Low energy cooling of buildings in central Europe - case studies

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Abstract
This paper addresses the applicability of passive and low energy cooling technologies in the Czech Republic. The main research methods are climate analysis and buildings and systems analysis, both with the objective to assess the building performance potential of passive and low energy cooling technologies. The analysis is based on case studies, which include building performance simulation as well as in-situ monitoring. The role of computer simulation in low energy building design and optimisation is briefly discussed. The main results of this study are …………………………….

Key words:
Cooling, computer simulation, low energy

1. Introduction
In Europe, buildings consume approximately 40 to 50 % of primary energy. 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 energy sources such as ambient air or ground or by cooling with relatively high supply temperatures. These technologies could be called passive or 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 which incorporate the main cooling source 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 energy sources for cooling, but most of them need fans or pumps as well. 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 energy sources for 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 exemple buildings in other regions but with similar climate and building technology.
In addition to the above, computational dynamic building performance simulations were carried out. For passive and low energy cooling technologies, the dynamic behaviour and interactions of building, systems, occupants and environment is very important. For design and performance prediction of such systems, the traditional engineering design methods which are typically based on peak gains and extreme boundary conditions are not suitable. In contrast to 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 a land-locked country in central Europe. Its capital and also largest city is Prague. Most governmental and business offices are located there. The Czech climate can be characterized as warm (summer peak design temperature 32°C) and semi-humid (summer design moisture content 10 g/kg and wet bulb depression 9 K).
From comparison of the Prague climate with that of other cities for which low-energy cooling studies have been carried out previously, it was found that the summer climate in Prague is very similar to Berlin (Figure 1). Therefore the Berlin summer results and experiences can be used for preliminary comparative studies for Prague.
For evaporative systems enthalpy hours are considered because these 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%. Table 1 shows enthalpy hours and cooling degree hours for Prague are several other cities.

Table 1 Cooling degree hours and enthalpy hours for several cities

City	CDH_{25} (Kh)	$EH_{25/40}$ (kJ/kg_{DA})	CDH_{18} (Kh)	$EH_{18/40}$ (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

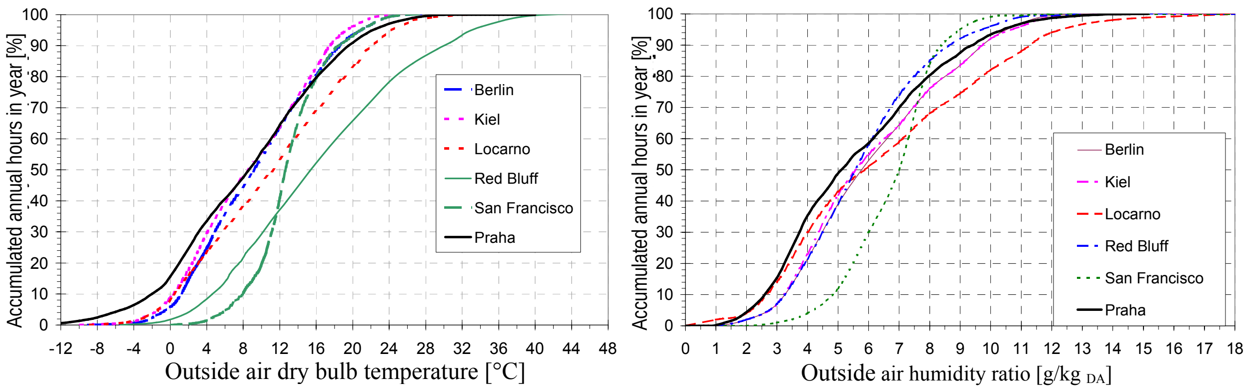

Figure 1 Cumulative distributions of the dry-bulb temperature (left) and humidity ratio (right) comparing Prague to five other climates (Behne 1997).

3. Factory hall

This case study is about the energy balance and indoor environment in an existing factory in the Czech Republic. The objective of the associated energy simulation is to predict the indoor environment in the building based on known internal heat gains. Until recently industrial halls were commonly only heated and ventilated without cooling during the summer. Due to some very hot summer’s (2003 and 2006) and increased demand for better working conditions nowadays air conditioning is increasingly used in industrial halls. The traditional design approach is based on nominal heat gains and thus often results in oversized cooling systems and subsequently in high energy consumption for cooling. Improved design methods, based on detailed analysis of heat gains and on dynamic building simulation will improve cooling system design resulting in lower initial costs as well as in lower energy consumption.

