Low Energy Cooling for buildings in the middle Europe -case studies

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Abstract
This paper deals with the applicability of passive and low energy cooling technologies in the Czech Republic. The work includes climate analysis as well as buildings and systems analysis in order to estimate the potential of passive and low energy cooling technologies. The latter is based on case studies, which include both building simulation and monitoring. The role of computer simulation in low energy building design and optimisation is briefly discussed.

Key words:
Cooling, computer simulation, low energy

1. Introduction

Buildings consume approximately 40 to 50 % of primary energy in European countries. Energy consumption for cooling represents approximately 10 % of the total consumption for commercial office buildings. The percentage of fully air-conditioned office floor area is increasing in Europe, especially in the Czech Republic, where full air conditioning is the current de facto standard in new or reconstructed office buildings. The increasing use of information technology has led to an increasing demand for cooling in commercial buildings. Cooling thus accounts for a significant proportion of the total energy consumption in buildings, and its impact on greenhouse gas emissions is enhanced by the fact that these cooling systems are usually electrically driven (Santamouris 1996, Heap 2001). The electricity in the Czech Republic is mostly produced by coal power plants.

1.1 Low energy and passive cooling technologies

Low energy cooling technologies provide cooling in an energy efficient manner, thus reducing 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).
Low energy cooling technologies can be divided into two groups: those including the main source of cooling and those that focus solely on delivery of cooling to the treated space (IEA 1995, Liddament 2000).
The first group of systems rely on natural sources of cooling, but fans or pumps are required for most of them. Examples of such technologies are:

- Night ventilation
- Evaporative cooling
- Ground cooling

The second group of technologies focus on delivering the cooling to the treated space in an efficient manner, those technologies usually work well with lower grade sources of cooling.

1.2 Research methods

Most low energy cooling technologies are strongly dependent on climate. Therefore a climate analysis was carried out to assess applicability and efficiency of these technologies. The analysis is based on a test reference year for Prague, which in itself was derived from 15 years of hourly data.

The second method, which was used to find out the potential of various low energy cooling technologies, is a review of existing exemplary buildings, at other regions with similar climate, buildings and systems.

The last but not the least method is building simulation. For passive and low energy cooling technologies, the dynamic behaviour and interactions of building, systems, occupants and environment is very important. To design such systems and verify its performance the standard design methods based on peak gains are not suitable. In contrast to the traditional simplified calculating methods (not considering the system dynamics), computer based modelling approaches reality much closer. The use of computer modelling and simulation for the design and evaluation of buildings and HVAC is quickly moving from the research and development stage into everyday engineering practice. For most of the presented studies the ESP-r simulation software was used; in some cases combined with other software.

2. Climate in the Czech Republic

The Czech Republic is an inland country located in the middle of Europe. The capital and also the biggest city is Prague. Most governmental and business offices are located there. The Czech climate can be described as warm (summer peak design temperature 32°C) and semi-humid (summer design moisture content 10 g/kg and wet bulb depression 9 K).

When comparing the Prague climate to other cities, where some low-energy cooling studies have been carried out, it was found that the summer climate is very similar to Berlin (Figure 1). Therefore the Berlin summer results and experiences can be used for preliminary studies for Prague.

For evaporative systems enthalpy hours are defined which take into account the humidity of the air (IEA 1995). The cooling degree hours (CDH) and enthalpy hours (EH) were calculated twice, using two different reference temperatures, namely 18°C (index 18) and 25°C (index 25). The reference relative humidity for calculating enthalpy hours was 40%. Enthalpy hours and cooling degree hours for Prague are compared to some other towns in Table 1.

Table 1 Cooling degree hours and enthalpy hours

Town	CDH_{25}	$EH_{25/40}$ (kJ/kg_{DA})	CDH_{18}	$EH_{18/40}$ (kJ/kg_{DA})
Prague	361	3 047	4 581	25 198
Dresden	527	3 040	5 154	28 068
Stockholm	150	1 350	1 000	16 425
Zurich	426	1 658	4 757	16 380
New York	2 570	25 698	15 942	68 783
Toronto	837	12 294	7 643	40 831

