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Design of passive cooling by night ventilation: evaluation of a parametric model and building simulation with measurements

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Abstract

At the new institute building of Fraunhofer ISE, both mechanical and free night ventilation is used for passive cooling of the offices. The results from a long-term monitoring show, that room temperatures are comfortable even at high ambient air temperatures. In two offices, experiments were carried out in order to determine the efficiency of night ventilation dependent on air change rate, solar and internal heat gains. The aim is to identify characteristic building parameters and to determine the night ventilation effect with these parameters. The experiments (one room with and one without night ventilation) are evaluated by using both a parametric model and the ESP-r building simulation programme. Both models are merged in order to develop a method for data evaluation in office buildings with night ventilation and to provide a simple model for integration in a building management system.

Keywords: Night ventilation; Design; Parametric model; Building simulation; Performance criteria

1. Introduction

Night ventilation potential for improving comfort has mainly been investigated by numerical means. Santamouris and co-workers [34,35] introduced an integrated method to calculate the energy contribution of night ventilation techniques to the cooling load of a building. Kolokotroni and Aronis [26] states that both free and mechanical night ventilation reduces the plant capacity and the energy consumption in air-conditioned office buildings.

This paper focuses on a full-scale experiment and its evaluation. Kolokotroni et al. [25] used temperature/humidity-charts for data evaluation of results from a simulation in order to generate a pre-design tool for summer cooling with night ventilation for office buildings in moderate climates. Geros et al. [17] carried out an experimental evaluation of night ventilation of four different buildings. Additionally, simulation investigations are used to determine how the air change rates, the building construction and the climatic parameters affects the night ventilation. The data evaluation deals with the nocturnal air change rates and the indoor air temperature. Givoni [18] carried out experiments in a low and a high mass building in order to determine the effectiveness of mass and night ventilation in lowering the indoor daytime temperatures. Givoni derives a simple model for the daytime maximum temperature from an extensive data analysis. This model does not take the user behaviour and internal heat gains into account. Blondeau et al. [6] carried out full-scale measurements in a three level office building. The data evaluation deals with both comfort criteria and energy balance. Blondeau points out that the modelling of heat transfer coefficients in building simulation programmes is difficult and emphasises that further research is necessary to characterise the building potential for night ventilation. Herkel et al. [21] used a similar approach in order to evaluate the night ventilation efficiency with data from a long-term measurement. The experiments, which are evaluated in this paper, have been designed against this background.

1.1. Modelling the night ventilation efficiency

In modelling the night ventilation effect there are some crucial points:

- *Natural, hybrid and mechanical ventilation*: As most night ventilation concepts are based on a free or a hybrid ventilation concept, the air change rates must be calculated. Due to the different driving forces (wind, buoyancy and fan driven ventilation), the design of free and hybrid ventilation and interzonal air exchange is complex. Therefore,

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sophisticated design tools should be used in order to determine the air change rates. Feustel and Dieris [14] presents a survey of airflow models for multizone structures. Aynsley [4] introduces a resistance approach to analysis of natural ventilation airflow networks. Most programmes work with a resistances approach. An extensive overview over the airflow through openings, ventilation, infiltration and interzonal air exchange is given by Allard and Utsumi [3]. Often the discharge coefficients for openings are unknown. Some measurements of discharge coefficients and conclusions on air flow through buildings are summarised by Flourentzou et al. [15]. Heiselberg [20] introduces the principles of hybrid ventilation. In urban areas, the environmental impact on passive ventilation cooling has to be taken into account. A survey is given by Kolokotroni et al. [27]. In addition to the interzonal air flow models, the air movements in naturally ventilated buildings should be taken into account. The air movements can be investigated using CFD [5] or measurements [12].

- *Heat transfer*: As the night ventilation cools down the building construction, an accurate modelling of the convective heat transfer coefficient is essential for the simulation of night ventilation. A good survey on different models for building applications is given by Dascalaki et al. [9]. The standard deviation in different models for calculation of heat transfer coefficients is around 20–40% (cp. uncertainty in modelling). From the multitude of models, the data correlations by Alamdari and Hammond [2] and Khalifa and Marshall [24] will be used for calculating the night ventilation efficiency because these models show a good agreement between measurement and simulation.
- *Heat storage*: The heat storage capacity of a room consists of the thermally utilisable heat storage capacity of all boundary surfaces and of the furniture. It is dependent on (1) the thickness of each construction, (2) its thermal properties, (3) the period of the fluctuation of the undisturbed air temperature and (4) the heat transfer at the surface or the Biot number, respectively. As the amplitude of the temperature oscillation diminishes with the depth, the analytical solution deals with the thermal penetration depth, cp. [7] or any other textbook on heat conduction. The thermally active heat storage capacity is calculated analytically according to Keller's [22] recommendation. This method is similar to the numerical solution, which is required by ISO 13786 [13], and results in the same heat storage capacity. A good survey on the convective heat balance of a room and the storable energy in a concrete slab was given by Koschenz and Dorer [28]. While the heat storage capacity influences the energy balance in winter only insignificantly, a high heat storage capacity diminishes room temperature fluctuations in summer during a change in the weather [19].

As the night ventilation lowers the room temperature in order to improve the thermal comfort, the data analysis should deal with comfort criteria. Different comfort criteria are in scientific discussion [31]. As the evaluation of passive cooling focuses on the energy balance, this paper deals with two simple comfort criteria, which are based on the operative room temperature:

- According to the German norm DIN 1946 [11], the operative room temperature should lie in between 22 and 25 °C up to an ambient temperature of 26 °C. Still acceptable room temperatures lie in between 20 and 26 °C. The comfortable room temperature is higher at ambient temperatures above 26 °C. Though this norm is valid only for ventilated and air conditioned buildings, it is also used for passively cooled buildings. As this comfort criterion takes the ambient temperature into account, it can be used directly for data evaluation, cp. Fig. 6.
- According to Rouvel and co-workers's study [10], the room temperature should not exceed a given temperature limit at more than 10% of the working time. The temperature limit is dependent on a pre-defined climate region (e.g. Freiburg, Germany: 27 °C). As this criterion is not independent from the ambient temperature, the evaluation of measured data is not universally valid. It can be noticed from an ongoing survey at a few office buildings [16], that these temperature limits are not restricted enough. Surveys in air conditioned residential buildings from the late eighties affirm [23], that room temperatures should not exceed 25 °C. Thus, Rouvel's comfort criterion is used with a temperature limit of 25 °C, cp. Fig. 5.

