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Free cooling with displacement ventilation

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SUMMARY

Free Cooling is a mode of operation of a mechanical ventilation system to remove excess heat from office rooms during summer nights. A case study demonstrates, that free cooling can be quite effectiv and consumes a comparatively small amount of energy. Computer simulations give insight into the physical mechanisms and allow parametric variations.

Introduction

During the last few years it has become widely accepted, that new ways for energy saving in building management must be found. A new concept, combining high insulation windows and displacement ventilation, leads to a higher user comfort and at the same time reduces the energy consumption. Several office buildings have already been constructed following this concept. Comfort and energy measurements have been made (1) and have been compared to dynamical computer simulations.

In this paper, special attention is directed to "free cooling". This is a mode of operation of the mechanical ventilation system in office buildings. During summer days, a large part of the internal heat load is stored in the thermal masses (floor, walls, etc.). The accumulated heat is removed at night with the mechanical ventilation. Since at night no comfort requirements have to be met, the cold outside air can be used without any further treatment.

Observation of a Regular Performance

A few years ago, Geilinger Ltd in Winterthur, Switzerland, has developed a new window system which is called High Insulation Technology (HIT). The transmission losses in winter are very low, so that they are easely compensated by the internal heat gains. Since the surface temperature of the window is only a few degrees below the room temperature, there is no need of any devices to prevent downdraft. The situation is ideal for a mechanical ventilation with source dominated displacement flow (2,3,4).

Detailed investigations were made in 1988 at an office building in Winterthur, Switzerland, which is equipped with this type of window and with a displacement ventilation.

A Conventional Building Extended with a HIT-part

Up to the fourth floor, the building has a conventional facade with insulated double glazing windows, natural ventilation and radiator heaters. On top of this building, two floors were erected in 1987 based on the HIT concept: high insulation windows (glazing-U-values of **0.65 W/m²K**), a mechanical ventilation of the displacement type with room-individual control, no radiator heaters. The geometry is identical for the new and the old part. All windows can be opened and effective sun protections can be lowered individually.

Mechanical Ventilation

The ventilation system of the HIT-part of the building operates with temperature demand controlled variable air volumes of 1.0 ... 5.0 air changes per hour. The outside air is heated up to 19°C by heat recuperation and - if necessary - by a water heater (connected to the central heating system of the older part of the building). On top of this, the air can be heated by a room individual electrical unit, if desired by the occupant.

The air-inlets are at the bottom of the exterior wall. The area of the opening is 0.35 m². The fresh air enters the room at a very low speed: 0.05 ... 0.25 m/s. The visualization of the air flow by smoke (video films) shows, that the fresh air moves across the floor and raises at the heat sources. The air outlet is at the top of an interior wall.

Turbulence measurements were made in different laboratory experiments with conditions similar to the real building (5). The results proved, that the flow is free of draft (6).

Since the ventilation system is not equipped with a cooling unit, it is turned off at outside temperatures over 22°C in order to prevent unwanted heating. Users are then recommended to make a reasonable use of the openable windows. During summer nights, the excess heat is removed by free cooling.

Unfortunately, the air ducts have no thermal insulation. Therefore, the efficiency of the ventilation system is in some situations (e.g. free cooling) not optimum, although the control unit works correct.

One year of observations

The energy consumption was investigated by weekly readings of different meters for electricity, heat supply and operating hours.

Further, two campaigns were conducted during winter 1987/88 and summer 1988, respectively. 30 parameters were recorded at time intervalls of 10 minutes. The objectives were:

- user comfort in a HIT room with displacement ventilation

and comparison with a conventional room
- efficiency of free cooling
- suitability of the control concept of the ventilation system
- monitoring of the mechanical ventilation

Both rooms (HIT and conventional) were oriented to the east.

Observed Effects of Free Cooling

During warm weather periods, large parts of the internally produced heat (persons, machines, sun) are stored in the thermal masses. If the daily mean temperature shall remain constant throughout such a period, the excess heat must find some way out of the building. In well insulated buildings, the removal by transmission in summer nights is not as effective as in traditional buildings. Free cooling is then a way to extract the excess heat in a controled fashion.