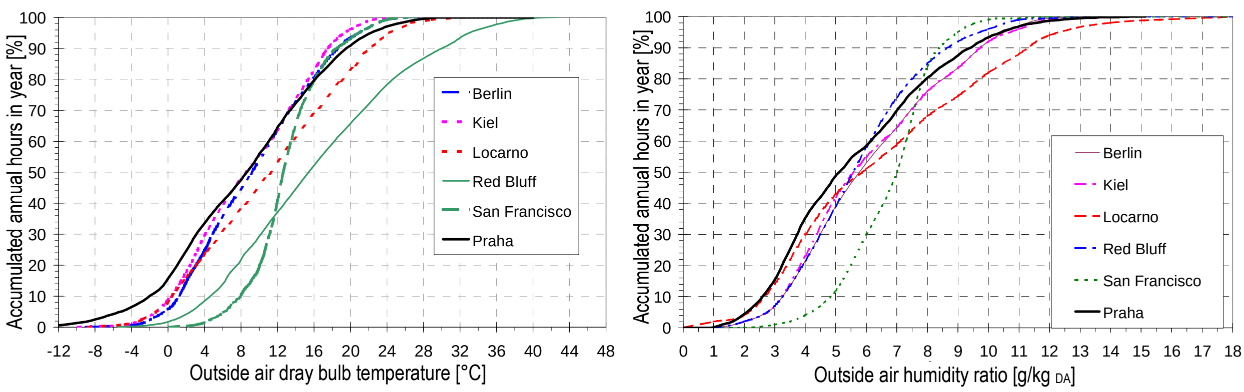

Figure 1 Cumulative distributions of the dry-bulb temperature (left) and humidity ratio (right) comparing Prague to five other climates (Behne 1997).

3. Industrial hall

This case study deals with energy balance and verification of indoor environment in existing factory building in Czech Republic. Objective of the energy simulation is to predict indoor environment parameters in the building based on the knowledge of internal heat gains. Up to now for industrial hall just heating and ventilation without cooling in summer was common praxis. Due to some very hot summer's (2003,2006) and request for better conditions for workers and technology leads to using air conditioning for industrial halls. The common design based just on the nominal internal gains and external gains leads to over sizing of cooling capacity and finally to high energy demand for cooling. More complex design, based on detailed analysis of internal gains and dynamic building model helps to rapidly decrease of investments and save a lots of energy.

3.1 The building

The solved hall is an existing single-storey building located in the Czech Republic close to Germany borders. Main unit of the building is a hall with kilns. The model of the hall deals with kiln hall energy balance with focus on summer extremes. The building constitutes of steel concrete basement slab and internal walls, which are made of bricks. Ceiling of the hall is insulated and there is a roof space above it. From day lightning reasons the western and eastern facades are fenestrated.

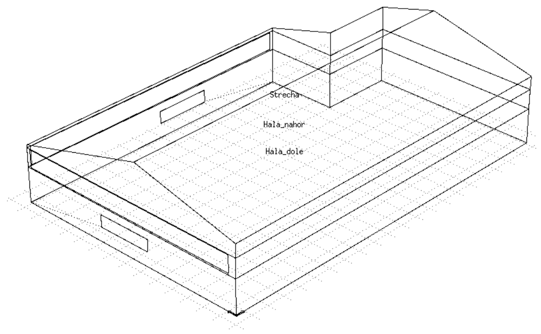

Figure 2 Model of the hall in ESP-r

3.2 Ventilation and infiltration

Mechanical ventilation of the kin hall was considered for energy simulations. In total 50 000 m^3/h (16.67 kg/s) of air was supplied into the hall. If outside air temperature was lower than 23 °C only outside air was supplied; if outside air temperature was higher than 23 °C only 16 000 m^3/h (5.33 kg/s) of outside air was supplied and the rest i.e. 34 000 m^3/h (11.33 kg/s) of air was circulated from the upper part of the hall.

Combustion air sucked from the lower parts of the hall was exhausted via smoke flue to the outside (10 000 m^3/h, i.e. 3.33 kg/s). The rest of air was exhausted to the outside from the upper parts of the hall.

3.3 Internal heat load of the building

Thermal environment in the hall was analysed for the common activity in the hall. Since influence of interior heat load is significant, its determination was done as accurately as possible. The determination of internal heat load of particular machines was based on three correction coefficients:

The coincidence factor reflects operation simultaneity of individual machines. The operation of electric furnace was continuous and the coincidence coefficient was set to 1.

The utilization factor takes into account actual operation consumption that could significantly differ from maximum nameplate value. The total power input of selected electric furnace on the hall was corrected (based on field experiment) by average utilization coefficient of 0.3.