Some planning tools has been established in the last years. Keller [22] presented an analytical method for the thermal design of buildings, which is based on characteristic parameters. These parameters are derived from a complete mathematics solution of the energy balance of a room and will be used in this paper. A similar model based on the non-linear coupling between thermal mass and natural ventilation in buildings has been presented by Yam et al. [38]. The design tool LESOCOOL [32] merges an air flow model with a heat transfer model. This simplified model for passive cooling can calculate the cooling potential, temperature evolution and air flow rates for given heat gains and losses. A comparable programme is introduced by Rousseau and Mathews [33]. The NatVent programme [30] takes infiltration, ventilation and thermal storage into account. The NatVent programme is made to serve as a pre-design tool that can be used early in the design process before explicit data about the building and the ventilation system are made within the programme. The Swiss EMPA published a handbook on passive cooling [40]. This handbook summarises boundary conditions for passive cooling and criteria for the design of different passive cooling techniques. Concerning night ventilation, the over all cooling load should not succeed 150 Wh/(m^2 per day), if the temperature difference between day and night is less than 5 K, and 250 Wh/(m^2 per day), if the difference is higher than 10 K. For cooling with free ventilation, Zeidler [39] gives a similar limit for heat gains of 30 W/m^2 in an

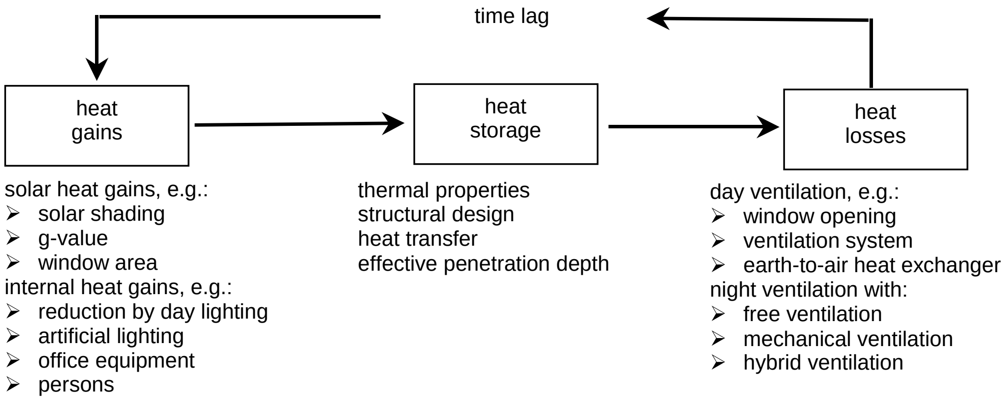

Fig. 1. Principle of night ventilation: energy balance.

office room with typical use. Surely, even more design tools are available. Self-evident, building simulation programmes can be used favourably for the design of free and mechanical night ventilation. In this paper the building simulation programme ESP-r [8] is used. In addition, different other strategies can be evaluated with building simulation in order to avoid over-heating in summer, i.e. optimised window fraction, solar gain coefficient, shading devices, hybrid ventilation with an earth-to-air heat exchanger, minimised internal heat gains and control strategies.

Finally, night ventilation should be designed according to national guidelines: the guideline VDI 2078 [36] specifies the calculation procedure for the cooling load in Germany. An uncertainty analysis should complete the design process and should be taken into account in the modelling of night ventilation. Macdonald and Strachan [29] shows the practical application of uncertainty analysis in building design. Herkel et al. [21] used an uncertainty analysis for data evaluation with building simulation.

1.2. Methodology on evaluation of experimental data

Fig. 1 outlines the principle of night ventilation: due to the heat storage, the daily heat gains are dissipated during the night. The night ventilation potential is deduced from this energy balance: heat gains, heat storage and heat losses. Thus, the aim is to identify three characteristic building parameters, i.e. the solar aperture G and internal gains Q (heat gains), the heat storage capacity C (heat storage), and the thermal loss factor H (heat losses). These characteristics, the weather data and their interactions are discussed in Section 4.

In two offices, experiments were carried out in order to determine the efficiency of night ventilation, depending on air change rate, solar and internal heat gains. During the experiments, meteorological data, air change rates, air temperatures (including three-dimensional temperature field), surface temperatures (floor, ceiling, window, and internal wall) and the operative room temperature (globe thermometer) were measured. The experiments (one room with and one without night ventilation) are evaluated by using both a parametric model and the ESP-r building simulation programme:

- The parametric model deals only with three building characteristics and few boundary data. There is a sufficient match between the parametric model and the measurements, though the model does not agree well with measurements at each time step. This model assumes, that the heat storage oscillates harmonically.
- The results from the building simulation match the measurements accurately at each time step. As the simulation programme deals with many input parameters, the night ventilation effect is intransparently evaluated. This model takes transient conditions into account.

Both the parametric model and the building simulation provide profits and hindrances. Therefore, both models are merged in order to develop a method for data evaluation in office buildings with night ventilation and to provide a simple model for

- comparison of different strategies (design process),
- data evaluation (during initial operation),
- integration into a building management system (operation and optimisation).

As a basic principle, results from experiments in buildings cannot be reproduced, as the heat storage of the building is a transient phenomenon. Using the building simulation, the measurements can be transferred into a harmonic oscillating model. With the parametric model, thermal building characteristics can be deduced from the simulation results. Thus, measured data are analysed by

1. Evaluation of measured data based on standardised graphs and indices.
2. Sophisticated building simulation using measured data and boundary conditions.
3. Data evaluation of the results from the building simulation with standardised boundary conditions using a parametric model.

1.3. *Definition of night ventilation efficiency*

Buildings with night ventilation reach lower room temperatures than buildings without active or passive cooling. Moreover, the maximum room temperature arrives later in the afternoon. Both effects are caused by the additional heat loss during the night and the heat dissipation from the fabric and the ceiling, respectively.

As shown in the previous section, the contribution of night ventilation to the operative room temperature is dependent on the heat storage capacity and the heat gains. Thus, the whole energy balance has to be taken into account though this paper focuses on night ventilation. Furthermore, heat gains and losses are dependent on the user behaviour (use of sun protection and windows) and on the operation of the ventilation system.

The night ventilation efficiency can be quantified by the thermodynamically cause (energy balance) and by its effect (room temperature): this paper evaluates the night ventilation efficiency with

1. the reduction of the room temperature,
2. the heat dissipation by night ventilation.

2. Data evaluation of long-term measurements

The institute building of Fraunhofer ISE consists of laboratories and offices [1]. The current use of the building for applied research inevitably results in a high energy demand.

Table 1
Key building information's

Gross volume (m^3)	64,320
Net floor area (m^2)	13,150
Working hours	Monday to Friday (8 a.m. to 6 p.m.)
Occupants	Approximately 300

Fig. 2. View of the institute building of Fraunhofer Institute for Solar Energy Systems, Freiburg (Germany).