3.1 The building

The factory is an existing single-storey building located in the Czech Republic close to the German border. The main unit of the factory is a hall with kilns. The computational simulation of the hall focuses on the energy balance during hot summer weather. The building has a heavy concrete floor and brick internal walls. The ceiling is insulated and there is a roof space above it. There are windows in the west and east walls for daylight reasons.

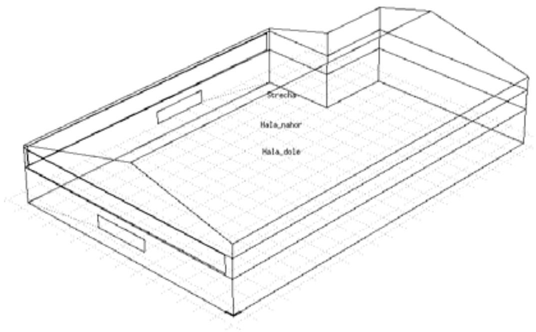

Figure 2 Model of the hall in ESP-r

3.2 Ventilation and infiltration

The hall has mechanical ventilation which amounts to a supply of 50 000 m^3/h (16.67 kg/s). If the outside air temperature is lower than 23 °C this is only outside air. It the outside temperature is higher than 23 °C only 16 000 m^3/h (5.33 kg/s) will be outside air and the rest i.e. 34 000 m^3/h (11.33 kg/s) is recirculated from the upper part of the hall.
Combustion air extracted from the lower parts of the hall is exhausted via a smoke flue to outside (10 000 m^3/h, i.e. 3.33 kg/s). The rest of the air is exhausted to outside from the upper parts of the hall.

3.3 Internal heat gains

The thermal environment in the hall was analysed assuming normal operating activities in the hall. Since the influence of internal heat loads is significant, the heat loads were determined as accurate as possible. In determining the heat gains of particular machines, three correction factors were considered as follows.
The diversity factor reflects to what extent individual machines operate simultaneously, The electric furnace operates continuously and so the diversity factor was set to 1.
The utilization factor considers the actual consumption relative to the nameplate value. In case of the selected electric furnace, the measured average utilization factor was 0.3.
The residual factor is applied in cases where part of the heat release is not transferred as a heat gain into the hall because it is directly removed, for example, by means of an exhaust hood or by water

cooling. Each electric kiln was fitted with a smoke exhausts by which approximately 2000 m^3/h smoke of about 140 °C (measured) was exhausted resulting in a residual factor of 0.34.
For the simulations, six electric furnaces with nominal power input of 360 kW each were taken into account.
Although the venting ducts in the upper part of the hall are insulated, because of the average exhaust temperature of 140 °C there is still a considerable amount of heat loss from the ducts and to take this into account the air temperature in the upper part of the hall was considered to be 30 °C.

Table 2 Internal heat gain in the hall

Heat source	**Internal heat load**	
	kW	**W/m²**
Equipment (kilns)	208.1	196.2
Equipment (venting)	9.2	8.67
Lights	10.37	9.8
Workers	1.8	1.7
Total	**229.5**	**216.4**

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

- 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 ceiling

The geometry of the zones was similar to the existing hall.

3.5 Results and discussion
Following the Czech standards for health protection of workers, the results were assessed in terms of thresholds for the mean operative temperature of 26 °C and a maximum of 32 °C. What follows are result sets for 4 options of operation which aim to optimise the cooling capacity of the chiller.

Option 1
In this option the air conditioning results in operative temperatures which are usually around 26 °C with a maximum of 26.4 °C. The occupied zone is kept at the required temperature levels throughout the whole summer period. The associated maximum sensible cooling output was 232.5 kW and cooling energy consumption was 152 MWh. The relative humidity was in between 55 and 80 % and most of the time near the lower value of 55 %. The results show that the use of adiabatic cooling would not lead to reduction of required cooling output and only marginally reduce the annual cooling energy consumption by about 8 %.

Option 2 (Figure 3)
In this option the maximum cooling output was reduced to 186 kW, which resulted in an air temperature rise up to 26°C and a maximum operative temperature of 29.1 °C during summer extremes. However the operative temperature was above 27 °C for only 181 hours i.e. for 5 % of the summer. The operative temperature was 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 energy consumption was 146 MWh.

Option X1
This option assumes a limited sensible cooling capacity of 50 kW. With an increased outdoor air supply of 50 000 m^3/h the results show that the air temperature in the hall will be below 26 °C during about half of the summer period and will rise above 32 °C for only 7 % of the time. The maximum temperature was 36 °C.

