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PASSIVE COOLING BY NIGHT-TIME VENTILATION USING CLIMATE RESPONSIVE ELEMENTS

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ZUSAMMENFASSUNG

In the first part of the project, the climatic potential for the passive cooling of buildings by night-time ventilation was evaluated. The results show a very high potential for night-time ventilative cooling over the whole of Northern Europe and a still significant potential in Central, Eastern and even some regions of Southern Europe. However, given the inherent stochastic properties of weather patterns, series of warmer nights can occur at some locations, where passive cooling by night-time ventilation alone might not suffice to guarantee thermal comfort. Furthermore a significant reduction in the potential for night cooling was found due to climate change. Even if the potential might not always be sufficient to assure thermal comfort, night-time ventilation can still be used to reduce the cooling energy demand in buildings using hybrid systems.

Parameter studies showed the effect and the interrelation of different parameters such as heat transfer coefficients, thermal properties, building construction, internal and solar heat gains, the night ventilation air change rate, and climatic conditions. Thermal comfort in an office with night-time ventilation was found to be highly sensitive to climatic conditions, which confirms the results from the climatic studies and underlines the significance of high-quality climatic data for building energy simulations. Building construction (thermal mass) and heat gains also have a considerable effect on thermal comfort in summer. Therefore, as much thermal mass as possible should be placed in contact with the room air (e.g. avoidance of suspended ceilings) and heat gains should be limited by applying energy-efficient office equipment, daylight utilisation, and the installation of an effective solar shading system. Simulations with different night ventilation air change rates clearly demonstrated the effectiveness of night-time ventilation, as increased flow rates significantly reduced overheating degree hours. Heat transfer between the internal surfaces and the room air was found to have only a minor effect if the heat transfer coefficients vary in the range from 5.9 to 10 W/m^2K. While further increase does not significantly improve night ventilation performance, much higher sensitivity was found for HTCs below about $h = 4$ W/m^2K. More detailed investigations of convective and radiative heat transfer including CFD-simulations and full scale experiments are needed in order to decide whether the resulting combined heat transfer coefficients lie within the range of high sensitivity.

Projektziele

During the last decades, a trend towards increasing cooling demand in buildings can be observed in Europe [1], [2]. This is especially true in commercial buildings, where high internal loads in combination with high solar gains through extensive glazing systems lead to considerable cooling loads, even in moderate and cold climates like in Central or Northern Europe. An additional rise of the cooling demand is caused by the global climate warming, which is expected to increase summertime temperatures significantly. While the heating demand can be effectively reduced by installing thermal insulation, cooling plays a more significant role in the overall energy demand of buildings.

Particularly in moderate and cold climates with relatively low night-time temperatures, night-time ventilation seems to be a promising technique to reduce the cooling energy demand of buildings. The basic concept involves cooling the building structure overnight in order to provide a heat sink that is available during occupancy periods. The ventilation with cold air during the night can be driven by thermal buoyancy and wind forces (natural ventilation), or be supported by a mechanical fan (hybrid/mechanical ventilation). As naturally driven systems are highly sensitive to ambient conditions, reliable planning tools are needed to encourage a widespread application of this method.

The goals of the project are:

- To evaluate possibilities and limitations of passive cooling by night-time ventilation in present and future climates
- To improve the building design knowledge in the field of passive cooling
- To understand the impact of geometrical and physical parameters (amount of thermal mass, heat gains, air exchange rate etc.) on the cooling effect
- To develop an engineering model to be implemented in Building Energy Simulation tools
- To demonstrate the application potential of climate responsive elements

Durchgeführte Arbeiten und erreichte Ergebnisse

Evaluation of possibilities and limitations of passive cooling by night-time ventilation in present and future climates

See last year's report (Passive cooling by night-time ventilation using climate responsive elements, Jahresbericht 2006) and [3], [4], [5].

Parametric study on the dynamic heat storage capacity of building elements

As heat gains and night ventilation periods do not coincide in time, the energy of daily heat gains needs to be stored until it can be discharged by ventilation during the following night. A sufficient amount of thermal mass is therefore needed for a successful application of night-time ventilation. For effective utilisation of the thermal mass both a sufficient heat transfer to the surface and sufficient conduction within the element are needed. The purpose of this study was to evaluate the impact of different parameters such as material properties, slab thickness and heat transfer coefficient on the heat storage capacity of building elements [6].