Therefore, the energy demand is reduced by both the building design and the operation management [37]. Table 1 gives the key building informations.

Fig. 2 shows the façade concept with optimised day lighting (indirect roof light) and solar heat gains (summer/winter): the deep winter sun can be used for passive solar heating while the solar obstruction prevents over-heating by the high summer sun.

The technical facilities, the energy use in offices and the room temperatures are monitored by a long-term measurement. This paper deals only with room temperatures in the office rooms in one of the three wings, Fig. 3.

The laboratories (facing North) are mechanically ventilated and must be hydraulically separated from the corridor. Due to the parallel use of laboratories and office rooms (facing South), the office rooms cannot be ventilated by free cross-ventilation. Thus, there is a need of mechanical ventilation (only exhaust air). The ventilation system ensures

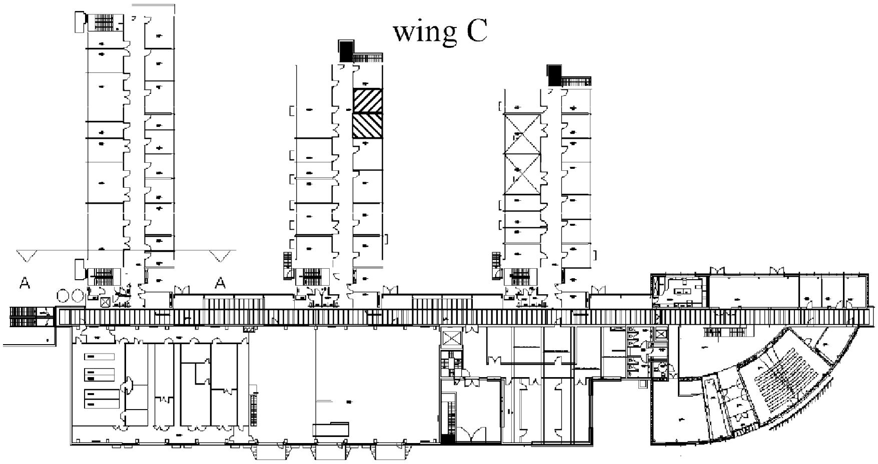

Fig. 3. Floor plan. All office rooms in the building wing C are facing South and the laboratories North. The two office rooms (experiments) are on the ground floor.

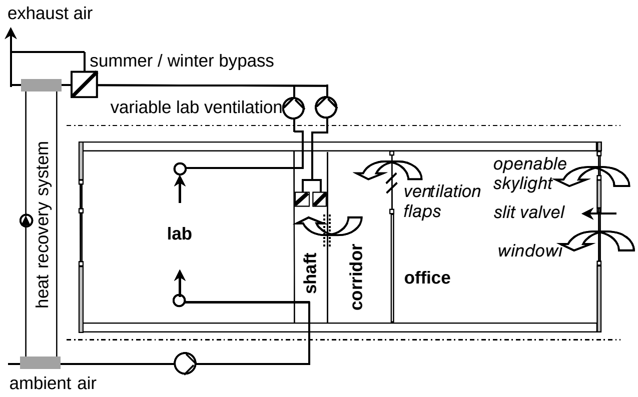

Fig. 4. Ventilation of the office rooms with heat recovery in winter and night ventilation in summer. The air exchange can be intensified by single-sided ventilation (windows).

a minimum air change rate of 1 h^{-1} during working hours. A heat recovery system recycles the waste energy to the supply air for the laboratories in winter. In summer nights, the air change rate in the office rooms is increased to 5 h^{-1}, Fig. 4.

The results from a monitoring of room temperatures in 21 office rooms during summer 2002 show that room temperatures exceeds 25 °C in less than 8% of the working hours, even at high ambient air temperatures. Fig. 5 illustrates the room temperatures in the office rooms in the ground floor (C1), the first (C2) and the second (C3) floor for the whole year 2002. Despite of identical construction and (almost) same climatic boundary conditions, there are strong differences in temperature level: the room temperatures differs dependent on user behaviour (window opening and sun protection) and internal heat gains (persons and equipment).

The different thermal behaviour in these office rooms can be deduced from a graphical analysis, if room temperatures are sorted by the ambient air temperature for the summer period:

- On the one hand, Fig. 6 shows a similar dependence of room temperatures on the ambient air temperature.
- On the other hand, the difference between room temperatures at a certain ambient air temperature is up to 6 K. These differences caused by the user behaviour, i.e. use of equipment and lighting, window opening and blind control.

The night ventilation was used only between 16 July and 31 August 2002 during the summer period. Thus, the operative room temperatures can be classified by days with and without night ventilation (1 June to 15 July 2002). Fig. 7 shows the mean value of the room temperatures which are shown in Fig. 6: night ventilation reduces the mean room temperature by 1.2 K during the working hours.

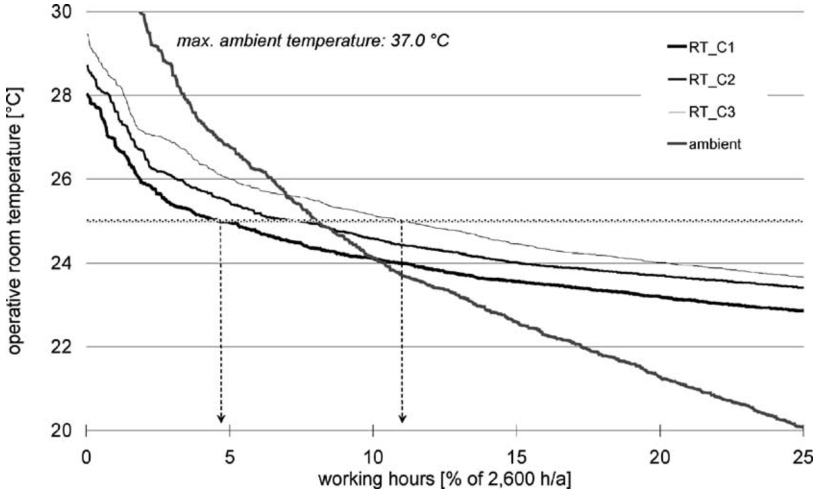

Fig. 5. Frequency distribution of operative room temperatures (hourly mean value) for the working hours during the whole year (1 January to 31 December 2002). The ambient air temperature exceeds 25 °C at 8% of working hours and its maximum is 37 °C.