During the measurement campaign in summer 1988, several warm periods occured. On august, 31 and september, 1 the outdoor temperatures exceeded 25°C. The records of the following night are presented in figure 1. The outdoor temperature dropped down to 13°C. The room air temperature of the HIT-room was reduced at a rate of 0.43 K/h by free cooling and transmission, whereas the heat extraction from the conventional room by pure transmission led to a temperature drop of only 0.25 K/h. This means that the heat removal process of the HIT-room with the combination of free cooling and (weak) transmission is considerably more effective than in the case of a traditionally insulated room.

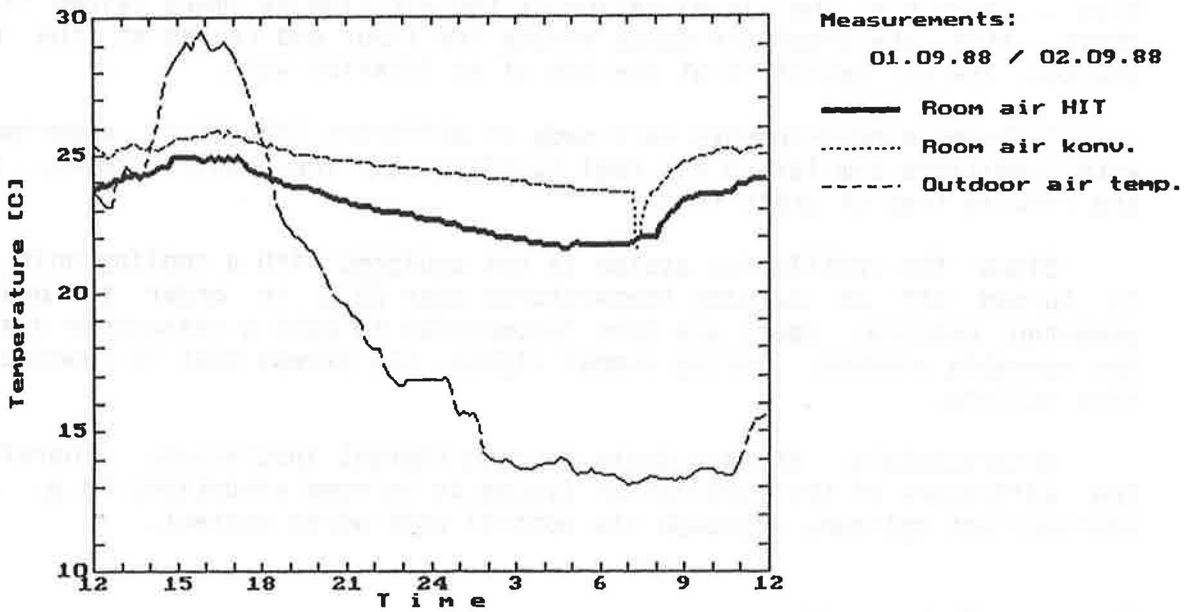

Fig. 1. Measured air temperatures of the HIT-room, the conventional room and outside for september 1/2 1988. At night, the mechanical ventilation of the HIT-part operated in the free cooling mode.

In the second half of july, the maximum outdoor temperatures ranged between 25 and 35°C. Due to an operating error, the mechanical ventilation was running with air volume rates of about 0.5 AC/h nearly all the time.

This means that free cooling was practically out of operation (the required air volume rate is 4.0 to 5.0 AC/h). The effect can bee seen in figure 2: the temperature change of the HIT-room was 0.17 K/h and therefore clearly below the 0.21 K/h of the conventional room.

