Lain, M., Bartak, M., Drkal, F. & Hensen, J.L.M. (2005).
Computer simulation and measurements of a building with top-cooling.
Proceedings of the 9th International IBPSA Conference on Building Simulation, 15-18 August, pp. 579-586.
Montreal: International Building Performance Simulation Association.

COMPUTER SIMULATION AND MEASUREMENTS OF A BUILDING WITH TOP-COOLING

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ABSTRACT

This paper deals with the use of computer simulations both for design support of a new building including its heating, ventilation and air-conditioning (HVAC) systems and for optimization of the HVAC control strategy during operation of the completed building.

In the early design phases for a new commercial building in Prague computer simulations were carried out in view of possible effects of night cooling ventilation. Predictions of the indoor environment and energy consumption for various options regarding cooling capacity and different outdoor ventilation rates supported the HVAC system design which included daytime top-cooling and night ventilation with outdoor air combined with accumulation of cold in building constructions.

After completion of the building, occupants' complaints and a set of measurements indicated some problems with the HVAC, which were subsequently solved. Long-term monitoring and further computer simulations were performed in order to optimize the control strategy of the top-cooling system.

INTRODUCTION

Buildings consume approximately 40 to 50% of primary energy in European countries. Energy consumption for cooling is about 10 % of the total energy consumption in commercial office buildings. The percentage of fully air-conditioned offices in Europe is increasing, especially in the Czech Republic, where many new or reconstructed office buildings are now completed with standard full air-conditioning. The increasing use of information technology has also led to increasing demand for cooling in commercial buildings. Cooling systems in buildings are significant energy users and the impact on greenhouse gas emissions is enhanced by the fact that these systems are usually driven with electricity which is, in the Czech Republic, mainly produced in coal power plants (Santamouris 1996, Heap 2001).

Based upon the Kyoto Agreement, European countries should cut down greenhouse gas emissions and accept that energy consumption has to be decreased too. The discrepancy between increasing demand for thermal comfort on one side and for the need to decrease CO_2 emission on the other side, can be solved by application of low energy cooling technologies in commercials buildings.

Low energy cooling technologies

Low energy cooling technologies provide cooling in an energy efficient manner, thus reducing building energy consumption and peak electricity demand. They do so by making use of low quality sources of cooling; whether it is ambient air or ground temperatures or warmer chilled water. Those technologies may be considered passive and hybrid cooling systems. (The term passive cooling should not be confused with passive cooling building design which is focused on reducing the cooling load.)

The basic method to design and analyze a building with low energy cooling technologies is building simulation. This is because in these applications the dynamics and interactions of building, systems, occupants and environment are both complex and very important. Traditional design methods assume only the extreme boundary conditions, and therefore they are not suitable for design and analysis of low energy cooling systems. Computer based modeling and simulation approaches are much better for this. That is one of the main reasons why building (including HVAC system) performance simulation is quickly moving from the research and development arena into everyday engineering practice.

Top-cooling systems

Top-cooling is a system with a cooling capacity considerably less than what would be needed according to standard cooling load calculations. Because of its limited cooling capacity, such a system removes only the top of the cooling load; the remaining load is "absorbed" by letting the indoor temperature rise above the "normal" temperature set-point.

BUILDING CONCEPT

The new headquarters for the ČEZ power company (one of the top ten largest European energy utilities and the strongest business entity on the Czech electricity market) in Prague (Figure 1) is the first headquarters building in the Czech Republic to employ night-cooling and top-cooling for most of its office spaces. Occupied by ČEZ since April 2002, it won the "Czech building of the year 2002" award by the Czech ABF foundation (Dvořák 2002).

Figure 1 The new ČEZ headquarters in Prague

The building is divided into three parts. It has two wings (six floors above ground, 600m^2 each) with open-plan offices and an all-air system with top-cooling and night ventilation. The central part houses the reception on the ground floor and individually air-conditioned offices on the higher floors. For night cooling, the thermal mass of the building is very important. The building features exposed concrete ceilings with ribs and concrete floors without any carpets. More than 50% of the façade is transparent. All south facing windows are fully shaded throughout the summer by external facade elements (Figure 2).