In this study a building element was represented by an infinite homogeneous slab with half-thickness d. One surface of the slab is exposed to a varying temperature, while the other surface is considered adiabatic. The analytical solution to the heat transfer problem in a slab with convective boundary condition and sinusoidally varying air temperature [7] was used to calculate the temperature profiles in the slab and the dynamic heat storage capacity of the element. Applying this model the impact of the following parameters was investigated:

- Heat transfer coefficient, h	(W/m^2K)
- Half thickness of the slab, d	(mm)
- Thermal conductivity, λ	(W/mK)
- Volumetric heat capacity, ρc	(J/m^3K)

As the performance of night-time ventilation mostly depends on diurnal temperature variations, all calculations were based on a 24 h time period.

The following effects were found:

The impact of the heat transfer coefficient depends greatly on slab thickness and the thermal properties of the material. For thick and heavy elements such as a concrete ceiling or lime sand brick walls increasing the heat transfer coefficient up to h = 30 W/m^{2}K significantly increases the diurnal heat storage capacity. In contrast, the heat storage capacity of thin, light-weight constructions such as gypsum board walls is generally small and can not be enhanced by increasing the heat transfer coefficients above h = 3 W/m^{2}K (Fig 1, left).

Increasing the slab thickness clearly raises the diurnal heat storage capacity until a maximum is reached. Beyond the maximum the capacity decreases slightly and converges to a constant value as the thickness approaches infinity. The optimum thickness depends on the thermal properties of the material and the heat transfer at the surface. For a concrete slab the optimum thickness increases from about d = 90 mm to 140 mm if the heat transfer coefficient increases from h = 5 W/m^{2}K to h = 30 W/m^{2}K (Fig 1 right).

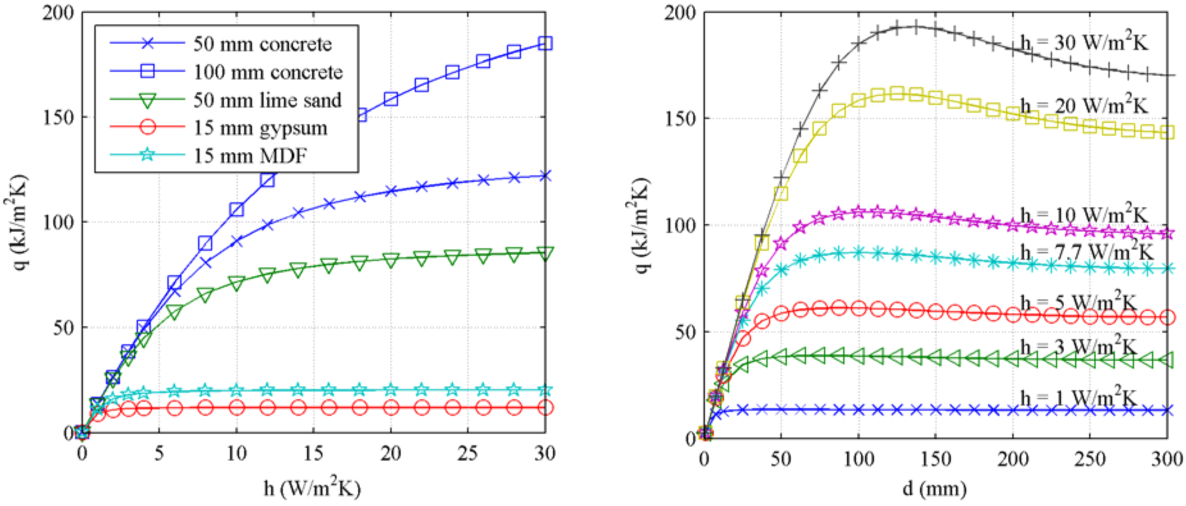

Fig 1 Diurnal heat storage capacity, q depending on the heat transfer coefficient, h for different materials and slab thicknesses (left). Diurnal heat storage capacity, q of a concrete slab depending on the thickness, d for different heat transfer coefficients, h (right).

For thin slabs (d = 15 mm) there is almost no impact of the conductivity in the range from λ = 0.05 W/mK to λ = 50 W/mK. For thicker slabs the heat storage capacity increases with increasing conductivity. However, in most cases the storage capacity increases only slightly for conductivities above 1.8 W/mK (concrete). Only in the case of thick slabs (d = 100 mm) in combination with a high heat transfer coefficient (h = 20 W/m^{2}K) does the storage capacity increase with conductivities up to 50 W/mK.

The heat storage capacity of very light materials such as insulation materials with ρc < 0.1 MJ/m^{3}K is generally very small. Increasing the thermal capacity to the value of concrete (ρc = 2.6 MJ/m^{3}K) significantly improves the storage capacity. Further improvement for capacities above ρc = 2.6 MJ/m^{3}K is only achieved for thin slabs or at very high heat transfer coefficients.