The residual coefficient is applied in cases when part of heat gain is not transferred into the hall (and it is directly extracted e.g. by exhaust hood or by water cooling). The electric kilns were connected to smoke exhaust and considered by residual coefficient. 2000 m^3/h of air was exhausted from each kiln with temperature of smoke of about 140 °C (measured). The residual coefficient was 0.34.

Six electric furnaces were considered in numerical predictions with nominal power input of 360 kW each.
Isolated ducting for venting is located in the upper part of the hall. Thus part of the heat exhausted from the kilns was transferred to the hall space through faces of ducting. Average exhausted gas temperature was 140 °C, air temperature in the upper part of the hall was anticipated of 30 °C.

Table 2 Internal heat load of the hall

Heat source	**Internal heat load**	
	kW	**W/m^2**
Technology (kilns)	208.1	196.2
Technology (venting)	9.2	8.67
Lighting	10.37	9.8
Workers	1.8	1.7
Total	**229.5**	**216.4**

3.4 Modelled zones
Since the focus was on energy balance in the hall (where temperature stratification exists) a three-zoned numerical model was designed:

- The lower part of the hall (up to 3.9 m) -1061 m^2 4140 m^3
- The upper part of the hall 1061 m2 2282 m^3
- The roof space above the hall

The shape of zones was identical to existing hall.

3.5 Results and discussion
According to Czech standards that determines conditions for health protection of workers, based on type of work. The results were analysed for thresholds of operative temperature mean of 26 °C and maximum of 32 °C.
The result sets are represented for 4 variants of operation and leads to optimise cooling capacity of the chiller.

Variation 1
It is air conditioning when the operative temperature is usually around 26 °C and its maximum is 26.4 °C. Required working thermal conditions was provided in the occupied zone for the whole summer period. The required sensible cooling output was max. 232.5 kW and consumption of the cooling 152 MWh. Relative humidity was in a range of 55 and 80 % and the values over 55 % were only rare. Results show that the use of adiabatic cooling would not lead to reduction of required cooling output and only marginally reduce annual energy consumption by about 8 %.

Variation 2 (figure 3)
The cooling output was reduced to 186 kW and air temperature in the zone increased in summer extremes (up to 26°C) as well as the analysed operative temperature when the. Maximum operative temperature was 29.1 °C, however operative temperature of 27 °C was exceeded only for 181 hours i.e. for 5 % of the summer. Operative temperature fluctuated mainly below 26 °C (78 % of the summer). Since the maximum tolerable temperature is 32 °C such working thermal conditions could be designated as acceptable. Thus it is not necessary to reduce the working time or to shorten working shifts. The cooling consumption was 146 MWh.

Variation X1
This variant with very limited output of mechanical cooling (50 kW sensible cooling output) and with intensive outdoor air supply (50 000 m^3/h) shows the air temperature in the hall were below 26 °C for a half of summer period and only 7 % of summer above 32 °C. Maximum temperature was 36 °C.

Variation X2
Representing the current stage when the hall is cooled by reduced cooling output 50 kW and ventilated by 16 000 m^3/h of outdoor air. This Variant showed unacceptable thermal working conditions in the hall. Air temperature exceeded 32 °C for most of the summer period and in extremes reached up to 46 °C, what correspond to current stage measurements.

3.6 Conclusions
In order to provide high standard of thermal working environment the cooling output of cooling coil is recommended to be 200 kW. Required total supply and combustion airflow is 50 000 m^3/h. Adiabatic cooling will not reduce required cooling capacity and it may save up to 8 % of running costs. Thus adiabatic cooling is not recommended in this case. The study helps to decrease the cooling capacity and prevent the over sizing of the whole system, original concept was based on nominal power input of kilns and no dynamic behaviour and capacity of chiller was 500 kW.

