Impact of Cooling Systems on the Energy Consumption and Indoor Environment in a Low-Energy Office Building

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ABSTRACT

The paper presents the results and analysis of the energy consumption of a newly designed office building in relation to quality of the indoor environment. The main energy consuming process in such a type of buildings is air-conditioning and cooling. The building was designed as a low-energy one, cooled by means of cooling ceilings. The architect's and designer's assumptions were checked by numerical simulation applying ESP-r software. Basing on the simulation results, the seasonal energy consumption was analyzed for different strategies of cooling. The changeability of the demand for cooling was also simulated for the summer period for one of the Polish towns. Thermal comfort in the building was assessed thanks to the simulation of the variability of the indoor air temperature, the temperature of the partitions and by means of the PMV factor.

KEYWORDS

Low energy building, simulation, cooling systems.

INTRODUCTION

The assurance of an adequate indoor environment in office buildings requires, among others, the retaining of a temperature in the room comfortable for those abiding there. In buildings of public utilities the problem is not the heating, but rather cooling of the rooms. This is due to the specifics of the utilization of the office space, where in a comparatively small cubature considerable internal heat gains do occur, resulting both from the presence of people and various appliances (Pfafferott at al 2004, 2007). From the technical point of view the existing systems of air conditioning can ensure the required microclimate in the offices, the problem, however, is the energy effectiveness of the applied solutions, as well as the costs of investments and utilization. Nowadays designed and constructed office buildings ought to be characterized by warranting the proper quality of the indoor environment, particularly thermal comfort connected with a minimum consumption of energy.

Investigations indicate that a reduction of energy consumption in this types of buildings depends mainly on (Tuohy at al 2005):

- the insulation of the building envelope,
- internal heat gains,
- the strategy of heating and cooling the building

These factors influence the consumption of energy in various ways, due to differences of the climatic conditions, the building and standard regulations and the way in which the buildings are used in the respective countries. the aim of the present paper is to analyze, basing on the results of simulations, the possibilities of reducing the cooling demand and the consumption of energy appropriate to Polish meteorological conditions and Polish standards.

THE BUILDING AND ASSUMPTIONS FOR SIMULATION

For the purpose of such analysis an office building was selected, designed in compliance with the passive technology. It is a building with nine stores (2 of them underground), with a heavy ferroconcrete structure (external walls – 25 cm ferroconcrete, floors 30 cm ferroconcrete). The external walls and roof are well insulated (U_{wall} = 0.13 W/m^{2}K, U_{roof} = 0.09 W/m^{2}K, U_{win} = 0.80 W/m^{2}K). The windows of the building are provided with electronically controlled external shutters. The fundamental way of cooling is a thermoactive cooling ceiling (tubes with a cooling agent of 16 ^{o}C embedded in the ferroconcrete ceiling). The total surface of the offices amounts to more than 20000 m^2. It is this area we are just interested in (on the ground floor there are service spaces with quite a different way of application).

The numerical model for simulative calculations was constructed for a single office room with the dimensions 2.6 x 8.1 x 2.8 m equipped with a single window (1.4 x 2.3 m). The external shutters of the model were designed assuming a constant inclination at an angle of 45^{o}.

In compliance with the assumptions in the design of the heating installation, ventilation and air conditioning it has been assumed that:

- the indoor air temperature would be 24 ^{o}C (the room being cooled),
- ventilation air supply (during the office hours): 90 m^3/h at a temperature of 24 ^{o}C; beyond that time the air flow is reduced to 30 m^3/h (0.5 h^{-1}); the infiltration of air from outside was assumed on the level 0.1 h^{-1}.
- internal heat gains (ASHRAE Handbook-fundamentals, 2005):
    - occupants (3 persons) 3 x 77 W = 231 W,
    - computers (3 sets) 3 x 150 W = 450 W,
    - lighting 3 x 50 W = 150 W.

The building was assumed to be used from Monday to Friday in the time from 7 a.m. to 6 p.m. and on Saturday from 7 a.m. to 2 p.m.

Simulation calculations were carried out by the ESP-r program (Clarke 2001) concerning climatic data of one of the Polish town. The aim of numerical calculations of the system building – HVAC system was to investigate the dynamics of the cooling load as well as the actual and seasonal demand for cooling in the time from June to September (average season of operating cooling systems in office buildings). Besides the internal heat gains, in the calculations also the gains due to solar radiation have been taken into account. As far as the situation of the building is concerned, two cases have been considered: the window of the office section faces either the north or the south.