A well known possibility for increasing the thermal heat capacity of building elements is the integration of phase change materials (PCM). PCMs, like paraffins or salt hydrides, absorb and release a considerable amount of heat during the melting and solidification process. If the melting temperature of the PCM lies in the range of thermal comfort, the latent heat can be utilised to increase the heat storage capacity of a building element. A possible approach is the integration of micro-encapsulated PCMs into gypsum plaster boards or plaster [8]. For a rough estimation of the effect of PCMs on the heat storage capacity a very simple model was used in this study [6].

The heat storage capacity of a 15 mm thick gypsum plaster board with different PCM contents was compared to concrete slabs of different thicknesses. While the heat capacity of the plain gypsum plaster board is constant for heat transfer coefficients above 3 W/m^{2}K, the capacity of the boards with integrated PCM continuously increase with increasing heat transfer coefficients up to 30 W/m^{2}K. The plaster boards with 20 % and 40 % PCM content show similar performance to a 50 mm and 100 mm thick concrete slab, respectively. This clearly shows the feasibility of PCM integration for improving the thermal performance of light-weight wall constructions.

The heat storage capacity of building elements is an important precondition for the application of night-time ventilation. However, the effectiveness of night-time ventilation also depends on other parameters such as internal and solar heat gains, outdoor air temperature and ventilation air change rate, which were not considered in the model used in this study. The impact of these parameters was investigated in the following study using building energy simulation.

Parameter study on performance of building cooling by night-time ventilation

The objective of this study [9] was to assess the effect of different parameters on the effectiveness of night-time ventilation. In contrast to other studies a wide range of heat transfer coefficients at the internal surfaces was considered, and their effect on the night cooling performance was compared to the effect of other parameters.

The HELIOS [10] building energy simulation programme was used to model a standard office room. Starting from a base case, different parameters were varied to assess their effect on night ventilation performance. Performance was rated by evaluating overheating degree hours of the operative room temperature above 26 °C (ODH$_{26}$). Different standards use different definitions for summer time thermal comfort with limits for overheating corresponding to about 100 to 400 Kh/a above 26 °C.

First the impact of climatic conditions was assessed by comparing different climatic data for Zurich. The datasets used were measured data from the period 1981 to 2005 (ANETZ, the automatic measurement network operated by MeteoSchweiz), Meteonorm [11] standard and 10-year maximum data and DRY data (Design Reference Year based on measurements from 1981-1990).

The different climatic datasets were used to simulate thermal comfort in a medium thermal mass office with high internal heat gains (Fig 2). Under climatic conditions measured during the period 1981-2005, overheating degree hours varied within a wide range from 24 to 900 Kh/a. The high value of 900 Kh was reached in 2003, with summer temperatures more than 3 K above the average. These results clearly demonstrate the high sensitivity to annual climatic variability and the climatic limitations of building cooling by night-time ventilation.

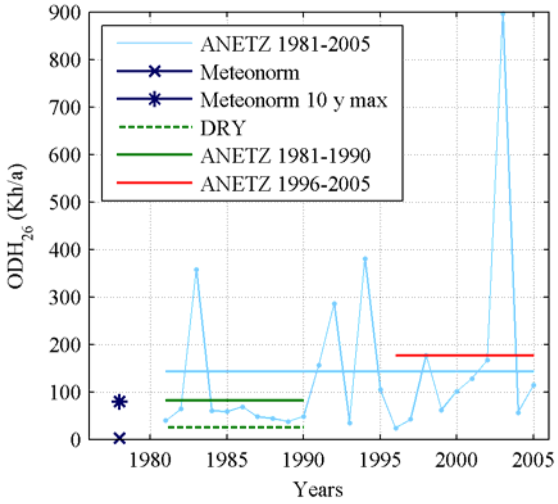

Fig 2 Overheating degree hours, ODH$_{26}$, based on different climatic data for Zurich SMA: ANETZ 1981-2005, Meteonorm (standard and 10-year maximum), DRY, ANETZ 1981-1990 (mean) and ANETZ 1996-2005 (mean); medium thermal mass, high level of internal heat gains, air change rate 6 ACH, all heat transfer coefficients h = 7.7 W/m^{2}K.