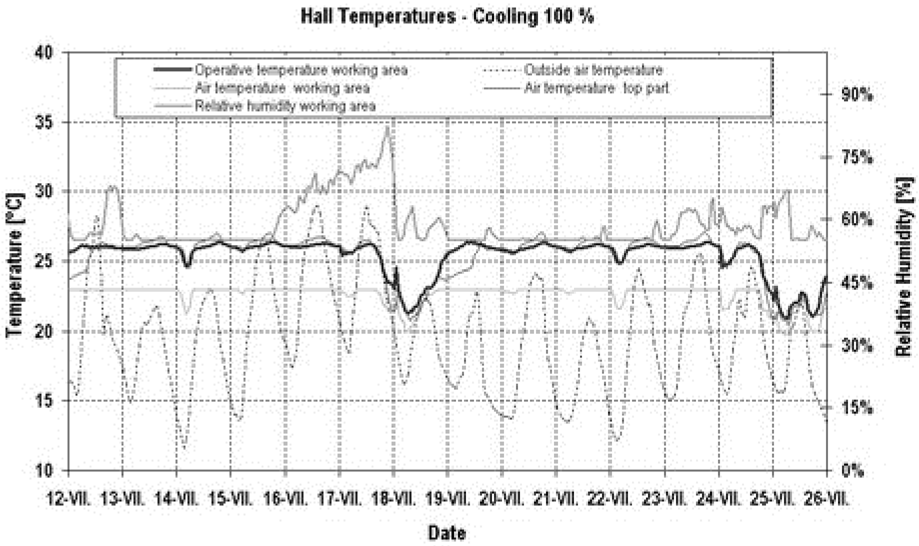

Figure 3a Temperatures in the hall variation 1 for selected period

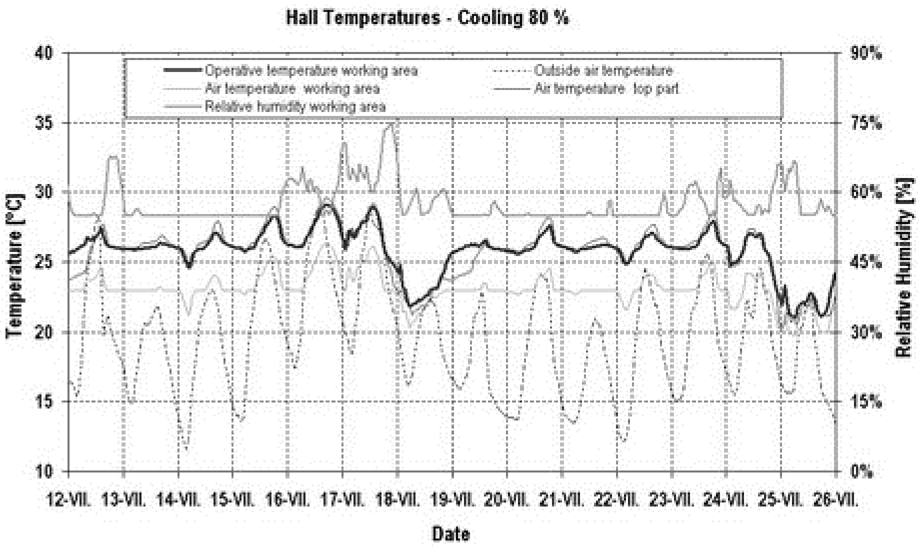

Figure 3b Temperatures in the hall variation 2 for selected period

4. Slab cooling in the new technical library building

4.1 Building concept

Technical library is a multi-storey object (6 floors and 3 undergrounds), which will be built in Prague 6 - Dejvice. The building is divided to the several functional units. The main part of the building, the public library, is located in over ground floors (2^{nd} – 5^{th} floor). The roofed atrium is integrated in the middle of the building (1^{st} – 5^{th} floor) and also two little opened roof lights are placed in 5^{th} floor. There is parking in the underground floors. The building consists of steel concrete frame; internal walls are made from gypsum partition or glassed wall. Double envelope façade is used. External envelope consists of glazed components “Profilit“. Internal facade is light with high ratio of glazing.

4.2 HVAC system concept

The slab cooling is introduced to ensure thermal comfort in the main library hall and study rooms. This system consists of a serpentine heating/cooling pipe embedded in the concrete massive ceiling. The thermal mass of the ceiling slab is therefore cooled by water.
The supply airflow can be therefore limited to the fresh air requirements. The fresh conditioned outdoor air is distributed in the building. All air is exhaust via the atrium to the exhaust openings under the roof. Natural ventilation by windows is supposed in the offices (north-east façade) in 2^{nd} – 5^{th} floor. The air change in offices is 2 h^{-1} during the day and 5 h^{-1} in the night is expected.
Condensation risk is one of the main issues in radiant cooling systems. The inlet water temperature for the cooled ceiling has to be such that no surface condensation will occur (i.e. the ceiling surface temperature has to be higher than the room air dew point temperature). Therefore the surface temperature must be kept higher than for the lightweight systems. In Czech offices with no additional moisture sources the maximum dew point temperature is about 16°C. This is why for real systems the supply water temperature usually varies from 16 °C to 20 °C.
For computer rooms, and the restaurants and shops there is a common fan-coil system applied, because of the needed cooling capacity. The idea is that the cooling source (chiller) will be operated during peak gains (daytime) for fan-coil systems and during of-peak period (night) for slab cooling system. This lead to significant decreasing of needed chillier capacity.