Option X2

This option represents the current state in which the maximum cooling output is limited to 50 kW and the hall is ventilated by 16 000 m^3/h of outdoor air. This option resulted in unacceptable thermal working conditions in the hall. The air temperature exceeded 32 °C for most of the summer period and during extreme weather the air temperature would go up to 46 °C. The latter actually corresponds to measured values in the current state of the building.

3.6 Conclusions

In order to provide a high standard of thermal working conditions it is recommended that the cooling output of the cooling should be 200 kW. The required total air supply and combustion airflow is 50 000 m^3/h. Adiabatic cooling will not reduce the required cooling capacity, but it may save up to 8 % of the running costs. Thus adiabatic cooling is not really recommended in this case. This study helped to reduce the cooling capacity and prevent over-sizing of the whole system, as the original concept was based on the nominal power input of the kilns, that dynamic behaviour was not taken into account and that the capacity of the chiller was 500 kW.

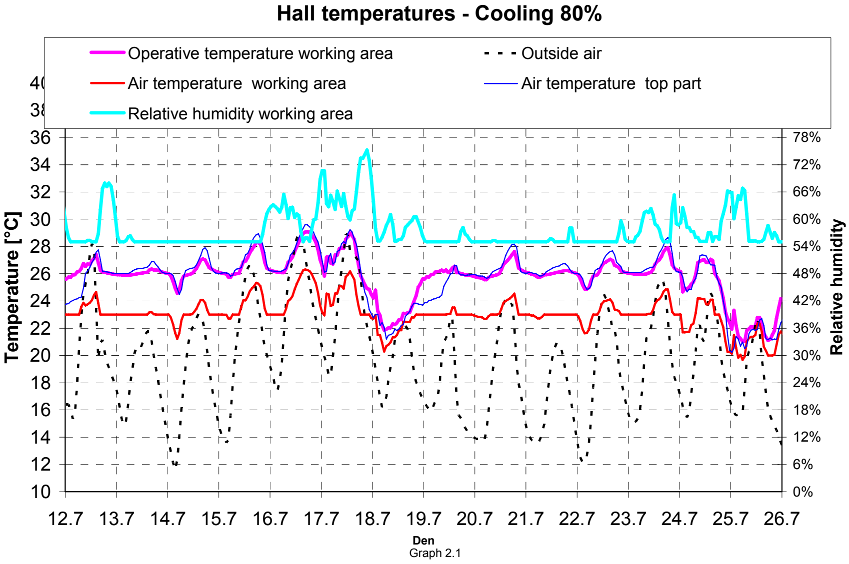

Figure 3 Temperatures in the hall during the selected period and assuming Option 2

4. Slab cooling in the new technical library building

4.1 Building concept

The new Czech technical library is a 6 storey building (with 3 floors underground), which is currently under construction in Prague 6 - Dejvice. The building is divided in several functional units. The main part of the building, the public library, is at ground level or above. The atrium is located in the centre of the building and spans 5 floors. The atrium has two small openable roof windows. There is parking at the lower level floors. The construction is basically a steel concrete frame; the internal walls are made from gypsum partition or glass. The building features a double skin façade. The external façade layer is fully glazed. The internal layer of the double skin façade is lightweight with a high window to wall ratio.

4.2 HVAC system concept

The building features slab cooling to ensure thermal comfort in the main library hall and study rooms. This system consists of serpentine heating/cooling pipes which are embedded in the concrete ceiling.

Since cooling takes place via the thermal mass of the ceiling, the supply airflow can be limited to the fresh air requirements. The fresh outdoor air is conditioned before being distributed over the building. All air is extracted via the atrium by exhausts near the roof. The offices on the northeast façade have natural ventilation via openable windows. In first approach, the air change rate in the offices is estimated at 2 h^{-1} during the day and 5 h^{-1} during the night.

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 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 between 16 °C and 20 °C.

Because of the higher cooling demands, the computer rooms, restaurants and shops will have fan-coil systems. The idea is that the cooling source (chiller) will be operated during peak loads (daytime) to service the fan-coil systems and during off-peak periods (night) for the slab cooling system. This results in a significant reduction of required chiller capacity.

4.3 Ventilated double-skin facade

Part of the ventilated double skin façade was simulated in order to predict whether or not the ventilation would work as anticipated. The underlying model represents part of the south façade and consists of 6 vertically stacked thermal zones. Each zone has a single layer of glass on the outside, and double glazing with internal shading on the building side. The thermal model was augmented with an airflow network for simulating the stack and wind effects which drive the airflow through the double-skin façade.