STRATEGIES OF COOLING THE BUILDING

Low-energy cooling systems while providing effectively cold permit to reduce the consumption of energy and also to decrease the peak demand for energy. In order to check the effectiveness and energy consumption of the building, several series of simulations were carried out concerning various cooling systems. Reference values for further comparisons were obtained by calculations of the cooling demand and the actual cooling power concerning the conditions of designing.

Figure 1 illustrates the exemplary progress of changes of the transient cooling demand in a selected period of simulation. The maximum cooling demand amounts to 1080 W for the office exposed to the south and 970 W for the office exposed to the north; the seasonal expenditure of cold amounted in the investigated season on the average to 56.0 kWh/m^2. It ought to be mentioned that in order to keep up the assumed temperature the room must be cooled for 24 hours a day.

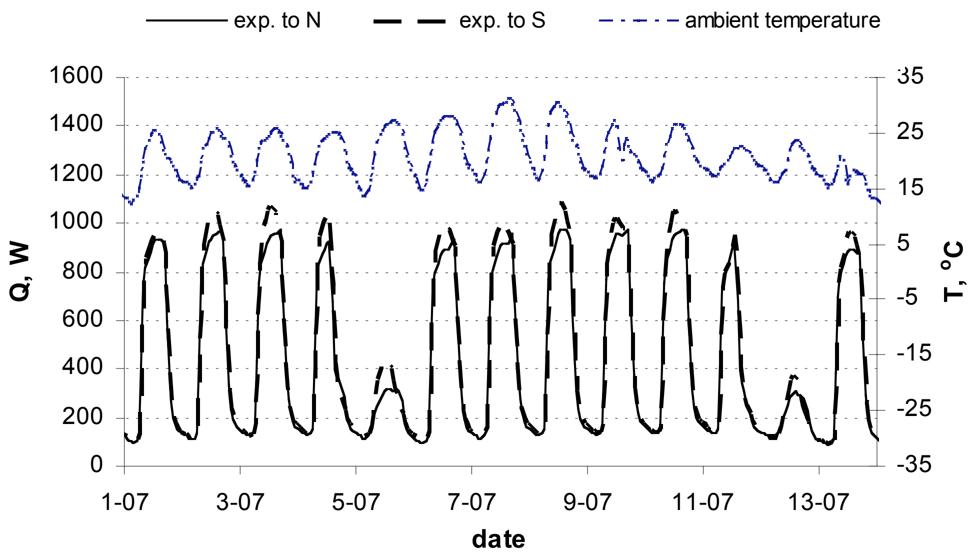


Figure 1: Variation of the actual cooling load in selected period in summer

Reduction of the Temperature of the Ventilating Air

The air supply from outside can be partly used as a source of cold. Simulations have shown that a reduction of the incoming air by 4 K to the value of 20 °C reduces the cooling demand to 860 W in the case of the office facing northwards and 970 W in the case of the office exposed to the south. The seasonal expenditure of cold drops to the mean value of 46.6 kWh/m^2. Though the preparation of the ventilating in this case requires a higher expenditure of cold (without taking into account the recovery of heat 3.4 kWh/m^2), the reduction of the temperature of ventilated air by 4 K permitted to decrease the seasonal cooling demand nearly by 11%.

Night-time Ventilation

The efficiency of free night cooling is particularly evident, when it is combined with a heavy structure of partitions inside the building with a considerable thermal capacity.

In commercial buildings with natural ventilation the temperature can be set down by about 3 K, provided that the adequate thermal buoyancy is achieved, usually by the presence of an atrium, wind towers or solar chimneys (Voss at al 2007). Mechanical ventilation may also be additionally applied.

Simulating the cooling demand it was assumed that at night (8 p.m. to 6 a.m.) the room was ventilated by opening the windows (5 h^{-1}), the mechanical ventilation being switched off. During the office hours the provided ventilated air has – in compliance with the assumption in the design – a temperature of 24 ^{o}C.

The maximum cooling demand in the office module amounted to 850 W (if exposed to the north) and 940 W (when exposed to the south). The maximum cooling power dropped, therefore, on the average by 11%, and the seasonal cooling demand dropped by as much as 48%, on the average to the value of 29.2 kWh/m^2 (in the month from June to September). Such a low value is achieved thanks to the fact that the room need not be cooled during the night. As long as the room is being aired the temperature does not exceed 24 ^{o}C.