4.3 Ventilated double facade

The selected South part of the ventilated double skin façade was modelled, to verify the proper ventilation. Model was vertically divided to 6 zones the outside facade is single glass, and the inside one double glass, there is internal shading element in each zone (floor). The flow network representing natural stack effect and wind driven flow was introduced to the model.

4.4 Building model

Computer model solves the energy balance of the public library area (2^{nd} – 5^{th} floor) with focus on extreme summer conditions. The verification of the system cooling performance was the main goal of the energy simulation
In a view of the fact, that the main accent was put on total energy balance in library space, the model was build up as whole building divided into 13 zones: public library (2^{nd} – 5^{th} floor), atrium (1^{st} – 5^{th} floor), office spaces (2^{nd} – 5^{th} floor), 2 reading rooms and 2 computer rooms. Two small roof lights in 5^{th} floor opened are a part of the model. The model was simplified, because of technical possibilities of using software. The geometry of the floors correspond with the real building shape, only curved facades had to be replaced with straight segments (Figure 4).

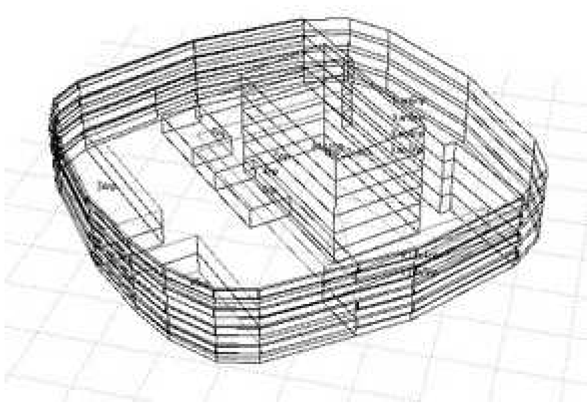

Figure 4 Model of the technical library in ESP-r software

4.5 Air flow model
Mechanical ventilation with constant airflow is supposed in the library. The temperature of the supply air is maximally 22 °C. If the outdoor temperature is less than 22 °C, the unconditioned outdoor air is supplied into the space. Also the ventilation of the offices is supposed in the model. The air changes in the offices are defined as:

- 5 h^{-1} when the outdoor temperature is in range 20 - 24 °C
- 3 h^{-1} when the outdoor temperature is in range 24 - 26 °C
- 1,5 h^{-1} when the outdoor temperature is less than 20 °C
- 0,7 h^{-1} when the outdoor temperature is higher than 26 °C

4.6 Heat loads of the zones
The internal heat gain schedule for a working day was entered for thermal environment analysis. The values of internal heat gains are approximately 13.4 W/m^2 in library and 70 W/m^2 in computer rooms. Heat gains operation is supposed during the library open time from 7 am till 9 pm.

4.7 Slab cooling model
The cooled ceiling with thermal storage into the building structure (concrete activation) – slab cooling will be used in the library and reading rooms. The cooling capacity of 40 W/m^2 is supplied into the concrete slab (at a depth of 150 mm) during the night (from 8 pm till 8 am). The temperature of cooling water is 18/21 °C; the spacing of pipe is 150 mm. The slab cooling area is less that total ceiling area. The slab cooling covers approximately 71 % of the ceiling. In the view of the simulation results, the concrete activation was completed with one hour during the day (1.30 pm – 2.30 pm).
The air temperature in computer rooms is set up to 26 °C (air-conditioned rooms) during the open time of the library from 7 am till 9 pm). No cooling in offices was reflected. The computer energy simulation determines the necessary sensible cooling performance to air temperature observance (26 °C).

4.8 Results
The simulations were focused on summer only, with simulation period from May till September. Only cooling operation was reflected, therefore decreasing of air temperature can get in May or in September (no heating regime during the simulation is supposed). Results of the simulation (Figure 5) are expected internal air temperatures, and cooling energy requirements. To find the optimal operation of the HVAC system there was 10 variants of slab cooling and ventilation operation simulated presented is just the final one.