Table 2
Working hours (2600 h) in 2002, when operative room temperature exceeds 25 °C

	X								
	05	07	09	11	13	15	17	19	21
RT_C3X	262	277	370	248	293	223	295	260	
RT_C2X	140	192	137	163	160	224	215	222	226
RT_C1X	229	283	188	135	Not used	Not used	Not used		

All rooms in wing C from West "_05" to East "_17, _19 or _21", see Fig. 3.

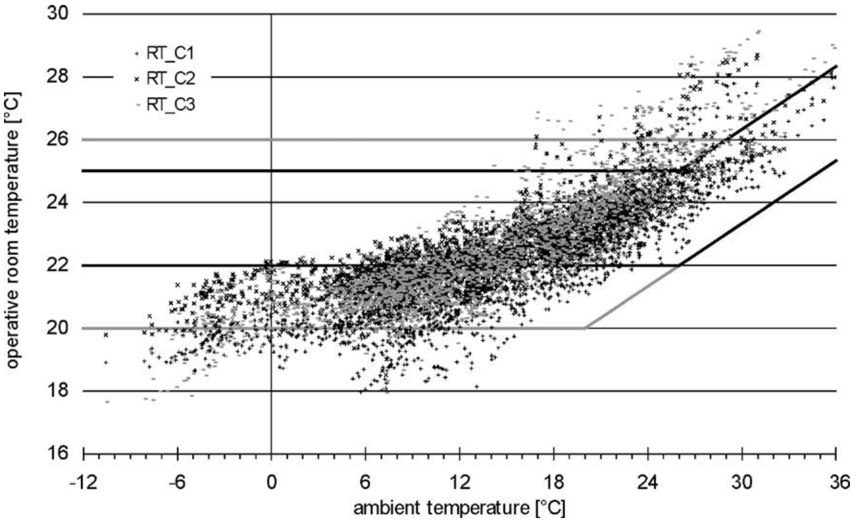

Fig. 6. Operative room temperature sorted by ambient air temperature for the working hours during the summer period (1 June to 31 August 2002).

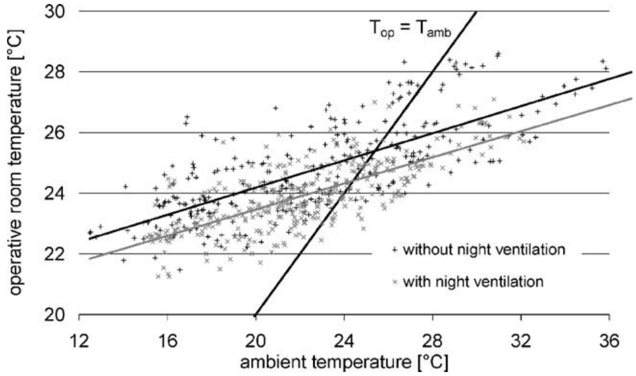

Fig. 7. Hourly mean value of the operative room temperature in the office rooms at the ground floor without (1 June to 15 July 2002) and with night ventilation (16 July to 31 August 2002).

The operative room temperatures are evaluated not only for the three floors in the ground floor but in all 21 office rooms in wing C: Table 2 shows the number of working hours with temperatures over 25 °C for each office room. In comparison with Fig. 5, the room temperature exceeds 25 °C in some rooms less (e.g. C205 and C209) and in some rooms more (e.g. C309 and C317), frequent then in the office rooms at the ground floor. This can be attributed to the user behaviour, too.

Fig. 8 shows the mean day for the working days during summer 2002. The mean operative room temperature in each of the three floors are sorted by time. Due to thermal stratification and solar radiation (static sun protection for the office rooms on the ground floor by the attached building), there is an increase in temperature of 0.5 K from one floor to the next.

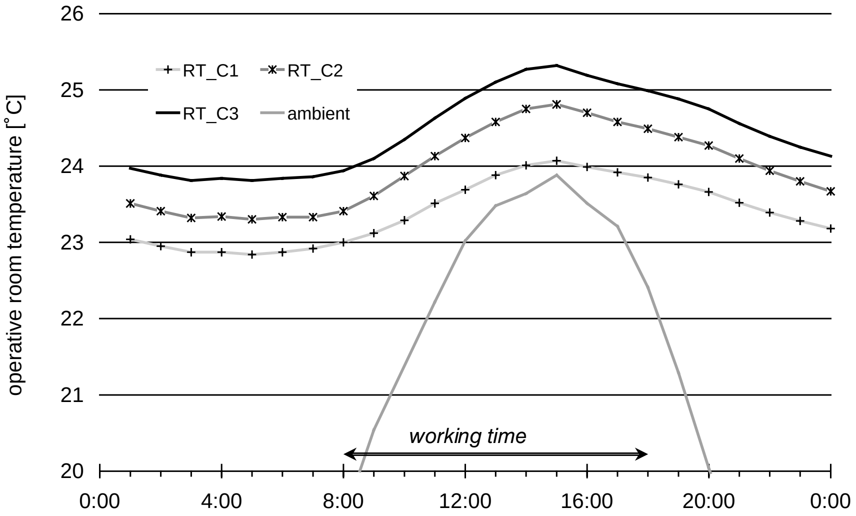

Fig. 8. Operative room temperature in the office rooms for the working days between 1 June and 31 August 2002.

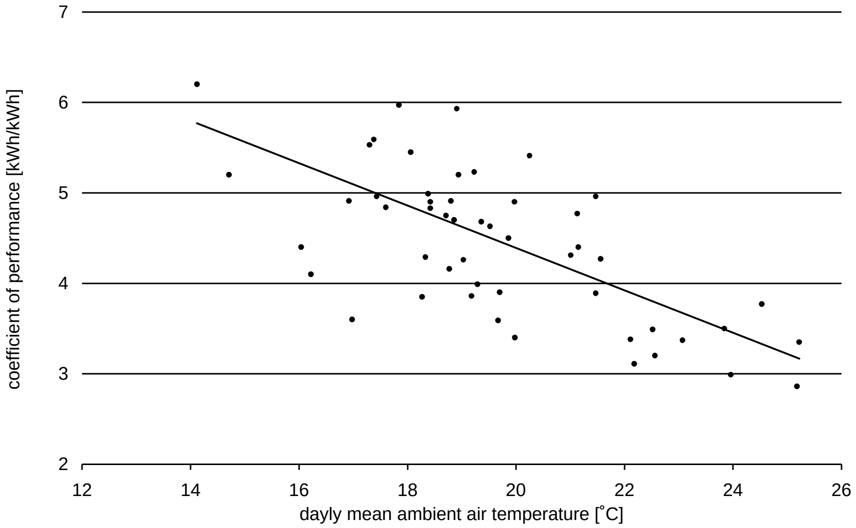

Fig. 9. Coefficient of performance for night ventilation between 16 July and 31 August 2002.

