in the technical limits of this system (Petráš 2001). During the heating operation, output is limited by a hygiene limit reducing highest intensity of radiation on the skull-cap up to 200 W/m^2 (Anonymity 2002). During the cooling operation it is limited by surface temperature, which should not drop below the dewpoint temperature (surface condensation).

PROBLEM DESCRIPTION

The main purpose of this paper is to investigate if an integrated heating/cooling system can reliably cover comfort requirements of an occupant in different typical building operation modes in Central Europe climate conditions. This task arose when several problems with system application occured despite following all the practical design recommendations (Kabele et al. 2002).

We focused on three types of the buildings where integrated heating/cooling ceiling system has been used and problems appeared.

a) residential building,
b) office building with small offices,
c) office building with open space offices.

The questions were: Is the integrated ceiling system able to secure comfort during the whole year operation? If not, how long will be the period of possible discomfort? Are the existing design recommendations in terms of maximum heating/cooling output of the ceiling applicable particularly in climate conditions of Central Europe?

RESEARCH METHOD

Problem analysis followed by computer simulation of an annual building energy performance was used in a case study. Parameters, that may have any influence on the possibility of system application were analyzed. ESP-r, an energy system performance simulation program, was used for this purpose (ESRU 2004). Multicriterion evaluation of the simulation results in terms of energy and comfort has been carried out to make a conclusion.

PROBLEM ANALYSIS

At first a list of parameters, that may have any influence on the possibility of the integrated ceiling heating/cooling system application was created. The list contains following parameters:

- Internal sensible heat load
- Internal latent heat load
- Infiltration air rate
- Ventilation air rate
- Humidity control
- Glazing ratio
- Quality of the windows – U value, permeability of solar radiation
- Active shading – jalousies
- Proportion of hight to depth of the room
- Orientation
- Set point for heating
- Set point for cooling
- Clothing insulation
- Activity of the occupants

From all those parameters we focused on highlighted different internal gains, which became variables in model set-up, used for energy and environmental performance simulation (Koschenz 1999).

Other parameters has been considered as constants with value typical for best-practice used in the Czech Republic construction practice (ČSN 730540-2005).

MODELING AND SIMULATION

Model Description

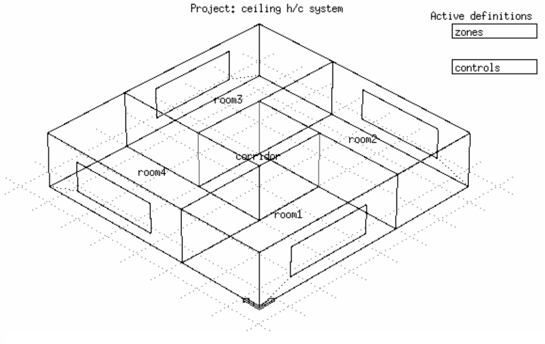

Figure 1 ESP-r model of the building

A five - zone model was created for this purpose (Figure 1, Figure 2). The model contains four equal zones with following dimensions 5 m x 9 m x 3, each facing different cardinal point, and a corridor in the centre with following dimensions 4 m x 4 m x 3m. Each of the zones has a glazing 5 m x 1.6 m in a longer exterior wall (30% of the wall). Medium-heavy constructions were considered with the value of overall coefficient of heat transmission according to Czech building regulations (ČSN 730540 2005). For an external wall U = 0.24 W/m^{2}K, for an internal wall U = 1.56 W/m^{2}K and for a glazing it is 1.20 W/m^{2}K. Detailed glazing parameters are in the table 1.

Room dimensions in the model follows recommended values for the proportion of height to depth of the room from the point of day lighting (h/d = 1.66), typical in the Central Europe geographical conditions.

No heat flux through ceilings and floors was assumed.