Cooling Ceiling

A source of cooling is in compliance with the design the cooling ceiling. The simulation model consists in this case of two zones (with a homogeneous temperature of the air), viz. “office zone” and the “cooling zone of the ceiling”. The maximum cooling power of the ceiling was assumed to amount to 40 W/m^2, and the source of cold to be active only when the room is being used. In result the simulation provided an image of the progress of changes of the temperature inside the room when the ceiling is the only source of cooling. Figure 2 presents exemplary results gathered in one selected week in July, as well as the additional demand for cooling power required to keep up a temperature of 24 ^{o}C.

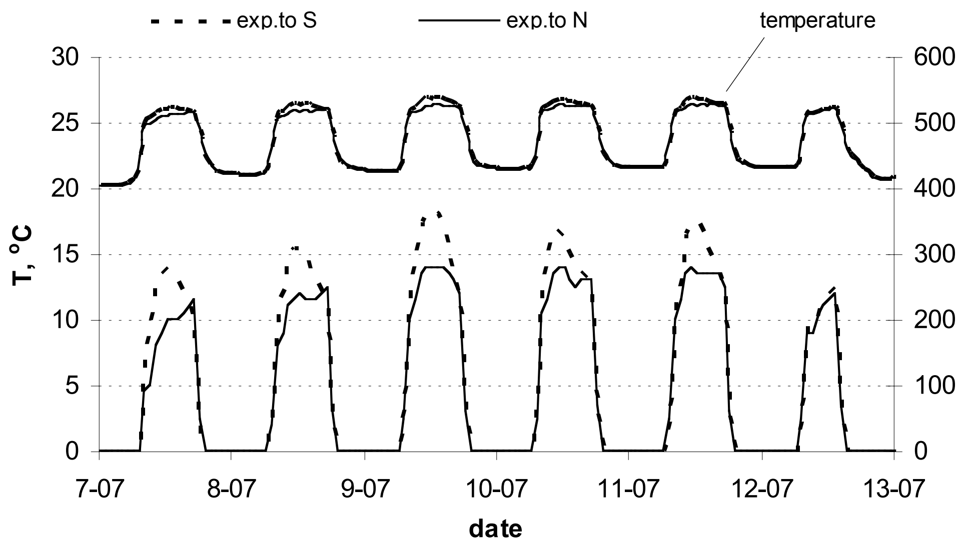
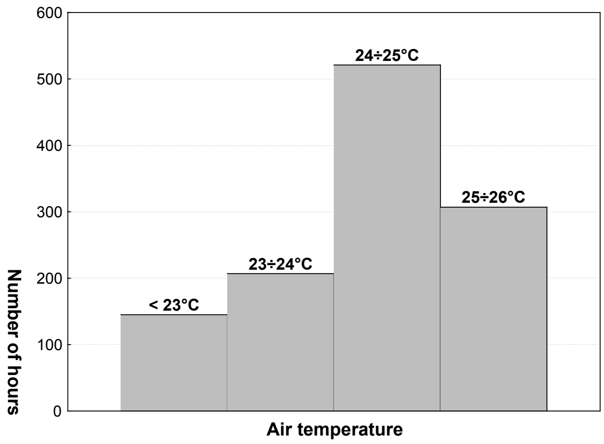


Figure 2: Time course of the temperature in the office room provided with a cooling ceiling as the only source of cold and the additional demand for cooling power required to maintain a temperature of 24 ^{o}C

The analyzed cooling ceiling with a maximum cooling power of 40 W/m^2 does not ensure the maintenance of a temperature of 24 ^{o}C inside the room; in the room exposed southwards the air temperature reached in the hot season as much as 27 ^{o}C. Applying, however, additionally the already mentioned sources of cooling, i.e. by decreasing the temperature of the ventilation air to 20^{o}C, the temperature never exceed 26^{o}C in the room (max. 25.9 ^{o}C in the office exposed to the south). In summer the thermal comfort is ensured by a temperature of 23÷26 ^{o}C, i.e. during the office hours the temperature is kept within the required range. The results of simulations have also shown that in the case of a higher cooling power of the ceiling amounting to 45 W/m^2 the maximum temperature in the office exposed to the south does not exceed 24.6 ^{o}C.