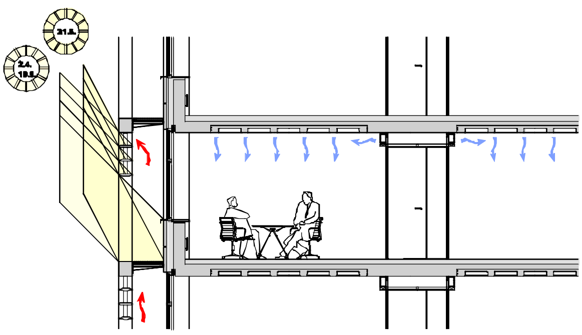

Figure 2 Principle of the shading and of the nighttime forced ventilation

The all-air centralized system for the two wings is controlled according to the return air temperature. It is a top-cooling system with cooling capacity estimated from simulations in the early design phase. There is no individual control in the rooms nor on the floors. The system is operated 24 hours per day with a constant set-point of 24 °C. Because of limited cooling capacity the indoor temperature is supposed to drift up to 26 °C during normal conditions and up to 28 °C during extreme summer periods.

EARLY DESIGN SIMULATIONS

In the early design phases of the building computer simulations were carried out to prove the concept of night cooling ventilation and to study some other effects.

Model and simulation

A section (2.5x15.5x2.7 m) of the open-plan offices was modeled in the ESP-r simulation environment. The model describes the building itself, including internal gains (58 W/m^2), the external shading devices and the previously mentioned ceiling ribs. The latter were represented by enhanced convective heat transfer coefficients.

The simulation was carried out in two steps. The first aimed to find out if night ventilation without mechanical cooling would be able to guarantee acceptable thermal comfort. If it wouldn't, then the next step was to assess the necessary cooling capacity taking into account the building thermal mass as well as night ventilation effects.

Discussion and result analysis

As can be seen in Figure 3, the predictions show that the internal air temperature would be very often (202 hours) above the thermal comfort limits (i.e. above 26 °C) if there would be no mechanical cooling.

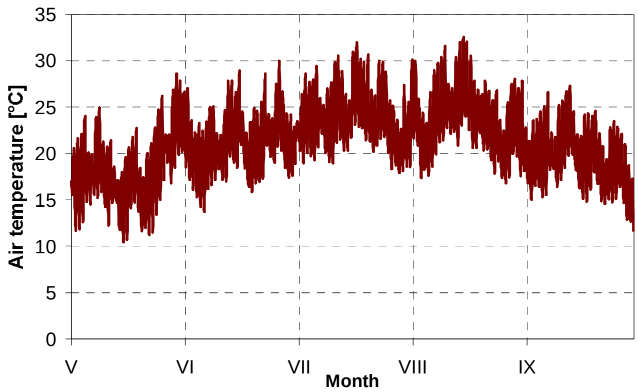

Figure 3 Indoor air temperatures if there is only night ventilation in the building

The mechanical cooling should be at least 0.9 kW (sensible) for the modeled section (23 W/m^2) to guarantee acceptable thermal comfort in the office according to the early design simulation results. This is much less then in common systems, because it is even less than 50% of the internal gains and there are also other gains by diffuse radiation, convection and outside air supply. The majority of the gains is absorbed by the building thermal mass and is removed by ventilation during the nighttime.

The early design simulations suggested that the high thermal mass and the night ventilation would decrease cooling energy consumption. However, there is additional cooling needed in order to obtain thermal comfort. Therefore 'top-cooling' system was subsequently applied.

BUILDING MONITORING

In the first year of operation there were many complaints from the open-plan office users; mainly about too high indoor temperature during the hot period of May 2002. Therefore measurements were carried out and the system performance was analyzed. Finally it was found that the reason was not poor HVAC design, but poor realization. The system was not tested in cooling mode during the commissioning and some components did not work properly. The heating coil valve was leaking and thus effectively the heating was on all the time. The fans had been operated just at half speed because of noise complaints in some offices. The night ventilation was not used at all. When the major problems were fixed and a night cooling regime was introduced, subsequent monitoring proved that the system functioned satisfactory.

CONTROL STRATEGY OPTIMIZATION

The second stage of the work used a more complex simulation model for system optimization. For calibrating this model, there were three types of measured data available:

1. data from the building energy management system;
2. data acquired from the long-term monitoring of indoor temperature and humidity and from the short-term detailed measurements of indoor temperatures and velocity distribution near the diffusers;
3. weather data from the CTU meteorological station.