Passive cooling concepts competes against mechanical cooling machines for an energy efficient cooling strategy. The coefficient of performance COP is the ratio of the utilised thermal energy and the inserted electric energy during night ventilation:

$$\mathrm{COP}_{\mathrm{NV}} = \frac{\int_{\mathrm{NV\,start}}^{\mathrm{NV\,end}} \dot{V}(t)\rho c[T_{\mathrm{room}}(t) - T_{\mathrm{ambient}}(t)]\mathrm{d}t}{\int_{\mathrm{NV\,start}}^{\mathrm{NV\,end}} P_{\mathrm{electric,fan}}(t)\mathrm{d}t} \quad (1)$$

The mean COP was 4.5 $\mathrm{kWh_{th}/kWh_{elt}}$ in 2002. Though this COP is comparable to an energy efficient chiller, an additional energy demand for ventilation has to be taken into account for an air conditioning system. As the electric energy demand for ventilation is 0.46 $\mathrm{W/(m^3\,h^{-1})}$, the COP for night ventilation is quite low. With a typical energy demand for ventilation around 0.2 $\mathrm{W/(m^3\,h^{-1})}$, the COP would increase to 10 $\mathrm{kWh_{th}/kWh_{elt}}$. Fig. 9 shows the COP for different mean ambient air temperatures. As expected, the COP decreases with the ambient air temperature due to the smaller temperature difference between inside and outside in the nights.

Though this section provides a first evaluation of the thermal behaviour, the night ventilation effect cannot be quantified. In the following Sections 3–5, experiments and data evaluation based on a parametric model and building simulation are used to draw an energy balance and to separate the night ventilation effect from the other elements in the energy balance, cp. Fig. 1.

3. Experiments on night ventilation

In April 2002 (28 March to 7 May 2002), some experiments were carried out in two office rooms in order to determine the effect of night ventilation. While one room was passively cooled by night ventilation the other room was not cooled (reference room). A small ventilator was used to draw a defined air flow rate through the office room during night (2 a.m. to 7 a.m.), instead of the exhaust fan (see Fig. 4). During day the air change rate is mainly dependent on the ventilation system and the status of flaps and windows in the two office rooms and the adjacent rooms. This interrelationship was taken into account by a simple air flow network to calculate the air change rate in each office room. As the air flow rate caused by natural ventilation is the most uncertain parameter, detailed measurements were repeated several times in order to set up and to validate the air flow model. Table 3 shows some results from these air change measurements in ordinary operation.

Besides the air, surface and operative room temperature, the air change rate was measured using tracer gas technique. The internal heat gains were "simulated" by a fan heater with a thermal energy performance of 980 W from 8 a.m. to 6 p.m. The venetian blinds were either closed or opened during the whole day.

Four periods were defined for detailed data evaluation. Each period is characterised by (almost) regularly oscillating

Table 3
Air change rates from measurements with tracer gas technique

	Day ventilation (exhaust fan), all windows and flaps open	Day ventilation (exhaust fan), windows and flaps open only in 1 room	Free day ventilation without exhaust fan	Night ventilation, all windows and flaps open
Air change rate ($\mathrm{h^{-1}}$)	0.5	2.7	0.3–1.7	3.7–5.25

Table 4
Boundary conditions and results from measurements

	Period 1 (31/03–08/04)		Period 2 (13/04–15/04; 27/04–29/04)		Period 3 (02/05–05/05)		Period 4 (19/04–26/04)	
Sun protection (venetian blinds)	Closed		Closed		Closed		Open	
$T_{a,m}$ (°C) (mean ambient air temperature)	11.31		9.42		8.5		11.97	
$I_{global,m}$ (W/m^2) (mean solar radiation)	204		84		52		134	
Q_m (W) (mean internal heat gain)	408		408		408		408	
Office room with night ventilation	Yes	No	Yes	No	Yes	No	Yes	No
Air change rate (2 a.m. to 7 a.m.)	3.16	≈1	5.03	≈1	2.16	≈1	5.03	≈1
$T_{i,m}$ (°C) (mean indoor air temperature)	21.8	22.4	21.1	22.6	20.7	22.8	21.9	22.7

climatic conditions. Table 4 gives an overview over the main experimental set ups and boundary conditions.

Fig. 10 shows measured temperatures in the office with night ventilation from 2 a.m. to 7 a.m. for 24 April 2002:

- As expected, the fluctuation of air temperature is higher than of the operative room temperature.
- According to the temperature stratification, the surface temperature at the ceiling is higher than at the floor.
- Due to its small heat storage capacity the temperature fluctuation at the internal wall (adjacent to a similar office room) is higher than at the floor or the ceiling.
- The wall-mounted air-thermometer "RT_C115" for long-term measurement do not give the air temperature at a certain time. The temperature is partly influenced by the wall temperature (adjacent to the corridor) but shows a sufficient match to the operative room temperature for a long period. The mean temperature RT_C115 is 21.03 °C and the operative room temperature 20.88 °C.

The surface temperature at the ceiling has been measured using an infrared camera. Fig. 11 shows the local temperature field (*y*-axis, window–door, cp. Fig. 4) for different times (*x*-axis) for 3 h starting at 8 p.m. At every time step, the ceiling temperature is higher in the centre than at the window or the door. Thus, the de-warming of the ceiling (and also of the other surfaces) is not identical at every place as it depends on local temperature differences.

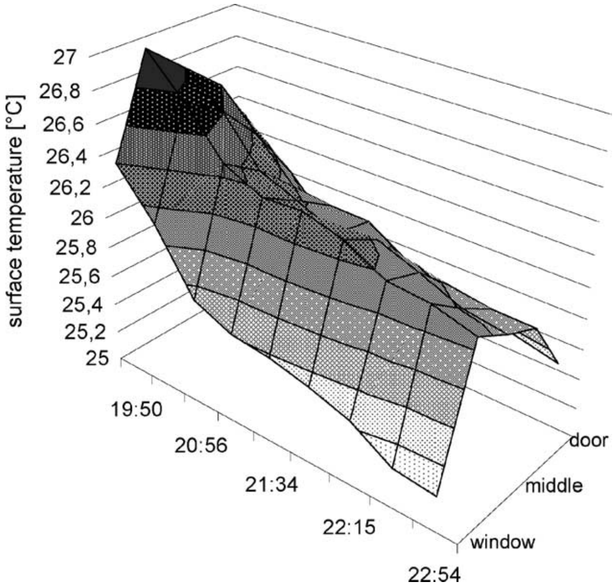

Fig. 11. Temperature field (local and time) at the ceiling, night ventilation on 15 May 2002.