Thanks to the strong accumulation of the cold in the heavy ceiling its effect is perceptible also at night when the installation is put out of action. At night the temperature does not exceed in the considered season 23 ^{o}C. A histogram of the interior temperature has been presented in Figure 3.



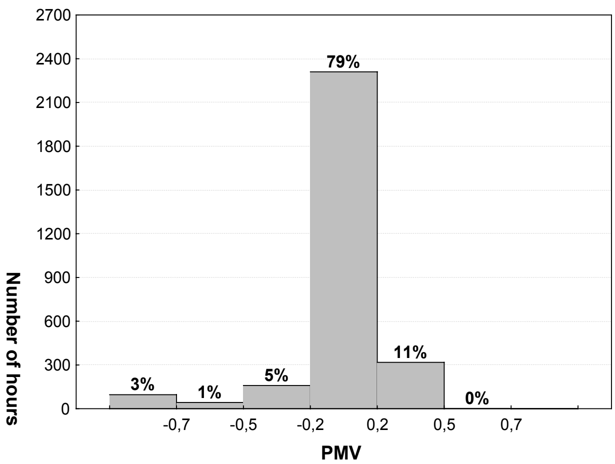


Figure 3: Histogram of the internal air temperature in the room (left graph) and the PMV index in the investigated room (right graph) – air supplied temperature: 20 ^{o}C, the office exposed to the south

The good energy efficiency of the cooling ceiling is connected with its properties of the accumulation of heat. This system has proved to be particularly effective when additionally other aiding cooling activities were involved.

The quoted results of simulations suggest that the technical solutions of cooling systems assumed in the design of the building permit to maintain the conditions of thermal comfort. In order to prove the feasibility of these assumptions within the entire considered period of time, the actual values of the indices of the predicted mean assessment of PMV have been determined (merely concerning the time when the offices are used). Analyses of the obtained results have shown that the index PMV is during most of the time when the office is occupied contained within the limits of ±0.2, and during 95% of the time within the limits of ±0.5 (Figure 3)

CONCLUSIONS

Office buildings as well as other structures of public facilities, the usage of which is connected with the presence of a large number of people, raise the problem of warranting adequate cooling.

Results of simulations have shown that all the three low-energy strategies of cooling reduce the actual and seasonal demand for energy.

Natural night-time ventilation exerts a considerable influence on the internal temperature, eliminating the need of cooling the room at night. It should, however, be stressed that the purpose of cooling a considerable exchange of air must be assumed. In fact, there may some difficulties turn up with the achievement of such values, as well as problems connected with an intensive natural ventilation (the hazard of draught etc.). Having to do with such a system, also adequate structural elements of the building must be kept in mind which permit to remove a large amount of air, e.g. an atrium.

Ceiling cooling has been approved to be a system which fully warrants thermal comfort in offices and also allows to reduce the consumption of energy. The effect of ceiling cooling proved to be much greater than any other considered technology. Thanks to it cumulative ability the rooms can be cooled also during the night. Results of simulation revealed even actual overcooling in the course of the first hours after day-beak. The application of cooling ceilings permits to set down the peak demand for cooling and to eliminate practically traditional such source of cooling as fan coils.

Potential profits resulting from the application of low-energy and passive technologies are high. Although there are no essential technical obstacles, these technologies are only scarcely implemented due to economical reasons.

References

ASHRAE Handbook-fundamentals. (2005). American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc., Atlanta, USA.

Clarke, J.A. (2001). *Energy Simulation in Building Design,* Butterworth-Heinemann, London, UK.

Pfafferott, J., Herkel, S. and Wambsganss, M. (2004). Design, monitoring and evaluation of a low energy office building with passive cooling by night ventilation. *Energy and Buildings* **36,** 455–465.

Pfafferott, J, Herkel, S., Kalz, D. and Zeuschner, A. (2007). Comparison of low-energy office buildings in summer using different thermal comfort criteria. *Energy and Buildings* **39,** 750-757.

Tuohy, P., McElroy, L. and Johnstone, C. (2005). Thermal mass, insulation and ventilation in sustainable housing – an investigation across climate and occupancy. *9th Int. IBPSA Conf. Building Simulation*. Montreal, Canada.

Voss, K., Herkel, S., Pfafferott, J., Loehnert, G. and Wagner, A. (2007). Energy efficient office buildings with passive cooling – Results and experiences from a research and demonstration programme. *Solar Energy* **81**, 424–434.