Compared to measured climate data, simulations based on Meteonorm or DRY data resulted in a far lesser extent of overheating (Fig 2). Even applying the 10-year maximum Meteonorm data (based on 10 year maximum monthly mean temperatures) resulted in ODH$_{26}$ values below the mean results based on ANETZ data. This clearly shows that simulations based on commonly-used climatic data do not allow reliable predictions of thermal comfort in summer. The application of climatic data from long-term measurements including extreme weather conditions is therefore recommended.

The effect of local climate variability was studied applying Meteonorm data from 8 different locations in Europe. Simulations for different locations yielded good thermal comfort for all Central and Northern European conditions, while overheating degree hours clearly exceeded the comfort limit in Southern European climate. This generally agrees with the findings of the study on the climatic potential for night-time ventilation [4] performed during the first year of the project.

For all following simulations ANETZ data from the period 1996 to 2005 for Zurich SMA were used (Fig 2).

In order to investigate the effects of thermal mass and heat gains, three different building constructions (light, medium and heavy) and three different levels of internal heat gains (low medium and high) were defined (see [9]). Both parameters had an effect of similar magnitude. Increasing thermal mass or decreasing heat gains from one level to the next decreased overheating degree hours by a factor of 2 - 3 each. In order to achieve good thermal comfort, as much thermal mass as possible should be placed in contact with the room air (e.g. avoidance of suspended ceilings) and heat gains should be limited by applying energy-efficient office equipment, daylight utilisation and the installation of an effective solar shading system.

Evaluation of thermal comfort as a function of the night ventilation air change rate clearly demonstrated the effectiveness of night cooling. In all cases, night-time ventilation even at relatively moderate air change rates of about 4 ACH significantly reduced overheating degree hours. In some cases, significant improvement was found when further increasing the night ventilation air change rate. The critical air change rate beyond which no significant improvement in absolute OHD_{26} values occurred was between 4 and 20 ACH, increasing with increasing heat gains and with decreasing thermal mass.

The very high sensitivity to night ventilation air change rates up to 4 ACH makes predictions of thermal comfort very uncertain. This is especially true for buildings using natural night ventilation, where the air change rate depends on ambient temperature and wind conditions. If natural ventilation depends mainly on buoyancy forces, low air flow rates coincide with high temperatures, and the cooling effect is smallest during warm periods. Additionally, sensitivity to the air change rate is enhanced even more if the dependency of heat transfer on the flow rate is considered. Therefore, in cases where air change rates in the range of high sensitivity are to be expected, the application of a hybrid ventilation system should be considered. In hybrid ventilation, a mechanical system is used whenever natural forces are not sufficient to ensure a certain ventilation rate. A shortfall of the critical air flow rate can thus be prevented and the risk of overheating reduced.

In contrast to many previous studies a wide range of heat transfer coefficients (HTC) at the internal surfaces from 0.7 to 22 W/m^2K was considered. For combined (convective and radiative) heat transfer the European standard EN ISO 6946 [12] states $h = 5.9\ W/m^2K$ for downward and $h = 10\ W/m^2K$ for upward heat flows. However, it must be considered that combined heat transfer coefficients are a very simplified representation of the real situation. In this model, heat can only be exchanged between wall surfaces and the room air, but not directly between surfaces. Heat transfer by radiation is accounted for by applying increased HTCs, and radiative heat flows therefore depend on the temperature difference between the surfaces and room air. If all surfaces have a similar temperature which is higher than the room temperature – this is a typical situation during night-time ventilation – the model overestimates the radiative heat flow. Particularly at surfaces with downward heat flow, the coefficient for convective heat transfer alone ($h = 0.7\ W/m^2K$ [13]) is considerably lower than the coefficient for combined heat flow ($h = 5.9\ W/m^2K$ [12]), i.e. during night-time cooling in particular heat transfer at the ceiling might be overestimated by a combined heat flow model. On the other hand during night-time ventilation, a higher heat transfer is expected due to the increased air flow rate and the possibility of a cold air jet flowing along the ceiling.

Figure 3 shows detailed information on the effect of combined heat transfer coefficients. In Figure 3a, the heat transfer coefficients at all internal surfaces were changed during day and night, while in 3b HTCs were changed only during night-time ventilation, and in Figure 3c only the HTC at the ceiling was changed during night-time ventilation. All other HTCs were constant $h = 7.7\ W/m^2K$.

Variation of HTCs at all surfaces during day and night within the range given in EN ISO 6946 [12] only showed a relatively small effect. Also increasing the HTCs during night ventilation up to $h = 22\ W/m^2K$ reduced overheating only slightly. However, the effect was much more significant for lower HTCs (below about 4 W/m^{2}K). Therefore depending on the expected range of HTCs, thermal comfort can be highly sensitive to heat transfer coefficients.