4.4 Building model

An energy balance computational model was set-up for simulating the public library area under extreme summer conditions. The performance prediction of the cooling system was the main goal of the energy simulation.

In a view of the fact, that the main focus was on the total energy balance for the library spaces, the building was modelled with 13 thermal zones: public library (4 floors), atrium (5 floors), office spaces (4 floors), 2 reading rooms and 2 computer rooms. Two small openable windows in the roof are incorporated in the model. As indicated in Figure 4, the geometry of the floors respects reality, however the curved facades had to be simplified to straight segments.

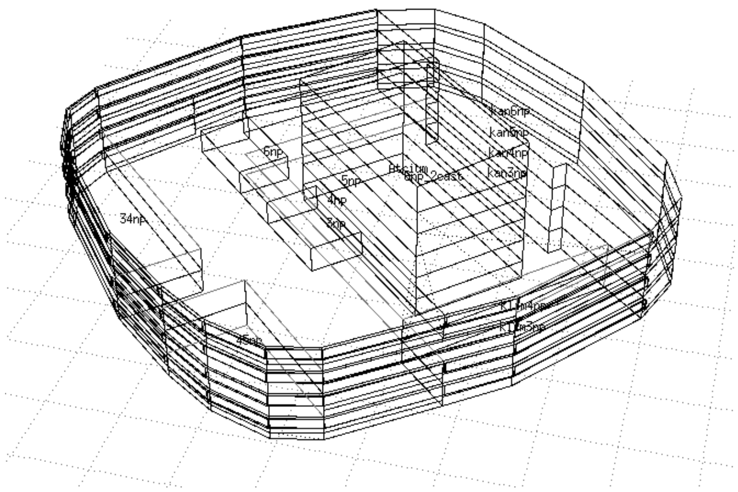

Figure 4 Graphical feedback of the ESP-r mode

4.5 Air flow model

Mechanical ventilation with constant airflow is assumed for the library. The temperature of the supply air is maximum 22 °C. If the outdoor temperature is lower than 22 °C, unconditioned outdoor air is supplied to the space. The model assumes ventilation of the offices as follows:

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

4.6 Casual heat gains

The internal heat gains are assumed to be 13.4 W/m^2 in the library and 70 W/m^2 in the computer rooms. These heat gains occur during library opening hours, ie. from 7 am until 9 pm on working days.

4.7 Slab cooling model

A cooled ceiling with pipes embedded in the floor slab (thermal core activation or slab cooling) will be used in the library and reading rooms. An equivalent cooling capacity of 40 W/m^2 will be supplied into the concrete slab at a depth of 150 mm during the night from 8 pm until 8 am. The temperature of the cooling water is 18 to 21 °C; the spacing of the pipes is 150 mm. The slab cooling area is less than the total ceiling area. The slab cooling covers approximately 71 % of the ceiling. On the basis of initial simulation results, the slab cooling was also activated for one hour during the day (1.30 pm – 2.30 pm).

The air temperature set point in the computer rooms is 26 °C during opening hours. The offices do not have mechanical cooling. The objective of the computational energy simulation is to determine the sensible cooling requirements.

4.8 Results

The simulations were focused on the summer period from May until September. Since only the cooling operation was assumed, it may happen that the air temperature are actually to low during May and September (in reality the heating will be activated when that occurs). Figure 5 shows some of the results for the predicted air temperatures and cooling energy requirements. To establish the optimal operation of the HVAC system, 10 variants of slab cooling and ventilation operation were simulated; Figure 5 presents results for the final variant.

4.9 Conclusions

The double-skin facade results confirmed that the temperature in the ventilated cavity is close to the outside temperature. To keep the inside air temperature below 27 °C during library operation in hot summer periods, it is necessary to cool the slab with chilled water not only during the night, but also at least for one hour during the day. The computer simulations confirmed the HVAC system concept and helped to establish the operation strategy for the building.