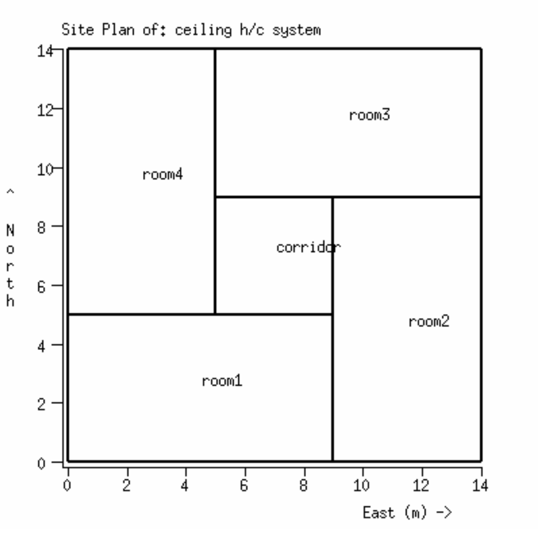

Figure 2 Site plan of the model

Heating and cooling system is radiant low temperature heating/high temperature cooling system with capillary mats placed inside the layer of gypsum plaster in a ceiling construction. System is defined by heating capacity controlled according to established practice in a range of 0-130 W/m^2, cooling capacity 0-80 W/m^2 in each of the rooms (Jeong et al. 2004). This technical solution is carried out in the model by placing a cooling and heating capacity to the axis of gypsum plaster layer. (R.K. Strand and K.T. Baumgartner 2005) The active ceiling construction layers are according to Figure 3.

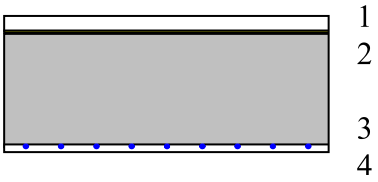

Figure 3 Active Ceiling/Floor construction: 1 Flooring, 2 Polyurethane foam board, 3 Heavy mix concrete, 4 Gypsum plaster with capillary mats

The control of the system is running as basic heat and cool controller according to sensors, located in each of the rooms, sensing dry bulb temperature. Set point for cooling is 26°C. Set point for heating is 22°C. This set point was used to achieve thermal comfort during heating period to eliminate low surface temperature influence of the window as it is usual in air systems. Set-up temperature optimisation for radiant systems is the question that is in the process of running research. There is no humidity control considered.

Model variations

The simulation ran in three variations of the model, focused on different room use:

- B1 - apartments
- K1 - small office rooms
- VK1 - open space office rooms

Ventilation. Mechanical ventilation besides the infiltration is considered only in cases of the office rooms. Required amount of fresh air in the apartment is covered by the infiltration. Air change rates are in the table 2.

Occupation and casual gains. Three different types of the buildings were considered. The first one was a residential building with maximum room occupation during weekends and relatively low internal heat loads. The remaining two types represented office buildings with maximum room occupation during the week and higher internal heat loads due to the office equipment.

Summary of model variations parameters is in Table 2.

Operation schedule of internal loads for solved variations is in figures 4,5 and 6.