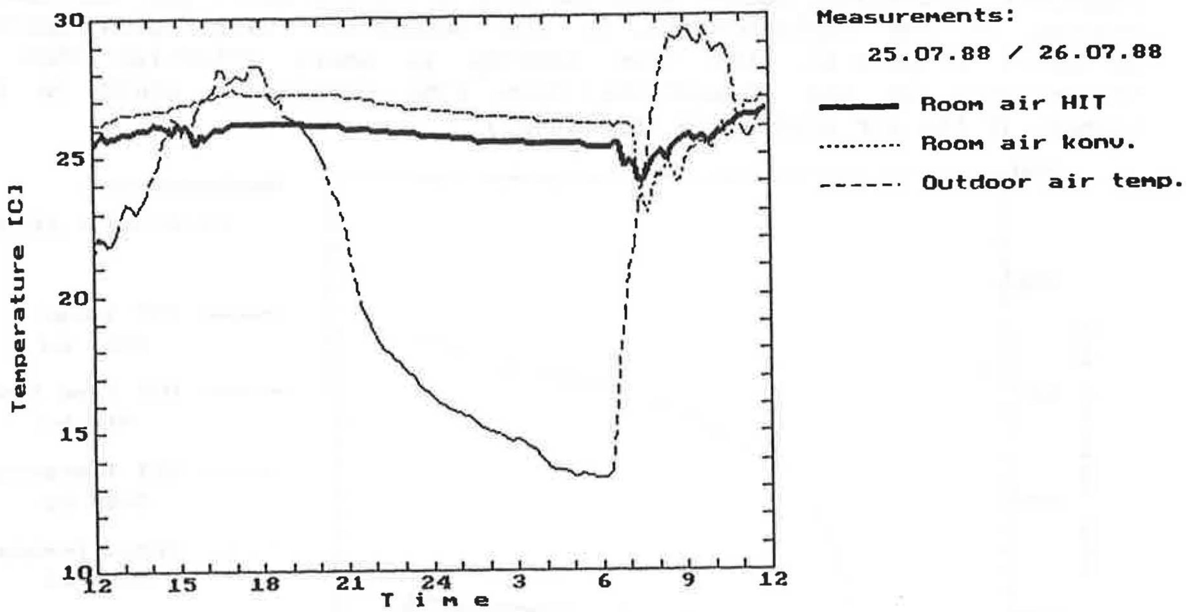

Fig. 2. Measured air temperatures of the HIT-room, the conventional room and outside for july 25/26 1988. At night, the mechanical ventilation of the HIT-part was practically out of operation.

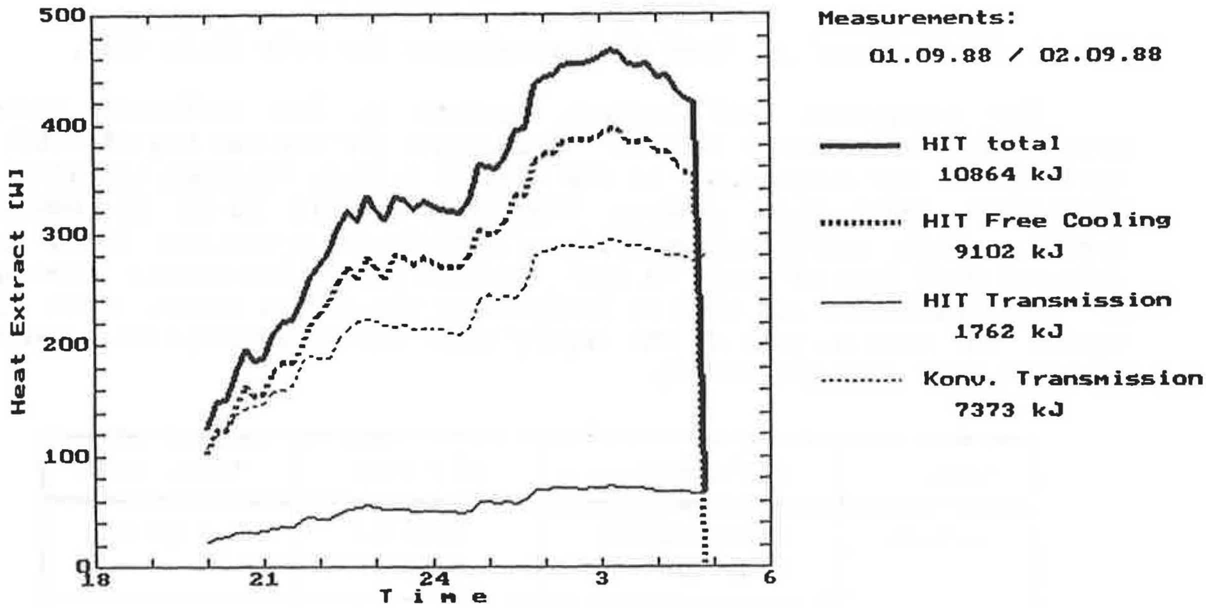

Fig. 3. Heat removal at night by free cooling and transmission for the HIT-room, and by transmission for the conventional room for september 1/2 1988.