4.9 Conclusions
The double facade results approved, the temperature in ventilated double facade is closed to outside temperature. To keep onside air temperature below 27 °C it is necessary to cool the slab by the chilled water not only during the night, but also at least one hour during the day, if the library is fully operated

in the summer peak. The computer simulation approved the HVAC system concept and helped to find out the operation strategy for the building.

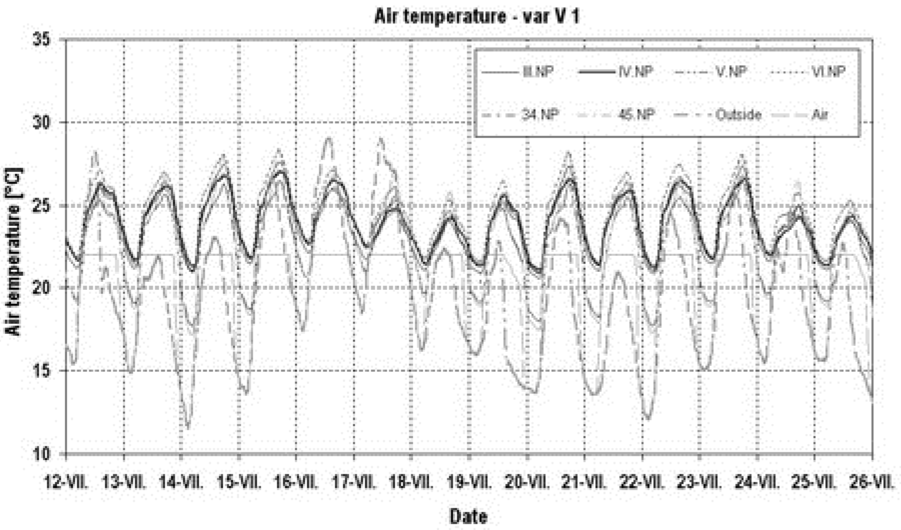

Figure 5 Air temperatures in library rooms for selected period

5. Night ventilation

There is a high potential for night ventilation in the Czech Republic. As can be seen in Figure 6, the difference between maximum day temperature and minimum night temperature is usually more then 10 K. (The mean daily temperature range is 11.6 K). Also, the minimum night air temperatures are well below 18 ºC.

Not only night ventilation but also daytime ventilation can be used for cooling purposes in the Czech Republic. During 93 % of the cooling season the outside air temperature is below 24 ºC. For working hours this is 94 percent.

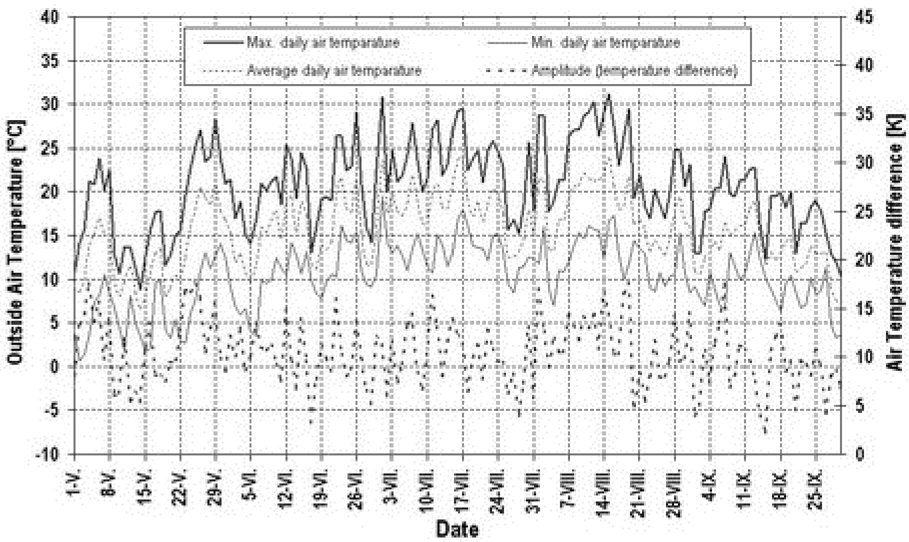

Figure 6 Air temperature difference in Prague during the cooling season.

The most common air-conditioning system nowadays consists of fan coil units in combination with a minimum of centrally treated fresh air supply (50 m3/h per person which equals about 2 ACH). Even this small amount of external air can be used to reduce the cooling loads and energy consumption by night ventilation as can be seen in the following example.