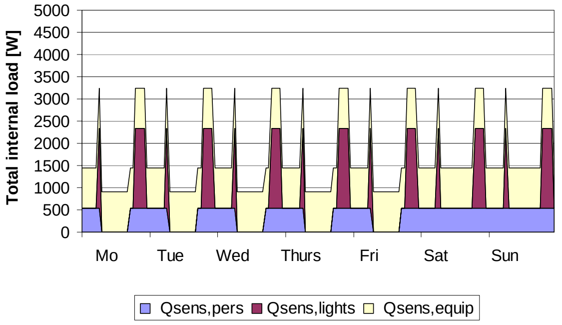

Figure 4 Week internal loads profile – variation B1

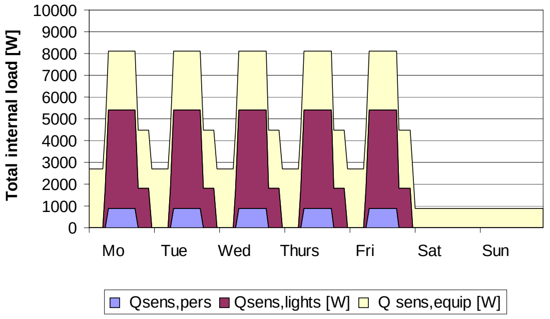

Figure 5 Week internal loads profile – variation K1

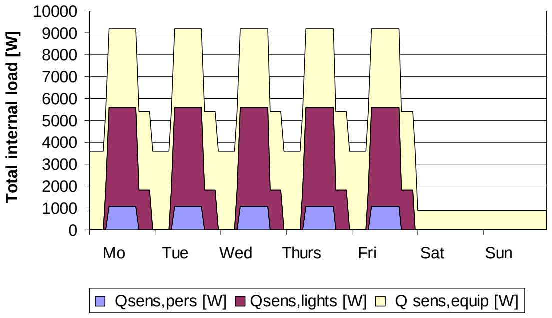

Figure 6 Week internal loads profile – variation VK1

Simulation

The whole year period was studied using Prague (Czech Republic) ASHRAE IWEC climate files (Figure 7, 8). An integrated building simulation was used, with time step 1 hour and initial period 11 days. Shorter time step has been tested during model tuning, but didn't have any important impact on the results. One hour step ensured sufficient accuracy. During simulation, no major problems were detected by the program. The discussion about the results was focused on

- annual heating/cooling energy consumption,
- comfort expressed by resultant temperatures, PMV and PPD parameters (Yang 1997, ČSN EN ISO 7730 2005)
- the possibility of condensation on the ceiling surface during the cooling period.

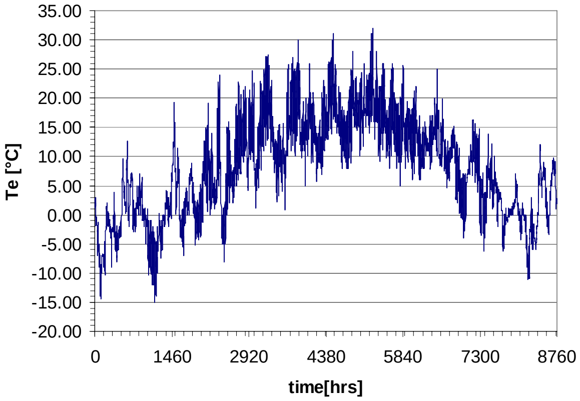

Figure 7 Annual ambient air temperatures in Czech Republic

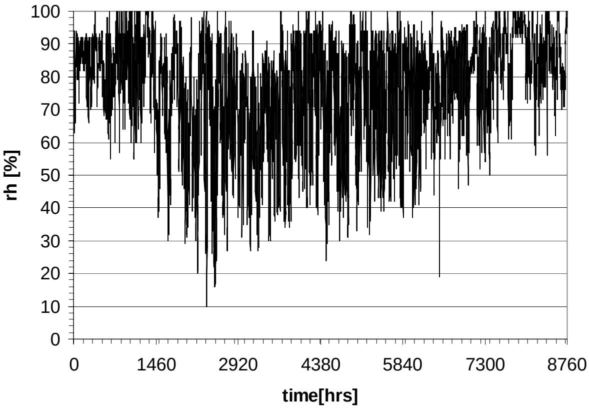

Figure 8 Annual ambient air relative humidity in Czech Republic

SIMULATION RESULTS AND DISCUSSION

In following tables and diagrams there are selected simulation results from ESP-r, related to the problem.

Annual energy

From the point of annual energy consumption (table 3) the results show a significant impact of the internal heat loads especially in variation K1 and VK1 (office rooms), which decrease energy demand for heating and increase energy demand for cooling.

Table 3 Annual heating and cooling energy

Zone	Heating [kWh]	Cooling [kWh]
B1	8151	-12468
K1	1339	-41118
VK1	1301	-47682

Thermal comfort – resultant temperatures

To get to know if the system capacity is well designed we focused on interior resultant temperatures first.

The temperature curves (Figure 9,10,11) confirmed the ability of the system capacity to guarantee set temperatures within all of the zones during nearly the whole year. Set point for cooling was exceeded only in several hot days during summer time (table 3,4,5). Results for winter period showed, that resulting temperature is higher than dry-bulb and the impact of cold window surface is fully eliminated by "warm" ceiling. Of course, that this model does not cover non-uniformity of temperature within the room, which is the subject of another study.