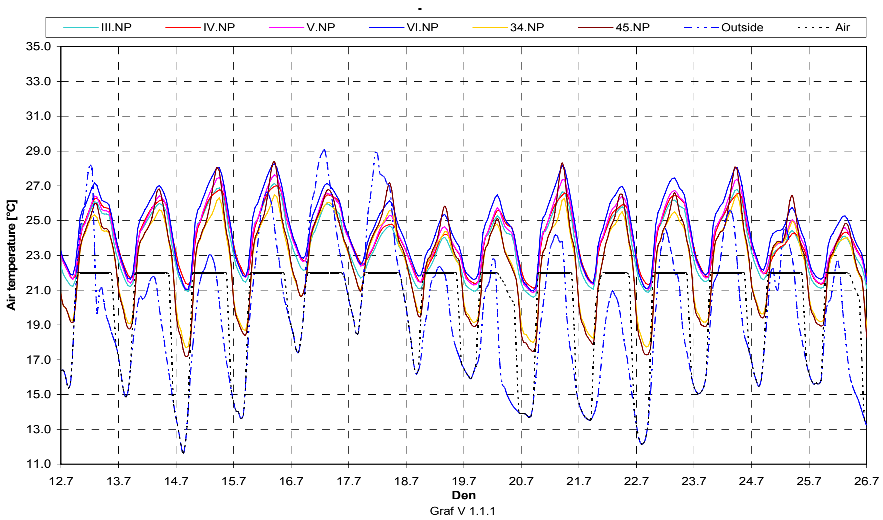

Figure 5 Predicted air temperatures in library rooms for a two week summer period

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 than 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 %.

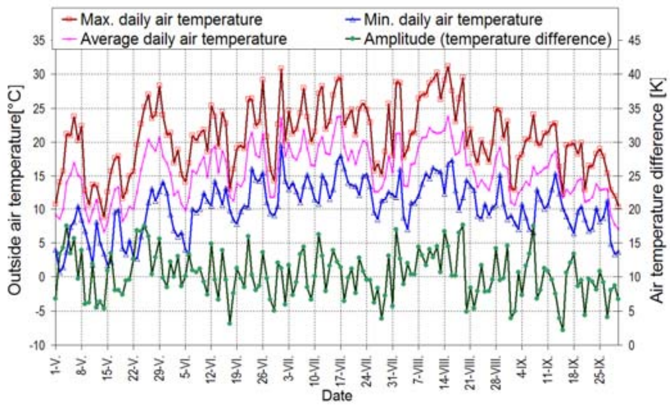

Figure 6 Air temperature difference in Prague during the cooling season.

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 to find 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).

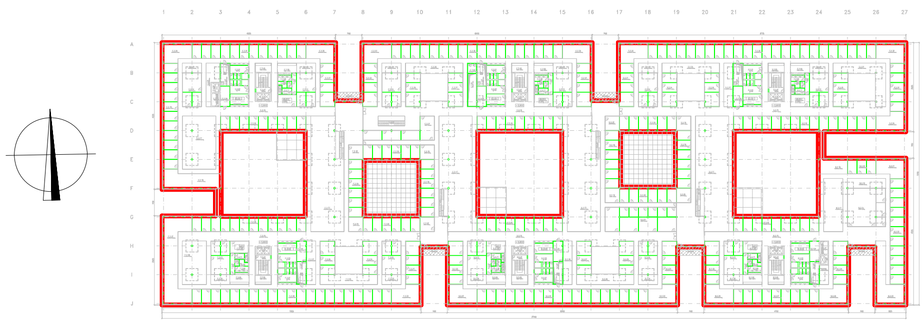

Figure 7 Ground plan of the office building

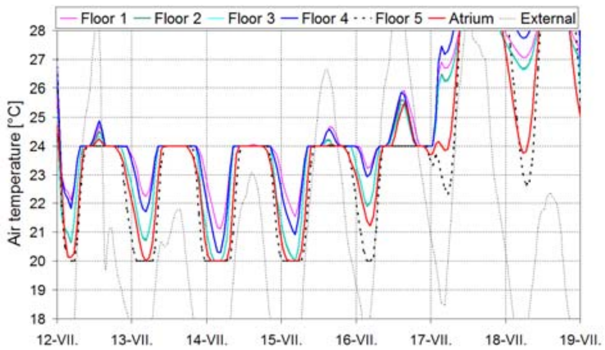

Figure 8 Inside air temperature in the bank office during a peak summer week

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, because only for a few hours per 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).

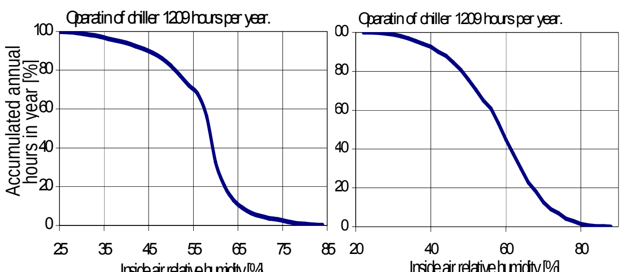

Figure 9 Cumulative distribution of indoor relative humidity for all air system (right) and indirect evaporative cooling (left)

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 results in higher energy saving than by 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 (especially 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.