5.1 New bank head office

For a new large bank head office in Prague, computer simulations were carried out to find solutions for reducing the required cooling capacity. Because the design included exposed concrete ceilings, the idea was to apply building thermal mass and find out a way, how to operate the building.
For the 13 000 m^2 building with 4 floors the cooling capacity was initially estimated at 3 MW. The simulations proved that if the air temperature set point would be 24 °C and the cooling capacity would be limited to 81 %, the inside air temperature will not exceed 26 °C.
If mechanical night ventilation would be applied, the cooling energy consumption decreases by 24% (from 1.6 GWh to 1.2 GWh).

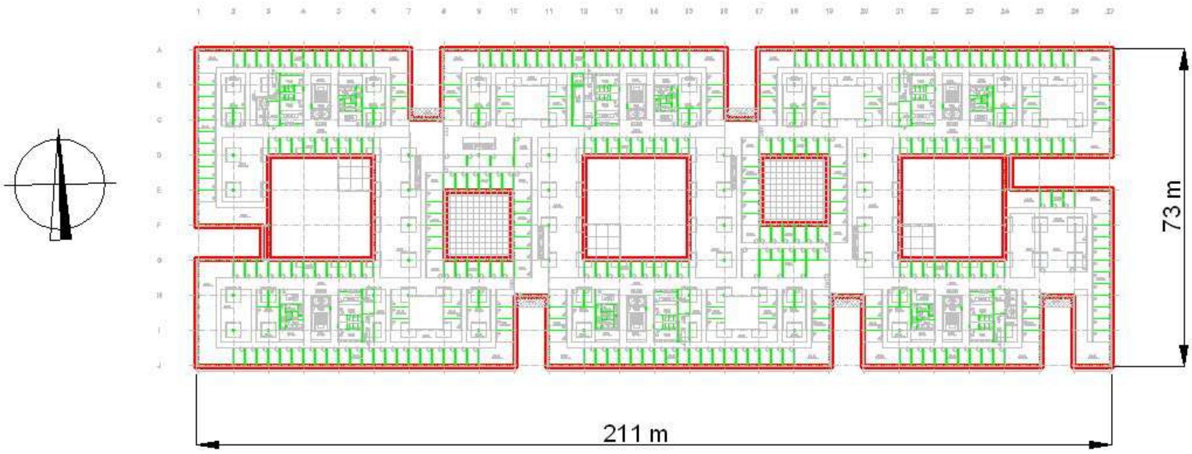

Figure 7 Ground plan of the office building

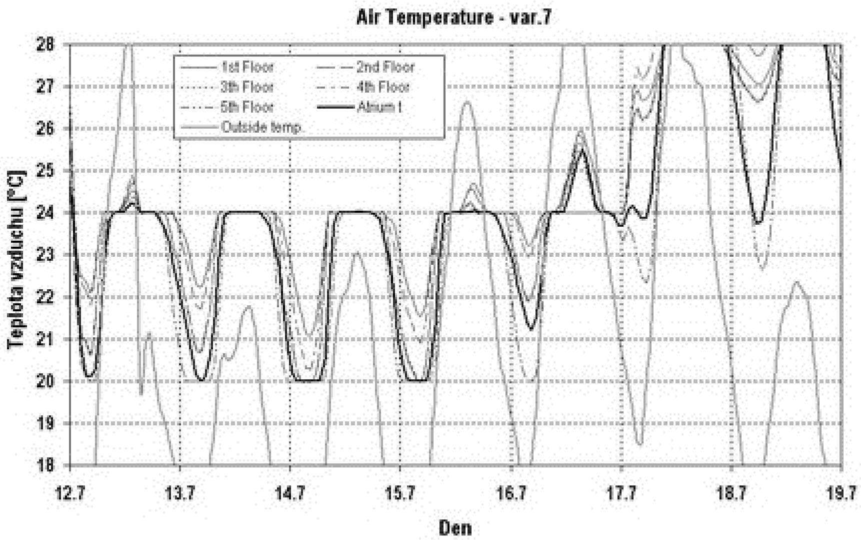

Figure 8 Inside air temperature in the bank office during a peak summer week

Evaporative cooling

Applicability of direct evaporative cooling in office or residential buildings is limited due to thermal comfort considerations. If the maximum internal air temperature is 26 °C and humidity is 60%, the enthalpy of the external air should not exceed 52 kJ/kg. Analysing the climate data it was found that there are 180 working hours when the outside enthalpy exceeds 52 and 82 hours when 26°C is exceeded as well. This is a considerable part of the cooling season. That is why direct evaporative cooling is usually combined with another cooling technology, in order to provide comfort throughout the whole year. The maximum capacity of the chiller would not decrease significantly, if such a hybrid