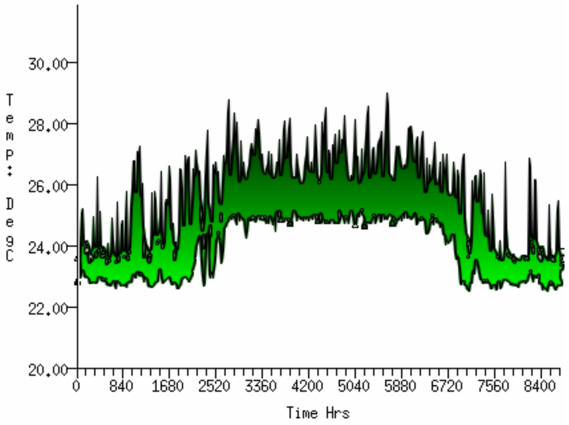

Figure 9 Annual resultant temperature range– B1

Table 3 Resultant temperature summary – B1

Zone	Max [°C]	Min [°C]	Mean [°C]	Mean-root-square error
room1	27.8	22.5	24.6	1.187
room2	26.9	22.5	24.4	1.1731
room3	26.9	22.6	24.4	1.1584
room4	29.0	22.5	24.6	1.2813

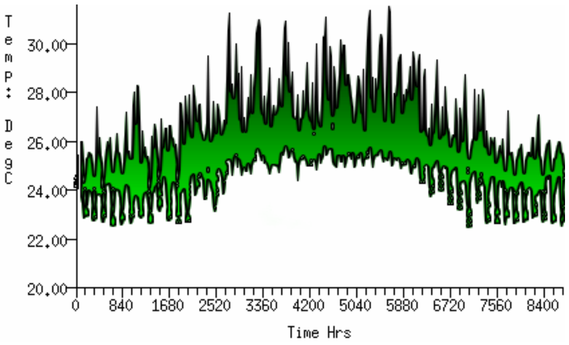

Figure 10 Annual resultant temperature range –K1

Table 4 Resulant temperature summary – K1

Zone	Max [°C]	Min [°C]	Mean [°C]	Mean-root-square error
room1	29.7	22.5	25.3	1.2079
room2	28.5	22.5	25.1	1.1186
room3	27.8	22.5	25.1	1.0106
room4	31.5	22.5	25.4	1.3316

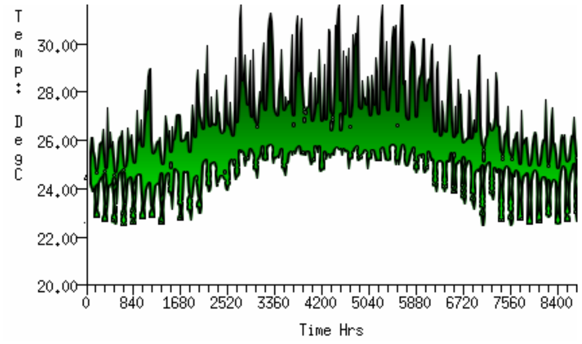

Figure 11 Annual resultant temperature range –VK1

Table 5 Resultant temperature summary – VK1

Zone	Max [°C]	Min [°C]	Mean [°C]	Mean-root-square error
room1	30.2	22.5	25.5	1.2856
room2	28.9	22.5	25.3	1.1892
room3	28.2	22.5	25.3	1.0910
room4	31.8	22.5	25.6	1.4266

Thermal comfort – PMV, PPD

Thermal comfort evaluation is based on PMV and PPD classification of heated/cooled spaces. PMV is defined by six thermal variables from indoor-air and human condition that is air temperature, air humidity, air velocity, mean radiant temperature, clothing insulation and human activity. The value of PMV index has range from −3 to +3, which corresponds to human sensation from cold to hot, respectively where the null value of PMV index means neutral to maintain the PMV at level 0 with a tolerance of ±0.5 to ensure a comfortable indoor climate. The PPD index is a description of estimated thermal comfort and a function of four physical parameters: dry bulb temperature, mean radiant temperature, relative humidity and air velocity, and parameters connected to the occupant such as clothing level, metabolic rate and external work. Comfort evaluation is based on activity level 1.2 met with clothing level equal to 0,7 clo (ASHRAE 2005, CSN EN ISO 7730).

Case B1 (Figure 12, Figure 15)

In this case PMV index appeared from -0.5 to 1.0. Index PPD in 77% of the time is up to 10% which means that during this time the number of dissatisfied occupants will not exceed 10%. Index PPD during 99% of the time is up to 20%.

