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Benefits and Limits of Free Cooling in Non-Residential Buildings

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in Non-Residential Buildings

Synopsis

In urban non-residential buildings air-conditioning systems are generally required to achieve acceptable air quality. To reduce the energy demand of HVAC-plants free cooling is proposed. The present study deals with free cooling by outdoor air (untreated or additionally cooled by evaporation) during the night. Therefore a sufficient building mass (about 600 to 800 kg/m²) is necessary which stores the heat produced in daytime and which is cooled down at night. In most conventional non-residential buildings, however, the building mass is at about 400 to 600 kg/m².

A reference room which provides optimum conditions for night cooling has been investigated using a dynamic building simulation program.
Three variants have been examined: Night cooling by untreated outdoor air and increased heat transfer to cool down the ceiling of the reference room, night cooling combined with evaporative cooling and ventilation through a false floor.

The simulation results show that room air temperatures below 28 °C can be achieved exclusively by combining night cooling and evaporative cooling as long as the total load does not exceed 55 W/m². For higher loads night cooling combined with mechanical cooling provides a 15 to 20 % reduction in the energy demand compared to mechanical cooling during the occupied period exclusively.

As the ventilation energy demand has a strong impact on the total energy demand decentralized systems with low pressure losses are required.
Without mechanical cooling less comfort and poorer air quality are inevitable, as dehumidification of supply air is a presupposition for high comfort and air quality.

Night cooling should be realized without mechanical systems, e.q. by using buoyancy forces of an atrium. This requires a close cooperation between the architect and the HVAC-engineer.

1. Introduction

In urban non-residential buildings air-conditioning systems are generally required as a result of traffic noise and air contamination. The discussion about fluorine chloride carbon hydrogen intensified the research into alternatives to conventional mechanical cooling, which are free cooling at night with cold outdoor air, with a cooling tower, evaporative and desiccant cooling.

This study has been limited to night cooling by outdoor air. The basic of night cooling is to eliminate the heat that was stored in the building mass during the occupied period, by an increased air exchange during the night. The supply air could either consist of untreated outdoor air or be additionally cooled by evaporative cooling. For given limits of thermal comfort and humidity the intension was to show under which conditions no mechanical cooling is required and how the energy demand can be reduced by combining of night cooling and a conventional air conditioning system. Various concepts of night cooling will be presented and discussed with respect to the reduction of energy demand and cost.

2. Numerical Simulation

2.1 Description of the Dynamic Simulation Program

The investigations have been done using the TRNSYS (transient system simulation) program, developed by the Solar Energy Laboratory at the University of Wisconsin - Madison. This is a modular program package which contains a detailed multi-zone building model. TRNSYS allows the dynamic simulation of buildings with respect to real weather data, occupants behaviour and the function of HVAC-plants. Each zone is modelled by one calculation node. Within a zone homogeneous temperature and humidity distribution is assumed.

2.2 Description of the Reference Room

Night cooling requires a sufficient thermal mass in the building to be cooled down during the night and and to store the heat produced in the daytime. In a preliminary study the thermal behaviour of rooms with different masses has been examined. The results of these simulations showed that the reference room for this study should have a mass of at least 800 kg per m² floor area. Figure 1 illustrates the temperature in a lightweight (360 kg/m²) and a heavyweight (850 kg/m²) room as results of