Furthermore, Fig. 12 shows the temperature profile before and during night ventilation: during night ventilation the incoming, cold ambient air falls down to the floor. Thus, there is a large temperature gradient at the surfaces. This should be considered for the evaluation of the heat transfer.

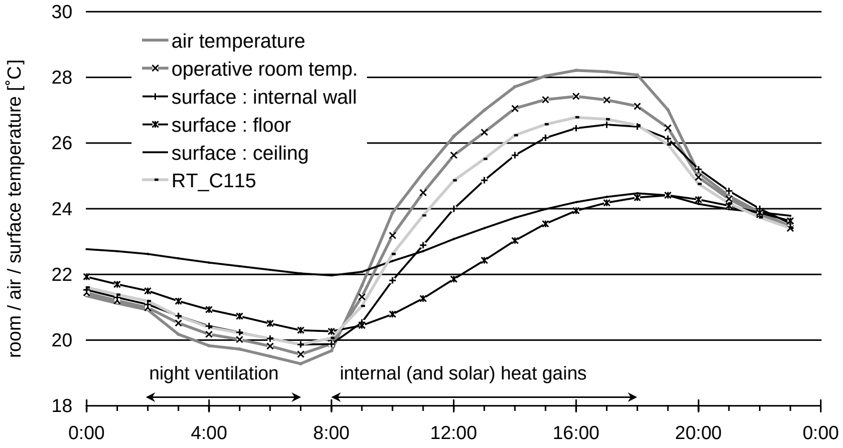

Fig. 10. Temperature fluctuation in the office room with night ventilation (air change rate 4 h^{-1}) at 24 April 2002.

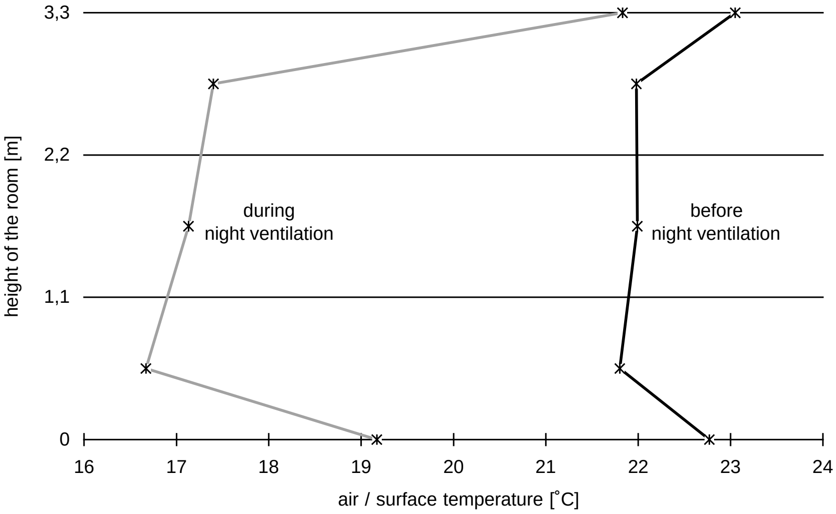

Fig. 12. Temperature profile before (8 p.m.) and during (2 a.m.) night ventilation, 4–5 May 2002.

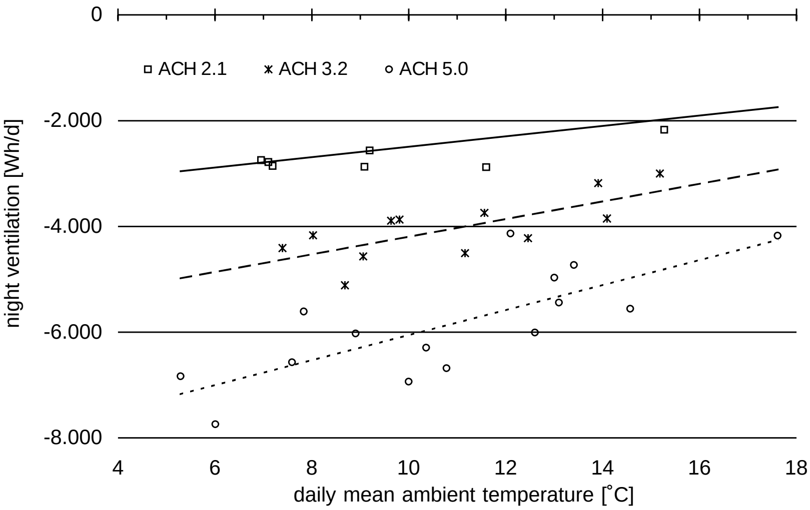

Fig. 13. Night ventilation during the experiments.

Starting from the monitored data, the energy fluxes can be calculated. Fig. 13 shows the night ventilation effect for three different air change rates during the night (cp. Table 4) dependent on the mean ambient temperature. As the experiments were carried out during spring, the ambient temperature is lower than in summer. As expected, the night ventilation effect increases with the air change rate and decreases with the ambient temperature. (As day/night temperature differences are higher in summer, these measurements should not be extrapolated for higher summer ambient temperatures: Fig. 7 indicates, that the night ventilation effect is independent from the mean ambient temperature in summer.)

There are many data from the experiments and the long-term measurements but neither Table 4 nor Fig. 10 provides data for comparison of night ventilation, because there are a lot of thermal influences (e.g. heat flow from or to adjacent rooms, fluctuating solar heat gains or air exchange between the office rooms and the corridor) which affect the energy balance in addition to the night ventilation. Thus, two models are introduced in order to evaluate the contribution of night ventilation to the energy balance and the temperature behaviour in an office room: parametric model and building simulation. Both methods aim at a separation of night ventilation from other influences and effects, such as user behaviour (blind control and window opening), effect of heat storage capacity or internal heat gains.

4. Modelling the night ventilation

4.1. Parametric model

The experiments can be evaluated with a very simple energy balance equation. Taking the most important energy fluxes into account, two main equations (Eqs. (3) and (4)) can be derived to calculate the mean air temperature $T_{i,\mathrm{m}}$ and its fluctuation ΔT_i according to Keller's approach [22]. In case all boundary conditions oscillate regularly, the variation of temperature with time can be approximated by Eq. (2):

$$T_i(t) = T_{i,\mathrm{m}} + \Delta T_i \sin(\omega t) \tag{2}$$

$$T_{i,\mathrm{m}} = T_{\mathrm{a,m}} + \frac{GI_\mathrm{m} + Q_\mathrm{m}/A_\mathrm{ext.wall}}{H} \tag{3}$$

$$\Delta T_i = \frac{T}{2\pi\tau} \cdot \left(\Delta T_\mathrm{a} + \frac{G\,\Delta I + \Delta Q}{H}\right) \quad \text{with} \quad \tau \approx \frac{C}{K} \tag{4}$$

In this paper, the data evaluated focus on the mean air temperature (Eq. (3)) and the energy balance for certain periods during the experiments. These periods are characterised by the mean ambient air temperature $T_{\mathrm{a,m}}$, the mean global solar radiation on the surface I_m, and the mean internal heat gain Q_m. All heat fluxes are related to the external wall area.