Building model description

The fifth floor of the wing C (37.9x15.7x2.7m) was modeled in ESP-r as one zone including all constructional details, shading properties and internal gains (Figure 4). The geometry was simplified in just a few points. The internal office blocks and the sanitary block, which are separated from the rest of the floor by internal walls, are not considered as individual zones, because they have the same type of control as the rest of the office space.

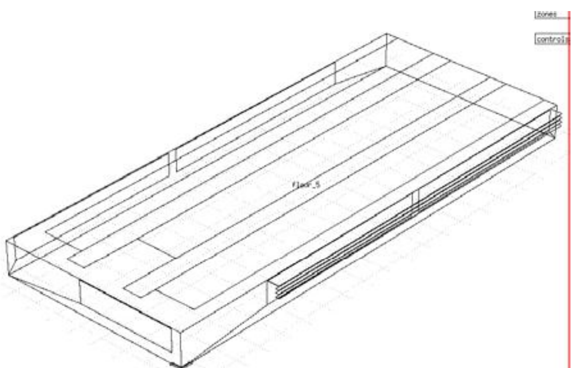

Figure 4: The ESP-r model of the building 5th floor

The exposed ceiling and the uncovered floor are made of concrete. The façade is insulated according to the Czech standard (u = 0.36 W/m^{2}K) and the windows have double glass (u = 1.3 W/m^{2}K; g = 0.5). The ceiling ribs are represented in the model by additional thermal mass. Only 80% of the real rib thermal mass was considered because of the 3D thermal transport while the surface area is equal to the ceiling plus ribs surface area.

Building model calibration

Proper values for the internal gains from office equipment are really lacking in computer simulation of office buildings. Although nameplate data from, for example, the actually used computers may be available, research shows that the real gains from this equipment may vary from 20 to 80% of the nameplate power (Duška 2004). In a well insulated and shaded office building with high occupant density, the nominal gain from equipment represents approximately 50% of all thermal gains. Obviously, the accuracy of dynamic building simulation becomes very questionable if there is so much uncertainty in one of the main input parameters.

Measured data were used to define the profile of internal gains due to office equipment. In first instance the model assumed ideal control of the indoor temperature. The set-point was derived from measured temperatures and the internal gains profile was altered to fit the cooling flux.

The figures present two sets of calibration results. Figure 5 (see end of the paper) is for the simulations with internal heat transfer coefficients of all walls based on the standard ESP-r buoyancy driven convection. For this model the zone cooling energy consumption, integrated over a two week calibration period, was almost the same as the measured one (102%). The internal surfaces temperatures are 2 °C above the air temperature and this does not really correspond to the measured values. Figure 6 (see end of the paper) shows the second simulation in which the mixed flow heat transfer functions based on the Fisher and Alamdari-Hammond models (Beausoleil-Morrison 2000) were used. The surface (floor and ceiling) temperature represents the reality much closer, but now the predicted cooling energy consumption is different from the measured (114%).

The result of the building model calibration is the profile of internal gains for a working day (Figure 7). The occupancy was defined as it was monitored and the lights were considered to be permanently switched on. The gains from the equipment (mainly PCs) were adjusted to 34% of their nameplate value according to the measured air temperatures and energy consumption. Note that the beginning of working hours was set to 6 a.m. due to the summer daylight saving time.

Plant model description

Next, the building model was extended with an explicit plant system model (Figure 8). This model comprises ducts, heat recovery, fan and cooling coil. To be able to control heat recovery bypass, a second branch with duct and fan was added. The control of the system consists of three loops. The first loop is a PID controller for the cooling coil flux in order to guarantee the air temperature in the zone (senses temperature in the return duct). Then there are two

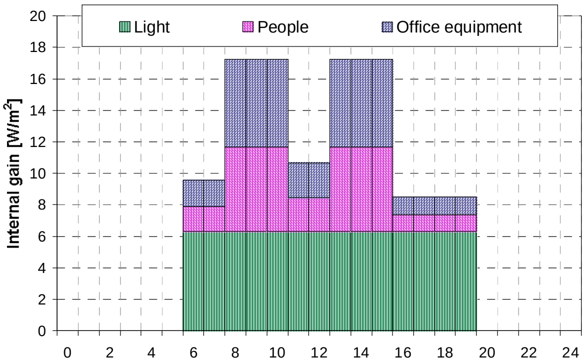

Figure 7: The internal gains profile for 1 day

ON-OFF controller loops, switching between the heat recovery and the bypass according to the outdoor temperature; the heat recovery is on only if the outdoor temperature is below 22 °C.