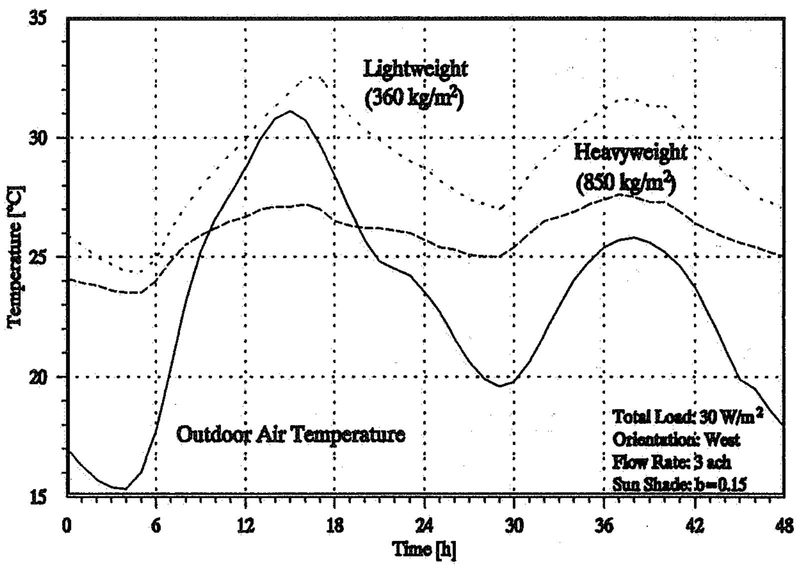

Figure 1:
Room air temperature versus building mass

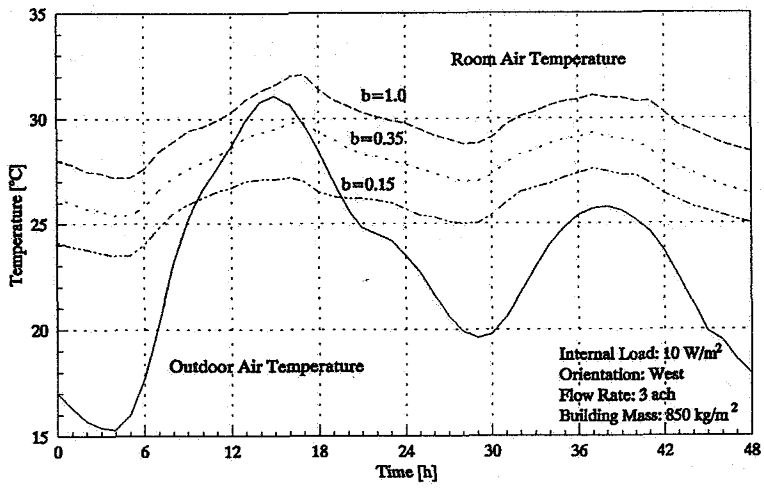

Figure 2:
Room air temperature versus sun shade

a simulated two-day period.

Another requirement for energy efficient buildings is an effective sun shade. In Figure 2 temperatures are plotted for the reference room without sun shade (b = 1.0), with blinds partially closed (b = 0.35) and totally closed (b = 0.15).

With good sun shade the impact of beam radiation and outside air conditions can be neglected if the building is well-insulated and air-tight. Therefore the orientation of the reference room is of less importance.

Referring to these issues a reference room has been defined. The calculations have been performed for a room of the following dimensions: 4.5 m x 5.2 m = 23.4 m^2 with a height of 2.7 m. The main structure is made of concrete. The external wall is insulated to a U-value of 0.5 W/m^2 K, the windows have a U-value of 2.9 W/m^2 K. Details are shown in Figure 3.

It is supposed that the test room is located in the west facade of the building and surrounded by identical rooms.