Case K1 (Figure 13, Figure 16) and VK1(Figure 14, Figure 17)

In this case PMV index appeared from -0.5 to 2.0. Index PPD in 48% of the time is up to 10% which means that during this time the number of dissatisfied occupants will not exceed 10%. Index PPD during 99% of the time is up to 50%.

From the point of heating there is no problem with thermal comfort in all of the examined cases; minimum value for PMV during heating period is -0.5, which means better than slightly cool.

On the other hand several problems with thermal comfort during cooling period were detected. In the case of a residential building the maximum PMV index reached 1.0, which means slightly warm., while in both office cases maximum PMV reached even 2.0, which means warm.

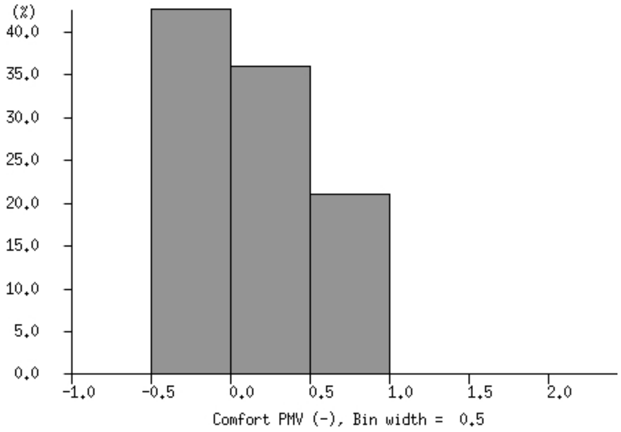

Figure 12 Annual distribution of PMV index –B1

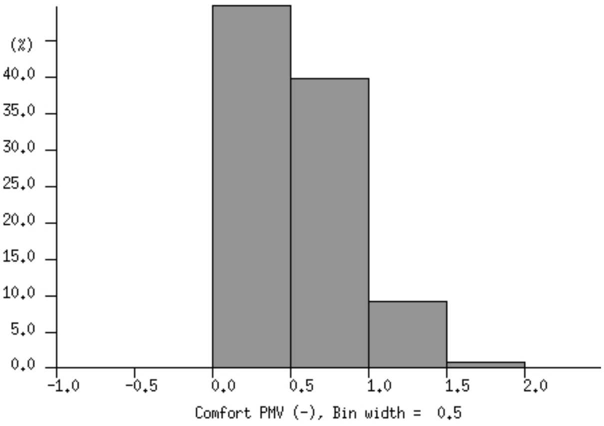

Figure 13 Annual distribution of PMV index –K1

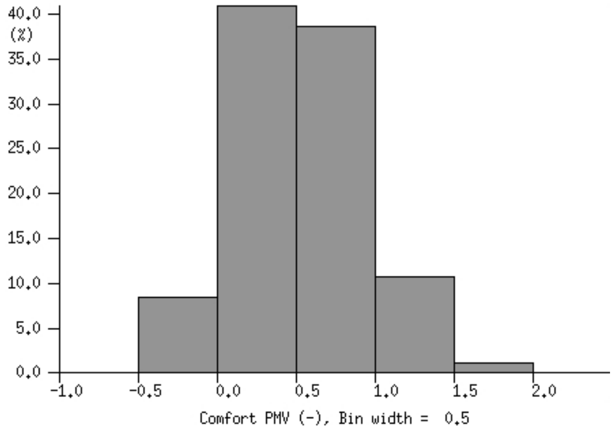

Figure 13 Annual distribution of PMV index –VK1