Plant model calibration

The plant model was calibrated as well. The component containments and heat gains were especially set up for the supply from outside to the air handling unit (AHU). The reason is that during the measurements it was found that the supply air temperature to the AHU was much higher than the outdoor temperature measured at a distance from the building. This strongly influences the performance of the night ventilation. The control law and the control set up was calibrated. The calibration results (Figure 9, see end of the paper) show similar indoor temperature and cooling flux to the zone. When comparing simulation results with measurements in a real building we should not expect a perfect fit. There are too many uncertain parameters (e.g. material properties) and unknown variables because they are not monitored (e.g. openable windows). Also the real system sensors are not very accurate. Finally, an office is not really a well mixed zone; at any point in time there may be air temperature differences within the office up to 1.5 °C.

Modeling the operation strategies

The calibrated building and plant models were simulated using Prague reference year weather data to find out the operation schedule with the lowest overall energy consumption. It is important to include the electricity consumption for fans and chiller (cooling water source). The overall COP of the chiller system was assumed to be 2.5 (usually 1.5 to 4). Fan electricity consumption grows exponentially with flow rate, therefore just comparing cooling energy consumption does not represent the systems properly. The energy consumption of the fan was calculated as a function of flow rate. The equation is based on data provided by the AHU manufacturer (Figure 10).

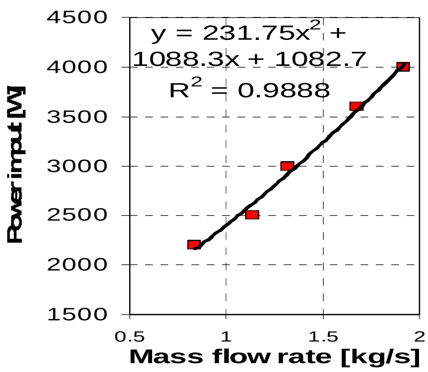

Figure 10 The fan el. energy input curve fitting

In total, ten operation scenarios were simulated. The system allows three flow rates 0.62 m^3/s, 1.06 m^3/s

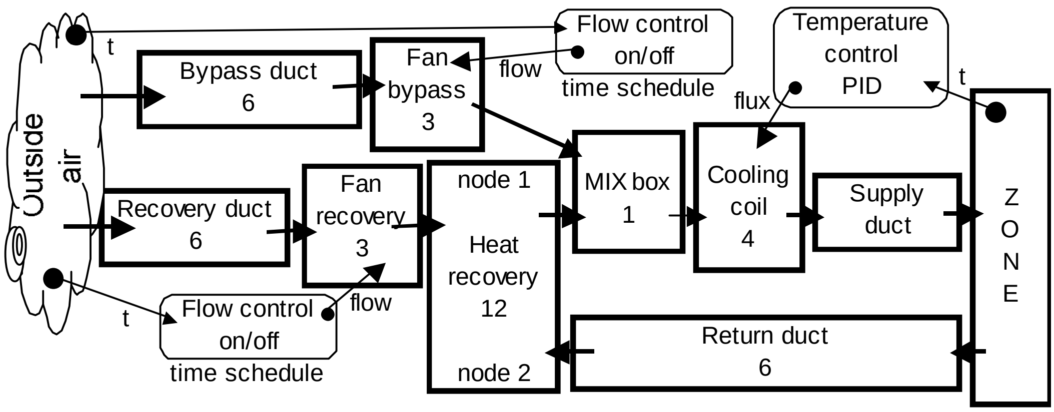

Figure 8: The plant system scheme with ESP-r component numbers

and 1.49 m^3/s and the control recognized four periods (from midnight till the beginning of working period, working hours, period of peak outdoor air temperatures, and after working hours till midnight). In the first six simulations various combinations of flow rates and time periods were tested. For the next five cases the cooling coil capacity was reduced.

Case 10 actually represents operation of the building without any cooling. For comparison, the Case FC represents the performance of the same building without thermally active ceiling (added insulation on inside surface) and floor (carpet) when just a minimum of fresh air is supplied during working hours and cooling is provided by a fan-coil system.