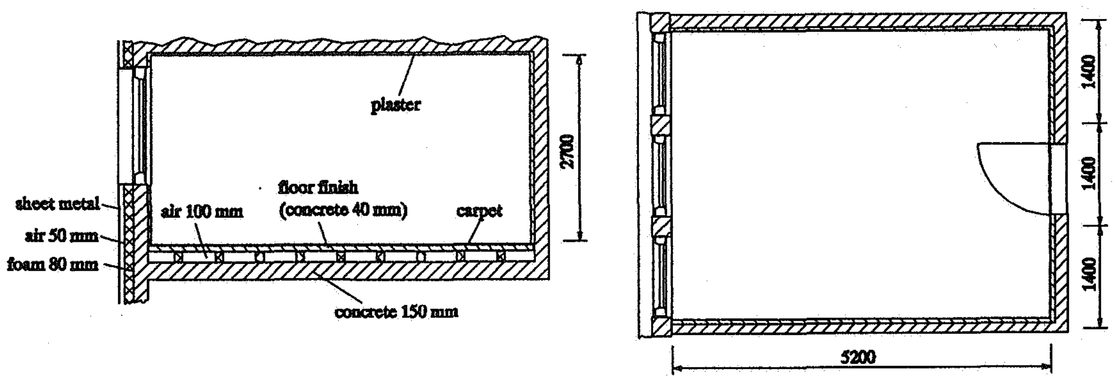

Figure 3:
Geometry of the reference room

2.3 Boundary conditions

The simulation was carried out using hourly weather data (outdoor temperature, diffuse and beam radiation on a horizontal plane and humidity) from the Test Reference Year for Frankfurt/Main. For the analysis of the maximum room temperature a two-day period was used which has been repeated until stationary conditions have been achieved. The outdoor air temperature for this period is shown in Figure 1. The diurnal variation of the hot day's temperature corresponds to a design day according to VDI 2078 /2/.

The varying occupancy patterns have been considered by switching the internal load as shown in Figure 4 and by closing the sun shade (b=0.15) when the beam radiation on the window plane exceeds 250 W/m². The maximum total load (external plus internal load) has been varied from 30 W/m² to 60 W/m².

The air exchange rate was chosen depending upon the temperature difference between inside and outdoor air. During the occupied period (from 7.00 a.m. to 7.00 p.m.) the ventilation rate was set to 3 ach if the room air temperature was higher than the outdoor temperature. Otherwise the ventilation rate was reduced to 1.5 ach. During the night an infiltration of 0.15 ach was presumed. Night cooling was activated if the difference between inside and outside temperature was greater than 3 K. The ventilation rate for night cooling was varied in the simulation (3 or 6 ach).

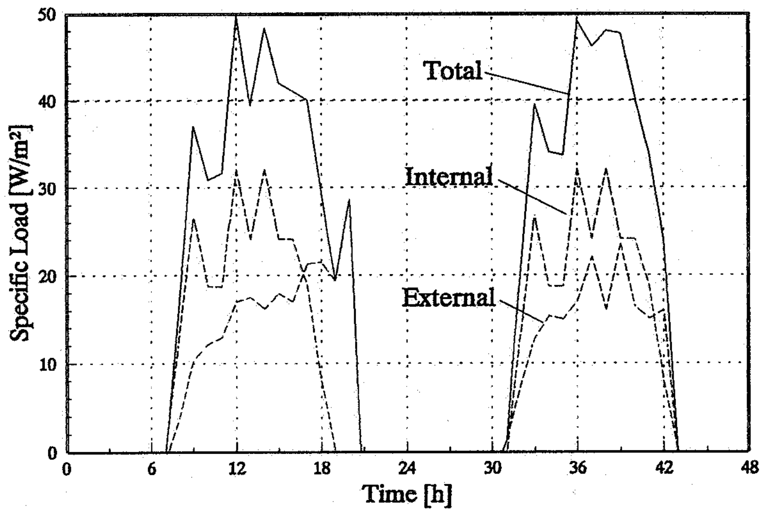

Figure 4:
External, internal and total load during the two-day simulation period (example)

To ensure thermal comfort the room air temperature should not exceed 27 °C. Without mechanical cooling 28 °C are supposed to be acceptable for 1 to 2 hours.
For calculations based upon combined mechanical and night cooling, room temperature was allowed to vary from 22 °C to 27 °C during the occupied period. To compare the cooling energy demand a three-month period from June to August (Test Reference Year Frankfurt) has been used in simulation.
In all calculations with air blown into the room by a fan, a rise in the supply air temperature of 1.5 K has been considered.