The transmission losses were calculated from the difference of the measured room air temperature minus outdoor temperature and with the U-values of the facade, which are known from the construction: 0.68 W/m²K for the HIT-part and 2.2 W/m²K for the conventional part. The heat extracted by the mechanical ventilation was calculated from the measured air volume rate and the measured temperatures at the air inlet and outlet. The evolution in time is shown in figure 3 (HIT-room with free cooling) and figure 4 (HIT-room without free cooling). Due to the permanent dropping of the outdoor air temperature during the course of the night, all the transport mechanisms become more and more efficient until the maximum is reached in the early morning. If the mechanical ventilation operates correctly (figure 3), the free cooling is moore effective than the transmission at the conventional room. (The efficiency could be much higher, if the air ducts were insulated.)

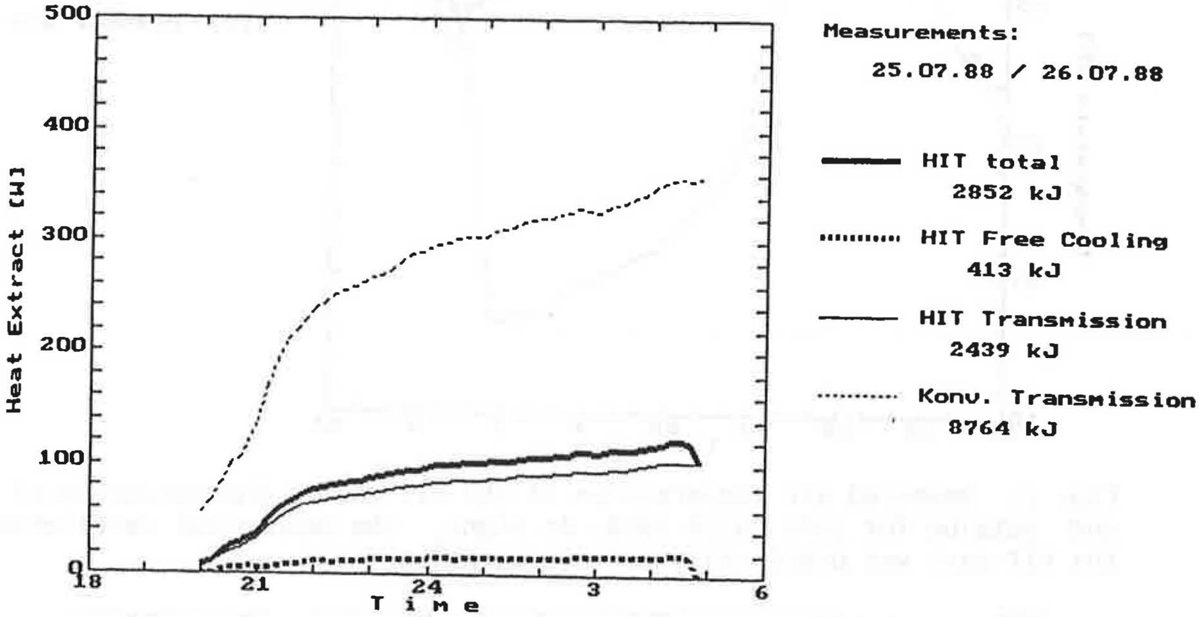

Fig. 4. Heat removal at night by transmission for july 25/26 1988.

The integrated heat amounts removed by the different transport mechanisms are listed in table 1. Once again one can see how effectiv free cooling is. For comparison: in the case of 1./2.9. (correct operation) the mechanical ventilation removes from 20.00 t until 05.00 an amount of energy, which could have been accumulated during 9 working hours by an internal heat load of about 12 W/m². In this case, the energy consumption of the ventilators was 6000 kJ (related to the office room). This amount should be seen as part of the yearly total energy consumption, which is extremely low (see chapter 4).

case	mechanism	HIT-room	conv. room
1./2.9.	transmission free cooling	1762 kJ 9102 kJ	7373 kJ -
	total	10864 kJ	7373 kJ
25./26.7.	transmission free cooling	2439 kJ 413 kJ	8764 kJ -
	total	2852 kJ	8764 kJ

Table 1: Heat amount removed from the two observed rooms, both with 24 m²

floor area, during the nights of 1./2.9.88, and 25./26.7.88, from 20.00 to 05.00.