Results analysis

Changing the flow rates during the day and night does not influence the overall energy consumption strongly as can be seen from the results for the Cases 0 to 5 in Table 1. Although the coil cooling energy consumption decreases considerably with higher flow rates, the higher energy consumption of the fan results in small differences in total energy consumption (Figure 11). In the cases with limited cooling coil capacity (Cases 6 to 10), the overall energy consumption decreases. In the cases when the cooling capacity was limited to 5 kW or to zero

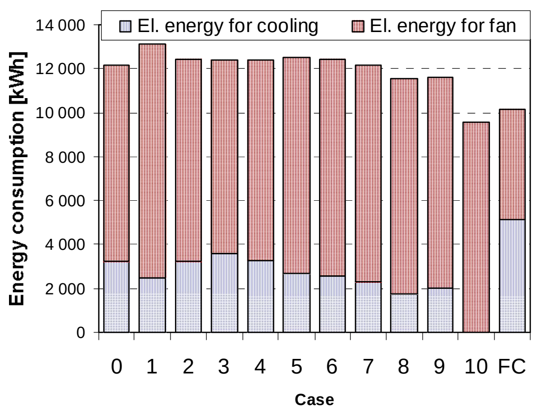

Figure 11: Comparing el. energy consumption over whole summer for all simulated test cases.

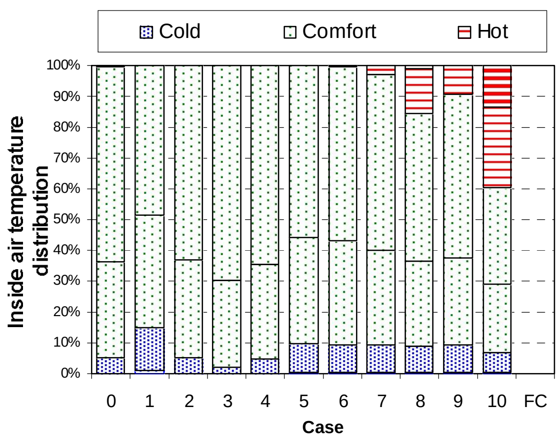

Figure 12: The indoor air temperature distribution.

(Cases 8 and 10) the indoor air temperatures are above the thermal comfort limits for a significant part of the summer period, which is not acceptable (Figure 12).

Finally, the Case 9 can be recommended, in which a reduced flow rate of 1.06 kg/s is applied over 24 hours during week days and the cooling coil capacity is limited to 7 kW. For the given weather data, the total energy consumption is estimated at 11.6 MWh representing a 12% reduction compared to Case 1. The indoor air temperatures would not exceed 28 °C at any time. The indoor temperature distribution (Figure 12 and Table 1) shows that there are some considerable periods with too low indoor air temperatures. This is mostly due to the fact that the plant system model is set up to consider cooling mode only. The simulations started at the beginning of May and ran until the end of September, but in May and September there are still some cooler days when the heating mode would be needed.

From the results for the Case FC (fan-coil and building without active thermal mass) it is clear that the cooling energy consumption would be much higher for the fan-coil system, but the overall electricity consumption would be the lowest of all cases. The chiller capacity for the fan-coil system is 27 kW, it is almost 3 times more than the optimized top-cooling system. The investments and maintenance costs for the chiller will be therefore much higher.

CONCLUSIONS

To design low energy cooling using night ventilation, computer simulation is a very important tool for predicting comfort without mechanical cooling and/ or the required cooling capacity for hybrid systems.

Internal gains from office equipment are very important in the thermal balance of office buildings. In reality the thermal gain from office computers and such is much lower than the power input on the nameplate.

Design and commissioning of low energy systems is usually more complex than for standard HVAC systems. It requires better cooperation of all participants in the building design, construction and maintenance. Unfavorable experiences with some realized systems are mostly due to the lack of information exchange. Sometimes during construction a system is simplified in such a way that it is not able anymore to work properly. Also, the systems are often operated without any knowledge about its principles.

In top-cooling and all-night ventilation systems the electrical energy consumption of the fans is very important. Due to the relatively high COP of mechanical cooling systems, even large cooling energy savings by night ventilation can be counter balanced by the electrical energy consumption of the fans. The system should be designed with low pressure losses in order to reduce the fan energy consumption.

Finally, the operation of a top-cooling (or night cooling) system should be optimized using both measurements and computer simulations.

REFERENCES

Barnard N. and Jaunzens D. 2001. Low Energy Cooling – Technology Selection and Early Design Guidance, Building Research Estabilishment Ltd, London.