3. Variants of night cooling

The easiest way to realize night cooling is to open the window. The air flow rate that could be achieved, depends on the area and the location of the open window as well as on wind velocity and direction. Therefore it is not possible to provide a defined air exchange. Furthermore, aspects of security and outdoor climate should be considered. Another disadvantage of ventilation through the window is that heat recovery is impossible in winter time.
With respect to these reasons mechanical ventilation systems are presupposed in the present study. Mechanical ventilation systems should increase the storage effect of the building mass. This is to improve the heat transfer to walls, floor or ceiling. To realize higher heat transfer coefficients, outdoor air should be blown out against the wall or the ceiling. Another possibility is to blow the air through a false floor or ceiling. The latter is a very ambitious solution if the building makes use of the stack effect of a central atrium to draw the air through the storage mass.

The advantage of mechanical systems is the possibility of combining night cooling and evaporative cooling.

In the present study the following variants have been examined:

1. mechanical ventilation with increased heat tranfer by blowing out untreated outdoor air against the storage mass (ceiling)
2. mechanical ventilation corresponding to 1., combined with evaporative cooling up to a maximum humidity of 11 g/kg dry air.
3. mechanical ventilation through a false floor with untreated outdoor air.

At first, the variants described above have been tested in view of the maximum total load still allowing comfortable room air temperatures without mechanical cooling. Therefore the two-day sequence of weather data has been used.

For higher loads three-month simulations have been carried out combining mechanical and night cooling. To quantify the benefit of the different variants of night cooling a reference simulation has been conducted with mechanical cooling only. In this case the air flow rate was fixed to 3 ach. Internal load and sun shade control were modelled as described above.

The scale of evaluation are the cost for mechanical cooling (0.066 DM/kWh) and for ventilation (0.05 DM/1000 m^3). For ventilation a decentralized system with extremly low pressure losses is supposed to be installed. With conventional systems ventilation cost are about 0.15 DM/1000 m^3. Differences in capital cost, space requirement for the HVAC-plant and heating energy demand have not been taken into account. It should be noted that all energy data only refer to the three-month summer period.

3.1 Mechanical ventilation with increased heat transfer

The relation between total load, air exchange rate at night and maximum air temperature in the reference room without mechanical cooling is shown in Figure 5. With three air exchanges per hour the temperature threshold (28 °C) is reached at a specific load of about 35 W/m². An air exchange rate of six per hour permits a load of about 41 W/m². Higher air exchange rates allow only slightly higher loads. Therefore it can be stated that in this case mechanical cooling is necessary if the total specific load exceeds 40 W/m².

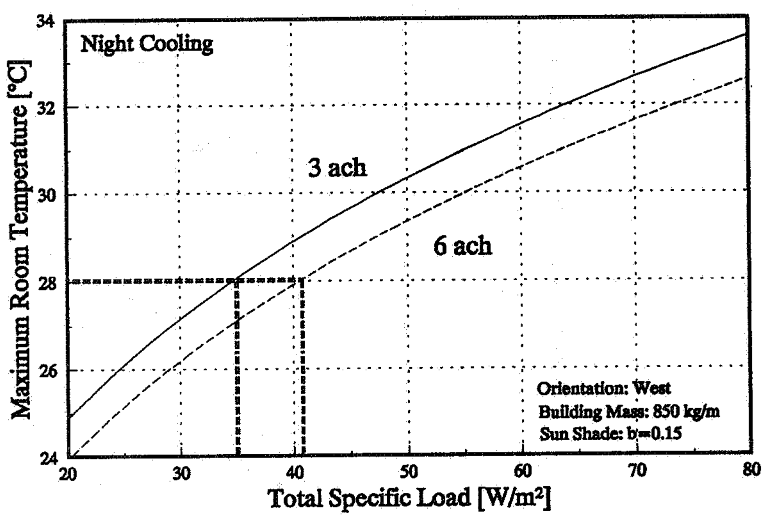

Figure 5:
Night cooling by increased heat transfer at the ceiling - relation between maximum room temperature, total specific load and air exchange

But the combination of night cooling and mechanical cooling results in a reduction of the cooling energy demand as shown in Figure 6. For a total specific load of about 50 W/m² the energy demand during the three-month summer period could be reduced by up to 18 %. For higher loads, however, the energy saving potential is negligable. Furthermore the difference between 3 and 6 ach is quite small. Therefore this variant of night cooling can only be recommended with three air exchanges per hour during the night.