The thermal loss factor H (with the surface area A of the external wall in m^2, rate ACH in h^{-1} and air volume V in m^3, all thermal properties in SI units), the solar aperture G (with the surface area A of transparent surfaces in m^2 and their total solar energy transmittance g), and the heat storage capacity C (with the thickness and the thermal properties of the fabric in SI units, the time period $T = 24$ h, and the Biot number) are defined as:

$$H = \frac{1}{A_\mathrm{ext.wall}}\left[\sum_{i=1}^{n} A_{\mathrm{ext.wall},i} U_i + \mathrm{ACH} \cdot V \frac{(c\rho)_\mathrm{air}}{3600}\right] \tag{5}$$

$$G = \frac{1}{A_\mathrm{ext.wall}} \sum_{i=1}^{k} A_{\mathrm{trans.surface},i}\, g_i \tag{6}$$

$$C = c\rho d_\mathrm{eff} \quad \text{with} \quad d_\mathrm{eff} = \sqrt{\frac{T}{2\pi}\frac{\lambda}{c\rho} C'(Bi, d)} \tag{7}$$

The thermally effective thickness d_eff is dependent on the thermal penetration depth and the heat transfer at the surface C'. The calculation procedure can be taken from [7]. The floor area is 18.4 m^2, the external wall area 12.4 m^2 and the gross volume 60.6 m^3.

As this model is based on a harmonic oscillating heat balance, some simplifications are considered: (1) the total solar energy transmittance g is independent from the incident angle, (2) variable shading is not taken into account, (3) constant air change rates, (4) no transient thermal behaviour, (5) fixed heat transfer coefficients, (6) no time shift between ambient air temperature and solar radiation, (7) user behaviour is calculated by a standardised time profile dependent on the working time, e.g. time profiles in [22] based on a Fourier analysis, (8) there is no solar radiation on external walls and (9) no heat flux through internal walls. (10) As night ventilation operates with an high air change rate during night and a lower air change rate during working hours, a variable air change rate in Eq. (5) necessarily has to be taken into account: the variation of the air change rate is much higher in the room with night ventilation (day: approximately 1 h^{-1}, night: maximum 5 h^{-1}) than in the room without night ventilation (around 1 h^{-1}). While a constant temperature difference between inside and outside is assumed, a thermally effective air change rate ACH$_\mathrm{eff}$ should be calculated from hourly data by:

$$\mathrm{ACH}_\mathrm{eff} = \frac{\sum_{t=1}^{24}[\mathrm{ACH}_t (T_{i,t} - T_{\mathrm{a},t})]}{\sum_{t=1}^{24}(T_{i,t} - T_{\mathrm{a},t})} \tag{8}$$

Table 5
Comparison for the air temperature according to Eq. (2) from the measurement and the parametric model

Air change rate	Period 1 (3.16 h^{-1})		Period 3 (2.16 h^{-1})		Period 4 (5.03 h^{-1})	
	Meas	Calc	Meas	Calc	Meas	Calc
$T_{\mathrm{i,m}}$ (°C)	21.3	21.4	21.2	20.8	22.0	21.9
ΔT_i (K)	4.1	2.9	4.0	3.5	2.9	2.0

Table 5 compares the mean temperature and the temperature amplitude from measurements (using Eq. (2) for parameter identification) with the results from the parametric model (using Eqs. (3) and (4)) for three of the four periods, which are defined in Table 4.

The parametric model fits better for the mean temperature than for the temperature amplitude: while the energy balance (mean temperature) can be calculated accurately, the modelling of the heat storage capacity (temperature amplitude) is uncertain due to the calculation procedure for harmonically oscillating temperatures (Eq. (7)), local temperature gradients (cp. Fig. 11) and uncertain heat transfer coefficients (cp. Fig. 12).

Though there are differences between measurement and calculation, the parametric model can be used in principle. As the heat balance is calculated dynamically by the building simulation program, a higher accuracy for the temperature amplitude can be reached by the use of a building simulation.

4.2. Building simulation

The ESP-r simulation program, version 4.37a of June 2002 [8] was used for data evaluation, apart from the parametric model. All input parameters and boundary conditions (i.e. climate, blind control, air flow rates, internal heat gains, user behaviour) are well known.

The data from April are used for *model set-up*. The aim of the parameter identification is to set up an accurate simulation model: the building characteristics (i.e. heat transfer coefficients at internal walls, solar absorption at the external wall, g-value and thermal conductivity of the ceiling) are known approximately and can be fitted to the measurements. Fig. 14 compares the operative room temperature from measurement (globe thermometer) and simulation for two days (1st period). The building simulation has been performed not only for the four periods, but for the whole experiment. Additionally, the results from the parametric model ($H =$

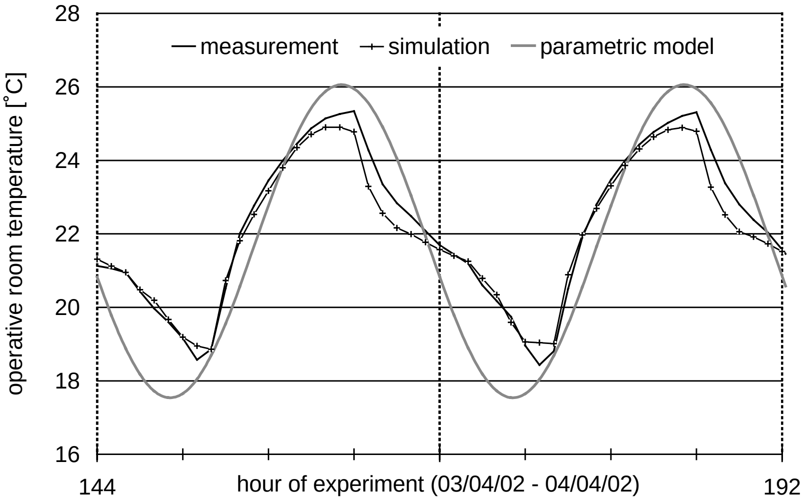

Fig. 14. Parameter identification with measurements from the experiments in April 2002: variation of temperature with time for two days: measurements, simulation and parametric model (with *H*, *G* and *C* calculated for the 1st period of experiment in April 2002, Table 4).