Behne M. 1997. Alternatives to Compressive Cooling in Non-Residential Buildings to Reduce Primary Energy Consumption, Final report, Lawrence Berkeley National Laboratory, Berkeley, California.

Dvořák J. 2002. Hlavní správa ČEZ: noční chlazení, in Proc. Simulace budov a techniky prostředí 2002, IBPSA-CZ, p. 15 - 17.

Duška M., Drkal F. and Lain M., 2004. Tepelné zisky z vnitřních vybavení administrativních budov, Vytápění, Větrání, Instalace journal, p. 198-201.

Heap R.D. 2001. Refrigeration and air conditioning – the response to climate change, Bulletin of the IIR-2001-5.

Liddament M.W., 2000. Low energy cooling, ECSU, Coventry, UK.

Beausoleil-Morrison I. 2000, The Adaptive Coupling of Heat and Air Flow Modelling within Dynamic Whole-Building Simulation, PHD thesis, University of Strathclyde, Glasgow UK.

Santamouris M. and Asimakopoulos D. 1996. Passive Cooling of Buildings, James & James Ltd., London.

ACKNOWLEDGEMENT

This work was supported by the Czech Ministry of Education through the Research Plan MSM6840770011.

*Table 1. The simulated cases and results for system control strategy optimizing (*means the results are just over working period)*

Test case		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**FC**
Start of day operation	hour	5	5	5	8	5	5	5	5	5	5	5	7
End of day operation	hour	22	22	22	20	20	20	20	20	20	20	20	21
Day time mass flow rate	kg/s	1.06	1.49	1.49	1.49	1.49	1.49	1.49	1.49	1.49	1.06	1.06	0.72
Night time mass flow rate	kg/s	0.62	0.62	0.62	0.62	0.62	1.06	1.06	1.06	1.06	1.06	1.06	0
Peak time flow rate	kg/s	1.06	1.49	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06	0
The cooling coil limit	kW	no	no	no	no	no	no	15	10	5	7	0	no
Results													
Total cooling energy to zone	kWh	19 490	20 204	19 531	19 283	19 479	19 906	19 844	19 699	19 447	19 554	18 691	12 844
Average air temperature	°C	23.1	22.5	23.0	23.2	23.1	22.7	22.7	22.8	23.1	22.9	23.8	23.7
Average air temperature (*)	°C	23.5	22.9	23.5	23.7	23.5	23.2	23.3	23.4	23.7	23.6	24.5	24.0
Max. air temperature (*)	°C	26.3	25.8	25.8	25.9	25.8	25.8	26.1	26.9	28.9	28.0	31.7	24.5
Min. air temperature (*)	°C	18.6	17.0	18.6	19.4	18.7	17.8	17.8	18.3	18.3	18.3	18.3	18.6
Cooling coil total energy	kWh	8 079	6 274	8 050	9 062	8 224	6 695	6 412	5 789	4 333	5 124	0	12 843
Cooling coil max. capacity	kW	19.6	19.6	19.8	19.8	19.8	19.6	14.9	10.1	5.2	7.0	0.0	27.4
Average supply air temp.(*)	°C	17.3	18.6	18.1	17.8	18.1	18.5	18.6	19.0	19.8	19.1	21.3	
Number of operation hours	hour	972	734	932	1 055	958	819	861	967	1 172	1 075	118	1 528
El. energy for fan	kWh	8 914	10 620	9 207	8 743	9 115	9 842	9 842	9 841	9 839	9 549	9 546	5 034
El. energy for cooling	kWh	3 232	2 510	3 220	3 625	3 290	2 678	2 565	2 315	1 733	2 050	6	5 137
El. energy total	kWh	12 145	13 130	12 427	12 368	12 405	12 520	12 407	12 157	11 573	11 598	9 552	10 171
Cooling coil total energy	kWh	129%	100%	128%	144%	131%	107%	102%	92%	69%	82%	82%	205%
El. energy total	**kWh**	**93%**	**100%**	**95%**	**94%**	**94%**	**95%**	**94%**	**93%**	**88%**	**88%**	**73%**	**77%**
Temperatures distribution (*)													
less than 20	hour	0	11	0	0	0	3	3	3	3	3	3	
from 20 to 22	hour	66	173	66	27	60	117	115	115	111	113	85	
from 22 to 24	hour	390	459	396	355	387	432	423	385	345	356	277	
from 24 to 26	hour	793	611	792	872	807	702	710	717	600	665	390	
from 26 to 28	hour	5	0	0	0	0	0	3	34	184	117	330	
more than 28	hour	0	0	0	0	0	0	0	0	11	0	169	