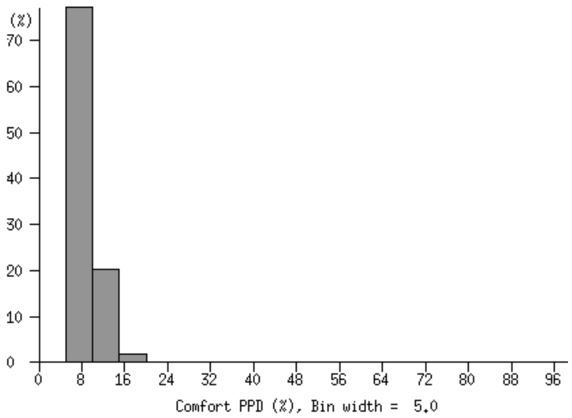

Figure 15 Annual distribution of PPD index –B1

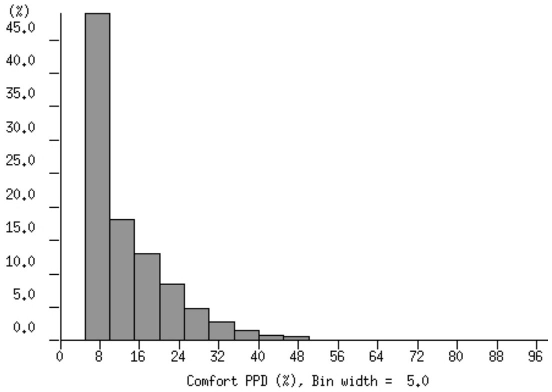

Figure 16 Annual distribution of PPD index –K1

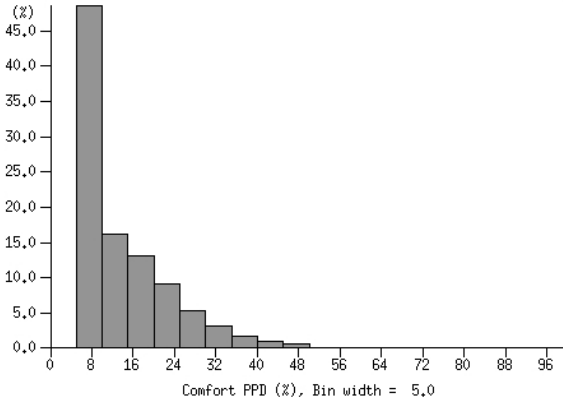

Figure 17 Annual distribution of PPD index –VK1

Active ceiling surface temperatures and condensation

The active ceiling surface temperatures coming out from the simulation are in Table 6.
In the first case in a residential building there was nothing like a surface condensation detected under the set conditions(fig.18). On the other hand in both of the office buildings the possibility of surface

Table 6 Extreme values of active ceiling surface temperatures

Case	Minimum [°C]	Maximum [°C]
B1	22	30.4
V1	20.8	27.5
VK1	20.8	27.7

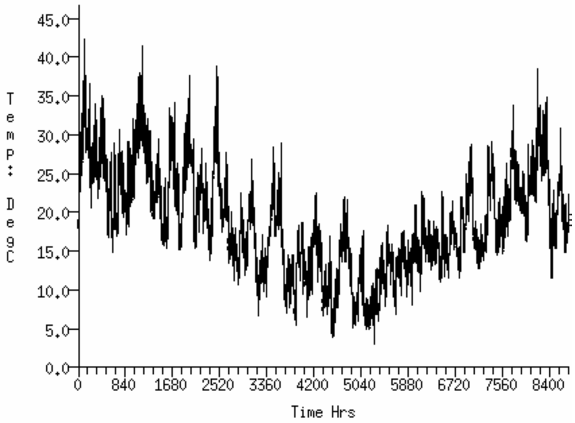

Figure 18 Difference between active ceiling surface temp and dew point temp during the year - B1

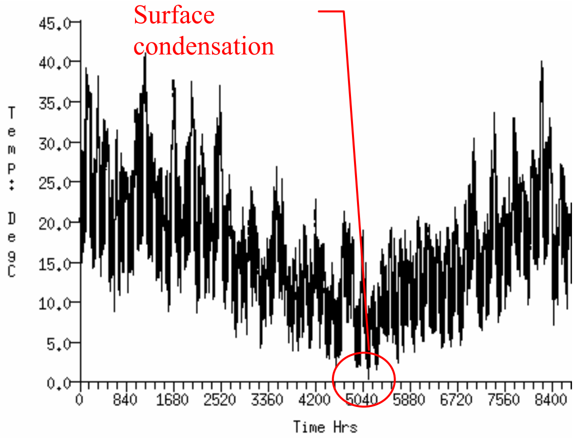

Figure 19 Difference between active ceiling surface temp and dew point temp during the year. –K1