Computer Simulation

A Simple, but Comprehensive Model

HIT-KOMFORT is a software package for the dynamical simulation of the thermal behavior of a single office room. Important features are the inclusion of the

- behavior of the occupant
- heat production of machines and lights
- heat load of the sun (with or without sun protection)
- transmission losses to the outside
- heat flux into heavy masses (floor)
- heat flux into light masses (walls and furniture)
- convective and radiative heat exchange between the different heat capacitors
- different HVAC and control systems (also window opening)
- real weather data (hourly observations)

The time step is 6 minutes (which is less than the time constant of the room air - capacity). The simulation time can be selected according to the aims:

- one year: energy consumption and statistical distribution of the room air temperature
- a few days: evolution of temperature in time, state of different devices, energy fluxes

The model has been validated with measurements of real buildings. It is a tool for parametric studies (research and consulting) and for the interpretation of observations (research).

The Simulation of Free Cooling

The free cooling - case 1./2.9.88 was investigated with the HIT-KOMFORT simulation model. Observational data were used as input. In order to overcome the problem with the start conditions (e.g. floor temperatures), a period of 7 days was precalculated (which is distinctly more than the time constant of the building). The calculated temperatures of the room air and of the inner window surface compare very well to the observations. This is especially true for the decay at night.

Figure 5 shows the energy fluxes to the room by the sources (sun, persons, machines), transmission and the mechanical ventilation. Different influences can be seen, for example:

- handling of the sun protection at 8 am and 2 pm
- reduction of the staff and machines at 1 pm
- ventilation turned off at 11 am (outdoor temperature exeeded 22°C)
- simulated window opening from 11 am until 1 pm.
- free cooling (compare the shape of the curve with the

heavy dotted line in figure 3)

In the morning of the first day, only a small part of the internal heat load was removed by ventilation. Consequently, the room air temperature was raised by 3.0 K within 8 hours. At 5 pm, the heat input practically stopped. The room air temperature immediately began to sink due to thermal discharge of the room air to the masses. During the night, the room air temperature was governed by free cooling. The overall temperature reduction was 2.8 K.

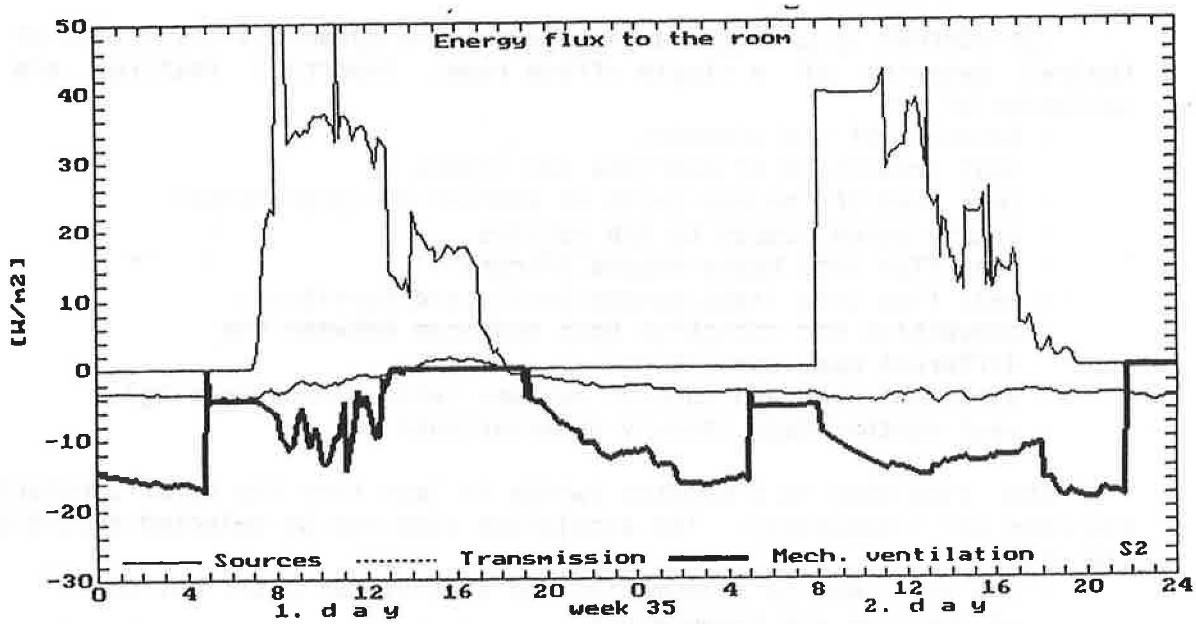

Fig. 5. Energy fluxes [W/m² floor area] to the room over 48 hours from the sources (sun, lights, machines, persons), the transmission and the ventilation (mechanical and window).