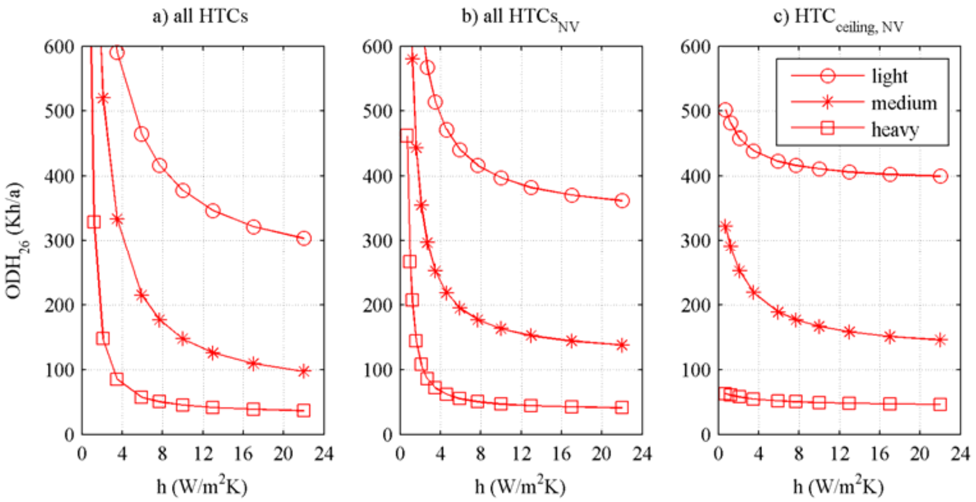

Fig 3 Overheating degree hours, ODH$_{26}$ as a function of heat transfer coefficients for different building constructions (light, medium and heavy mass); a) all surfaces, day and night, b) all surfaces, night ventilation and c) ceiling, night ventilation; high internal heat gains; 6 ACH; Zurich, ANETZ 1996-2005.

Nationale Zusammenarbeit

The evaluation of future climate scenarios has been performed in collaboration with D. Gyalistras, Institute for Integrative Biology, ETH Zurich.

Internationale Zusammenarbeit

Within the frame of this BFE-project a PhD-thesis (N. Artmann) will be written. The major professor is P. Heiselberg from the, Department of Civil Engineering, Aalborg University, Denmark. Full scale experiments will be conducted in the laboratories of the Hybrid Ventilation Centre.

The project is integrated in the IEA Annex 44 Integrating Environmentally Responsive Elements in Buildings which is led by P. Heiselberg. Until now N. Artmann participated in three meetings: Torino, March 29th to 31st, 2006, Graz, September 11th to 13th, 2006 and Lisbon, April 16th to 19th, 2007.

Bewertung 2007 und Ausblick 2008

A parametric study using an analytical solution to the heat transfer problem in an infinite homogeneous slab clearly showed the impact and the interrelation of different parameters on the dynamic heat storage capacity of building elements. This study also demonstrated the effectiveness of phase change materials integrated in thin light-weight elements.

The analytic model is appropriate to analyse the dynamic heat storage capacity of a single element. However, several building elements with different properties are typically present in a real room. If the different elements have different surface temperatures, energy is not only transferred by convection to the room air, but also by radiation between the elements. The interaction of different building elements and the impact of convective and radiative heat transfer need to be investigated in more detail.

In a second parameter study building energy simulation was used to investigate the effect of climatic conditions, internal and solar heat gains, building construction, air change rate, and heat transfer coefficients on the performance of building cooling by night-time ventilation. Thermal comfort was found to be very sensitive to climatic conditions. This clearly shows the significance of high-quality climatic data for building energy simulations and demonstrates the importance of the climatic studies performed during the first year of the project.

Simulations with different night ventilation air change rates clearly demonstrated the effectiveness of night-time ventilation, as increased flow rates significantly reduced overheating degree hours.

During night-time ventilation the heat transfer coefficients between the internal surfaces and the room air can vary within a wide range. While increasing HTCs to values up to h = 22 W/m^{2}K improved night ventilation only slightly, a very high sensitivity was found for HTCs below about h = 4 W/m^{2}K. More detailed analysis of convective and radiative heat transfer is needed to determine under which condition the resulting combined HTC is within this range of high sensitivity.

Therefore, the effect of indoor air temperature distribution and near-surface velocities on heat transfer needs closer investigation. Further work will be conducted within the project including a detailed simulation of the indoor air flow patterns by means of computational fluid dynamics (CFD) and full scale experiments.

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Anhang