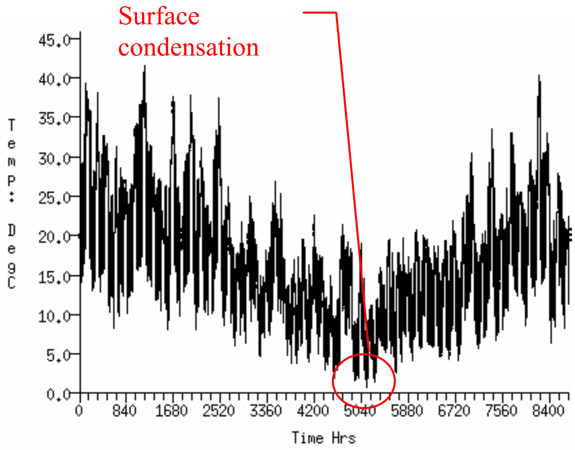

Figure 20 Difference between active ceiling surface temp and dew point temp during the year –VK1

condensation occurred in a range of one or two hours during one critical day of the year in summer(fig 19,20), when the exterior relative humidity was very high.

CONCLUSION

We were looking for the answer if it is possible to use an integrated heating/cooling system in a modern building with respect to energy efficiency and valid standards in Czech climate conditions. The question has been analyzed and parameterized. A case study, describing three typical examples of this technology application was created to predict thermal behaviour of the room heated/cooled with the system and to describe thermal comfort behaviour in time during a whole year operation. ESP-r, a modelling tool was applied. This case study focused on the evaluation of the impact of internal loads describing different types of room use. System was running in switching operation mode which means, that during the whole year both heating and cooling energy sources are available and the technical solution of the system enables to switch heating mode to cooling mode (and vice versa) automatically according to the control system.

In all of the cases there are no problems with the heating. The system can reliably guarantee the required temperature during the whole year. At the same time the simulation shows that common designed heating/cooling capacities (130 and 80 W/m^2) of the ceiling surface are appropriate. Several problems are detected with the cooling, when the designed capacity cannot cover the temperature requirements and occasionally a short-term condensation can occur. This means that the application of this integrated system is limited by its capacity. Especially in the buildings with higher internal gains and connected cooling demand this application is disputable.

The results from above and the conclusions made from them are valid for the conditions of this simulation.

The future work in this field will be focused on sensitivity analysis on other parameters affecting energy and environmental behaviour of an integrated system aiming to create general design conditions of integrated heating/cooling systems in Czech Republic.

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Tab.1 Glazing

Layer	**Thickness**	**Conductivity**	**Density**	**Specific heat**	**IR Emmissivity**	**Solar absorptivity**	**Diffusse resustance**	**Thermal resistance**
	[mm]	*[W/m.K]*	*[kg/m$^{3]}$*	*[J/kg.K]*	*[-]*	*[-]*	*[-]*	*[m^{2}K/W]*
6mm Antisun	7	1.05	2500	750	0.59	0.06	19200	0.01
air	12	0	0	0	0.99	0.99	1	0.65
Plate glass	6	0.76	2710	837	0.83	0.05	19200	0.01

ISO 6946 U values (horiz/upward/downward heat flow)= 1.20 1.24 1.14 W/m^{2}K, Poly float 76/71,6mm, no blind: with id of: DCF7671_06nb, with 3 layers [including air gaps] and visible trn: 0.76 (ESRU 2004)

Table 2 Operation parameters for the cases

CASE	**B1**	**K1**	**VK1**
Description	Apartment	Office room	Open space office
Heating set-point Θ_i min [°C]	22	22	22
Cooling set-point Θ_i max [°C]	26	26	26
Infiltration [h^{-1}]	0,5	0,3	0,3
Ventilation [h^{-1}] Θ_{sup} = 20°C	0	0,7	0,85
Sensitive heat load, people $Q_{sens,pers}$ [W.m^{-2}]	3	5	6
Sensitive heat load, lights $Q_{sens,lights}$ [W.m^{-2}]	10	25	25
Sensitive heat load,equip $Q_{sens,equip}$ [W.m^{-2}]	5	15	20
Latent heat load, people $Q_{lat,pers}$ [W.m^{-2}]	1,5	2,8	3
Heating capacity [W/m^2]	130	130	130
Cooling capacity [W/m^2]	80	80	80
Clothing [clo]	0,7	0,7	0,7
Activity [met]	1,2	1,2	1,2