Another aspect of night cooling is illustrated in Figure 7. Night cooling reduces the required cooling capacity of the HVAC-plant. Even for high specific loads, where the reduction of energy demand is low, the cooling capacity can be reduced significantly.

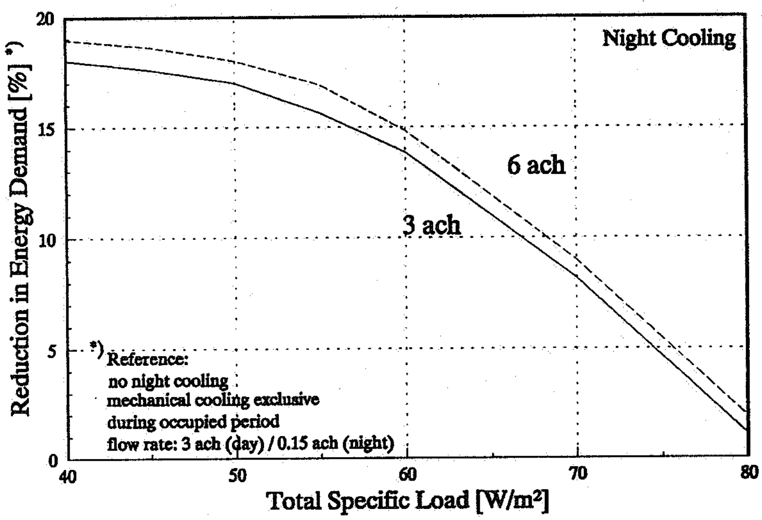

Figure 6:
Reduction in energy demand (night cooling combined with mechanical cooling, no evaporative cooling) compared to the reference room with mechanical cooling only.

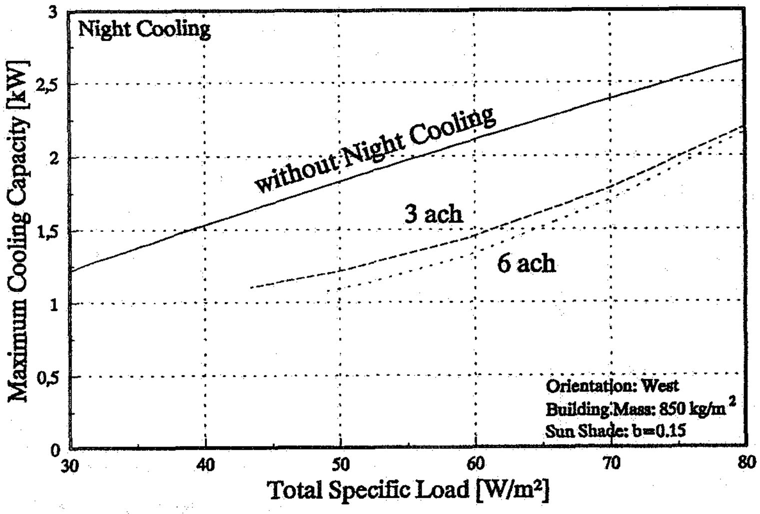

Figure 7:
Maximum cooling capacity requirement versus the total specific load and air exchange (night cooling with outdoor air)

3.2 Mechanical ventilation with increased heat transfer and evaporative cooling

Evaporative cooling by humidification of the supply air is only a slightly higher technical effort compared to variant 1. But Figure 8 shows the remarkable benefits of this improvement. Without mechanical cooling acceptable room air temperatures can be achieved as long as the total load does not exceed 46 W/m² (3 ach), 56 W/m² (6 ach) respectively. In the simulation the supply air has been humidified to a threshold of 10,3 g/kg dry air (day and night). Outdoor air conditions permit the highest evaporative cooling capacity during the day, as at night relative humidity is often near dew point.