All heat input, which is not immediately removed, is stored in the different masses: these are the massive materials (floor, walls, furniture) with a thermal capacity of approximately 20 MJ/K and the room air with a capacity of somewhat less than 0.1 MJ/K. Clearly, the air is unimportant as a heat capacity.

Figure 6 shows the process of the thermal charge and discharge of the massive materials over the period of the two days. Until around 7.00 a.m. of the first day, heat is removed by free cooling (until 5.00 a.m.) and passive cooling by the mechanical ventilation. During the working time of the first day, the larger part of the internally produced heat energy (0.75 MJ/m²) is stored in the masses. Running in the free cooling mode (until 5.00 a.m.), the mechanical ventilation (and to a small extent the transmission) removes 0.53 MJ/m². At 8.00 a.m. of the second day the surplus amount of 0.15 MJ/m² is still present.

If free cooling would be out of operation, the transmission would remove only 0.10 MJ/m² until 5.00 a.m. (instead of 0.53 MJ/m²). As a consequence, the room air temperatures would be 0.5 K higher during the next day. During a hot weather period, this would result in an effective heat accumulation. (This theoretical result was observed in reality: Due to an error, the free cooling was not in operation during a few summer days.)

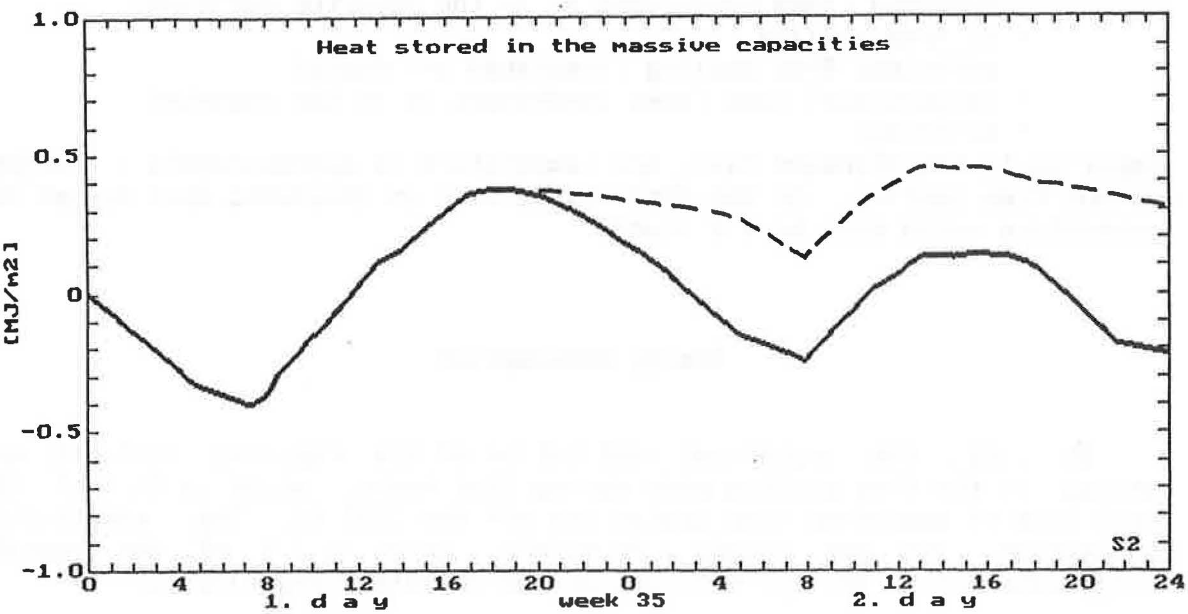

Fig. 6. Heat energy stored in the masses (floor, walls, furniture) in [MJ/m² floor area]. Simulation of the real case (solid line) and of the hypothetical case without free cooling (broken line).