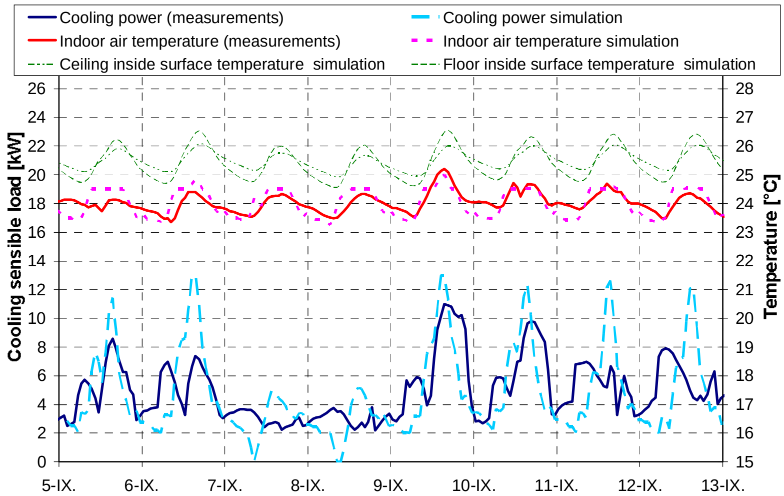

Figure 5: Comparison of measured and simulated cooling flux and temperature (basic heat transfer coefficients)

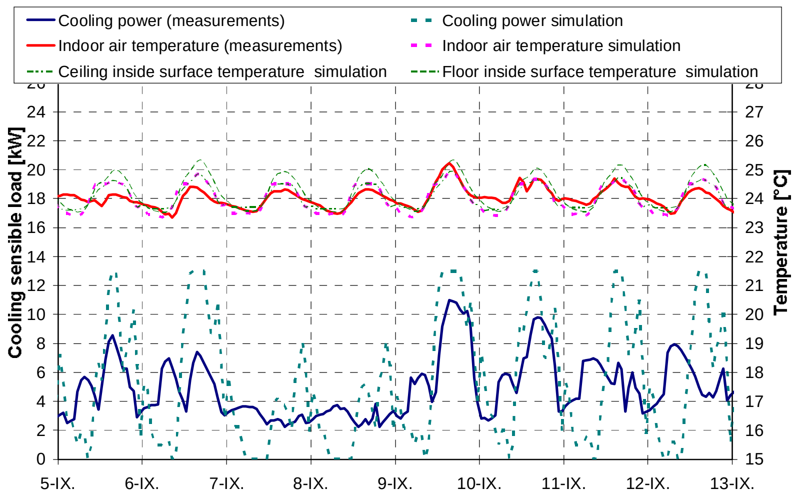

Figure 6: Comparison of measured and simulated cooling flux and temperature (system extended heat transfer coefficients)

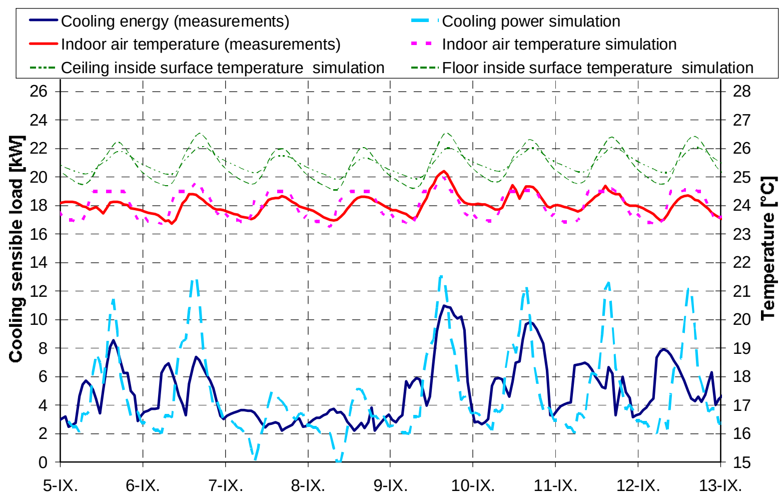

Figure 9: The building with plant system calibration results