The combination of mechanical cooling, evaporative cooling and night cooling reduces the energy demand by up to 20 % during the simulated period. There is no significant difference in energy saving with changing the air exchange rates.

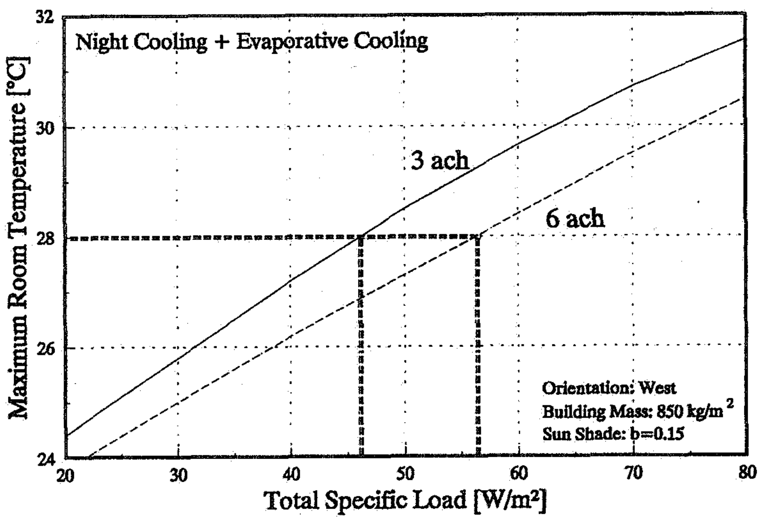

Figure 8:
Night cooling combined with evaporative cooling - maximum room temperature versus the specific load and air exchange

3.3 Night cooling by mechanical ventilation through a false floor

The results in this case are similar to the first variant. The maximum room load is about 35 W/m^2 with an air flow corresponding to 3 air exchanges per hour in the room, 42 W/m^2 with 6 ach respectively. There are no significant differences in energy consumption, too. The advantage of this system however is that room ventilation and night cooling are seperate. Remarkable reductions in energy consumption can be achieved by using the stack effect of an atrium to draw the air through the false floor or if room ventilation during the occupied period is realized through the windows. As the windows are closed at night, this system does not cause security problems.
But it should be noted that it might be difficult to close the false floor tightly against outdoor climate in winter to prevent heat loss at low outside temperature.

4. Conclusions

The variants of night cooling with outdoor air discussed above permit a 15 to 20 % reduction in the energy demand if they are combined with mechanical cooling. Without mechanical cooling acceptable room air temperatures can be achieved at total specific loads of up to 55 W/m^2 if evaporative cooling is used additionally. With untreated outdoor air the room load should not exceed 40 W/m^2.
The basic requirement for night cooling is however, that there is a sufficient storage mass which can be cooled down during the night. Simulations have shown that the specific building mass should exceed 800 kg per m^2 floor area. In practice this value can only be achieved with a reinforced concrete floor and heavyweight walls. These surfaces however must not be insulated for thermal or acoustic purposes.

As the ventilation energy demand has a strong impact on the total energy demand and the operation cost decentralized systems with low pressure losses are required. With conventional systems significant energy savings cannot be achieved.

Comfortable indoor air conditions are hard to realize without mechanical ventilation. During a longer heat period increased room temperatures might occur if the outdoor temperature does not cool down at night and the storage mass is completely loaded. Dehumidification of supply air is a presupposition for high comfort and air quality. Therefore night cooling cannot replace mechanical cooling, but can reduce energy cost and refrigeration capacity.

In most conventional non-residential buildings, however, the building mass is about 400 to 600 kg/m^2. Floors are insulated by carpets and false ceilings are common installations. In this case the benefits of night cooling using the conventional HVAC-system is rather small.

Night cooling should be realized without mechanical systems, e.q. by using buoyancy forces of an atrium. This requires close cooperation between the architect and HVAC-engineer.

Acknowledgement

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