system consists of a direct evaporative cooling device and standard chiller. However, the number of operation hours and energy consumption decreases markedly (Lain 2003).
For spaces with higher required humidity (some industrial and agricultural applications) evaporative cooling is more suitable as became clear from a study for a new Indonesian jungle pavilion in the Prague Zoo. Water sprayed into the pavilion interior decreased the maximum cooling load from 215 kW to 160 kW. The time when the cooling system would be in use was reduced from 2000 hrs to about 1000 hours per year (Barták 2001).
For indirect evaporative cooling the situation is similar, for the few hours in the year, the outside air enthalpy is so high that the system would not work.
Although the Czech climate is semi-humid, dehumidification is not needed for non-industrial buildings. Most air-conditioning systems incorporate some dehumidification by means of cooling coil condensation. If there is no condensation (or dehumidification) anywhere in the system the inside humidity exceeds the recommended maximum as can be seen in Figure 9 (Lain 2003).

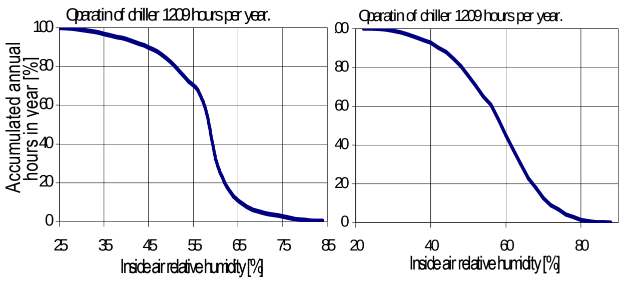

Figure 9 Cumulative distribution of indoor relative humidity for all air system (right) and indirect evaporative cooling (left)

6. Conclusions

The benefits of using low energy and passive technologies are potentially very high in the Czech republic. Although there exist no major technical barriers, these technologies are not rapidly introduced due to economic reasons. Often proper use of fresh air, careful design, commissioning and operation of the system leads to better energy saving then some applications of not properly designed and operated low-energy cooling technologies.
The design and commissioning of low energy systems is usually more complex then using standard air-conditioning. It requires better cooperation of all participants in the building design, construction and maintenance. Bad experiences with some systems are mostly due to lack of information exchange. Advanced design methods (such as computer simulations) are already established in the Czech Republic, but the design fees (specially for HVAC system design) are usually not adequate for such complex methods. Most large buildings in the Czech Republic are constructed by developers, who are primarily interested in decreasing investment costs and who do not particularly care about operational costs (energy consumption). It is up to building owners/users and legislation to drive the concern about building and system performance.

Acknowledgement

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References

Barták, M., Drkal, F., Hensen, J., Lain, M. et al., 2001, Simulation for (Sustainable) Building Design: Czech Experiences, Clima 2000 – Napoli, Milan, p. 354-363.
Bartak, M., Drkal, F., Hensen, J., Lain, M., 2001, Design Support Simulations For The Prague Zoo "Indonesian Jungle" Pavilion, BS 2001, IBPSA, p.841-845.
Behne, M., 1997, Alternatives to Compressive Coolingin Non-Residential Buildings to Reduce Primary Energy Consumption, Final report, Lawrence Berkeley National Laboratory, Berkeley, California.

Heap, R.D., 2001, Refrigeration and air conditioning – the response to climate change, Bulletin of the IIR-2001-5,
IEA, 1995, Review of Low Energy Cooling Technologies, Natural resources Canada, Ottawa, Canada, 88 p.
Lain, M., Duška, M., Matějíček, K., 2003, Applicability of Evaporative Cooling Techniques in the Czech Republic, Proceedings 21st International Congress of Refrigeration, Washington DC, IIR Paris.
Lain, M., Drkal, F., Hensen, J., Zmrhal, V., 2004, Low Energy Cooling Techniques for Retrofitted Office Buildings in Central Europe, Ventilation and Retrofitting Prague, AIVC Brussels, p. 79-84.
Liddament, M.W., 2000, Low energy cooling, ESSU, Coventry, U.K., 32 p.
Santamouris, M., Asimakopoulos, D., 1996, Passive Cooling of Buildings, James&James Ltd., London, U.K., 472 p.