The effect of free cooling during long warm periods

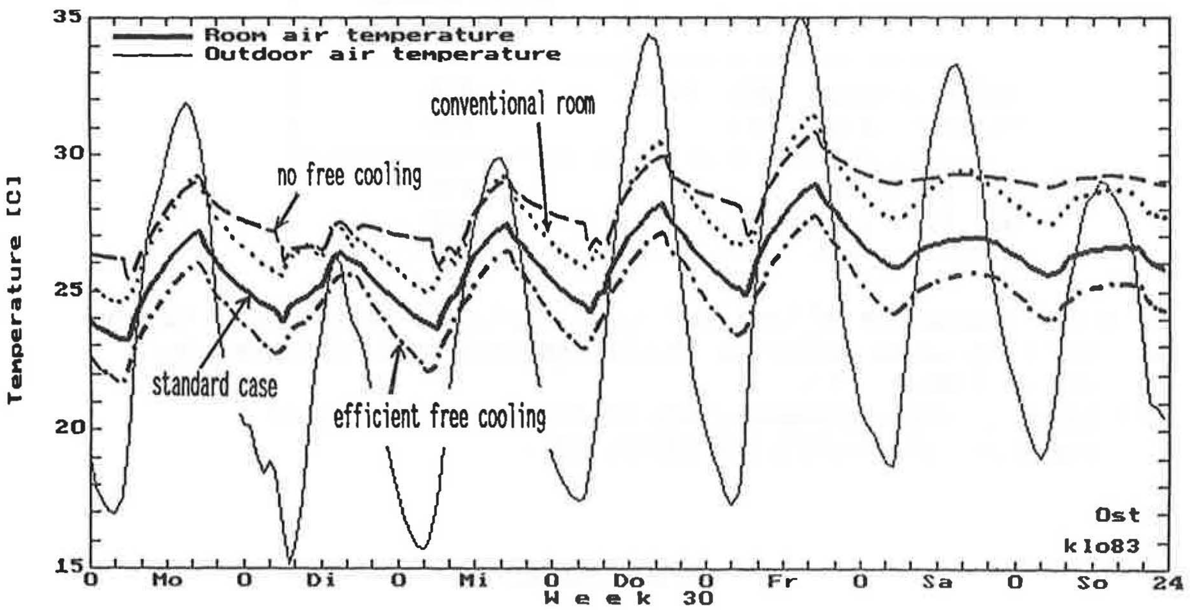

Fig. 7. Results of simulations with weather data of an extremely warm period of Zürich-Kloten 1983. Different cases are presented: standard, no free cooling, efficient free cooling, conventional room (natural ventilation only)

The simulation model allows to investigate the effect of free cooling during long warm periods. The weeks 29 and 30 in the meteorological data set of Zürich-Kloten 1983 were chosen as an example. Again, the first week was used as precalculation period for mathematical reasons. In figure 7, the results of different cases are presented:

- standard (same conditions as in the reported building)
- no free cooling
- efficient free cooling (insulated air ducts)
- conventional room (same conditions as in the reported building)

Comparing to the standard case, the temperature is approximately 2 K higher without free cooling. On the other hand, with an insulated duct system the temperature could even be 1 K lower.

Energy Consumption

In 1988, the mechanical ventilation of the reported building was running in the free cooling mode during 1502 hours, which is 28 % of the total time of operation (the system was off for 3390 h). The electricity consumption was approximately 24 MJ/m^2a, which is 7 % of the overall energy consumption for the HIT-part of the building (360 MJ/m^2a).

Although conditions for the extension of the building were not optimum (certain heat leaks such as outside columns could not be avoided), the energy consumption is far below the nominal value for Switzerland. In other words, free cooling consumed only a small portion of the total energy consumption, which was also extremely low (see table 2).

	total energy MJ/m^2a
swiss average 1988 (*)	825
nominal value (**)	415
HIT 5. floor	332
HIT 5. + 6. floor	360

Table 2. Consumption of heat and total energy of different buildings.
(*) Existing swiss buildings (buildings with heavy deficiencies are excluded), (7).
(**) based on the recommendations of the Swiss Society of Engineers and Architects (SIA), (8).

Conclusion

Measurements of the performance of a real office building prove, that free cooling is an effective and energy saving means to remove excess heat from the rooms. During the day, a large portion of the internal heat load is stored in the masses. The discharge follows at night by free cooling.

Free cooling can be used to avoid the operation of a cooling unit. But if the HVAC-system has a cooling unit, the free cooling mode is a way to reduce the energy consumption of the air-conditioning.

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