4.0 W/(m^2 K), $G = 0.046$ and $\tau = 22$ h for the 1st period) are shown.

The accuracy of the simulation model is checked with data from July 2002, when the office rooms were under ordinary operation. This *model validation* uses the model from the model set-up. The internal heat gains, the operation of the ventilation system, the status of flaps, windows and blinds are well known. In contrast to the simulation with the measured air change rates from the data in April, the air flow rate (infiltration from outside, ventilation with adjacent zones and exhaust air from the ventilation system) is calculated by the simulation. Fig. 15 shows a good agreement between measurement and simulation results. Thus, all boundary conditions and thermal interactions are taken accurately into account.

The simulation model is set up and validated with measurements from two different periods (April and July) and can be used for data analysis. The assumptions, which are made in the parametric model, can be taken into account, if the heat fluxes are calculated accurately by the building simulation programme.

5. Analysis

Using an accurate model for building simulation, the measurements from a real, transient experiment can be evaluated for artificial, regularly oscillating boundary conditions.

5.1. Model comparison

Starting from realistic assumptions, the parametric model does not agree with transient measurements at a certain time

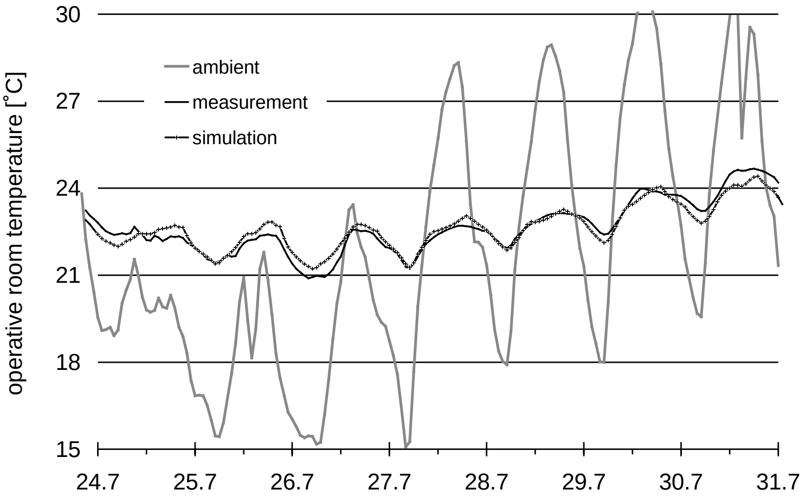

Fig. 15. Model validation with measurements from the long-term monitoring: comparison between measurements and simulation in July 2002 for ordinary service.

Table 6
Model comparison for the thermal loss factor H between the parametric model and simulation

	Air change rate (h^{-1})			
	0	1	4	8
H from parametric model with Eq. (5)	1.3	2.95	8.0	14.5
H from simulation with Eq. (3)	1.3	2.9	7.9	13.2

step while the building simulation shows a sufficient agreement with measured temperatures.

As the parametric model deals with simplified assumptions, the accuracy of the parametric model and the building simulation should be checked. The comparison is based on the office room, Fig. 4. If (1) solar heat gains are ignored, (2) internal heat gains and (3) air change rate are considered to be constant during the day, and (4) the ambient temperature oscillates regularly, then both models will result in a similar conclusion:

- The parametric model overestimates the thermal loss factor H by about 0–10%, Table 6.
- The modelling of the heat storage capacity (cp. measurements, Fig. 11) is completely different: the parametric model solves the heat conduction equation analytically and the building simulation numerically, but gives the same results for different thickness' and heat transfer coefficients, Fig. 16.
- The night ventilation effects the heat transfer at the surfaces (cp. measurements, Fig. 12). As the heat storage capacity (cf. Eq. (7)) is calculated by the parametric model independent from temperature gradients, it cannot take night ventilation into account. According to the heat storage capacity, the time constant is overestimated by the parametric model at low air change rates, Fig. 17. At high air change rates the numerical and analytical solutions approximates each other.

Starting from this validated model, realistic assumptions can be taken into account in the parametric model. Therefore, both models are merged.

5.2. Merging of parametric model and building simulation

A promising approach for data analysis is to transfer the results from a parameter identification with the building simulation to the parametric model: first, the simulation model is fitted to extensive measurements (here, April simulation). This model is validated with measurements from the building under ordinary operation (here, July simulation). At last,

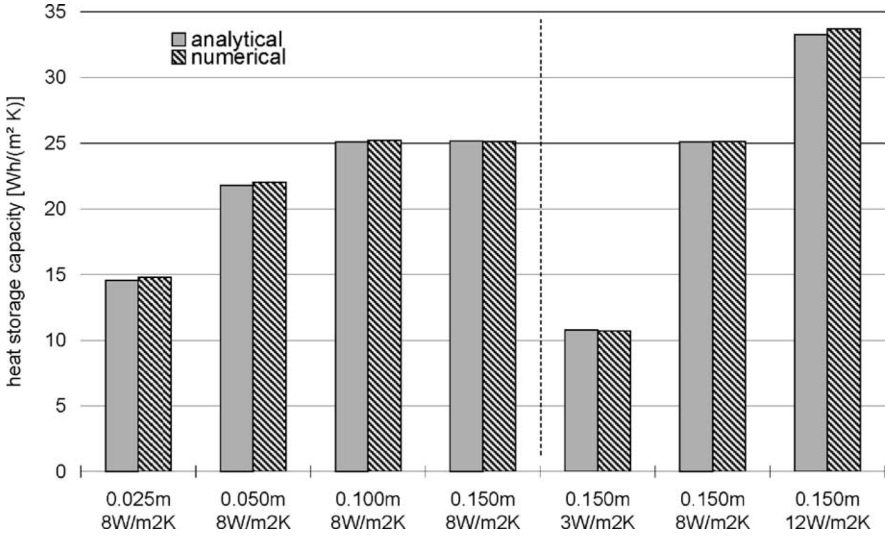

Fig. 16. Heat storage capacity dependent on thickness and heat transfer.

Table 7
Standardised input parameters (ACH and $g_{\perp}$) and results (H and G) for the simulation of two strategies to lower the indoor air temperature: night ventilation and sun protection

	No night ventilation, no sun protection	Night ventilation, but no sun protection	No night ventilation, but sun protection	Night ventilation and sun protection
ACH (1 a.m. to 24 a.m.)	1	1	1	1
+NV (2 a.m. to 7 a.m.)	0	3	0	3
$g_{\perp}$	0.51	0.51	0.11	0.11
H	1.7	3.4	1.7	−134.8
G	0.061	0.066	0.017	0.020

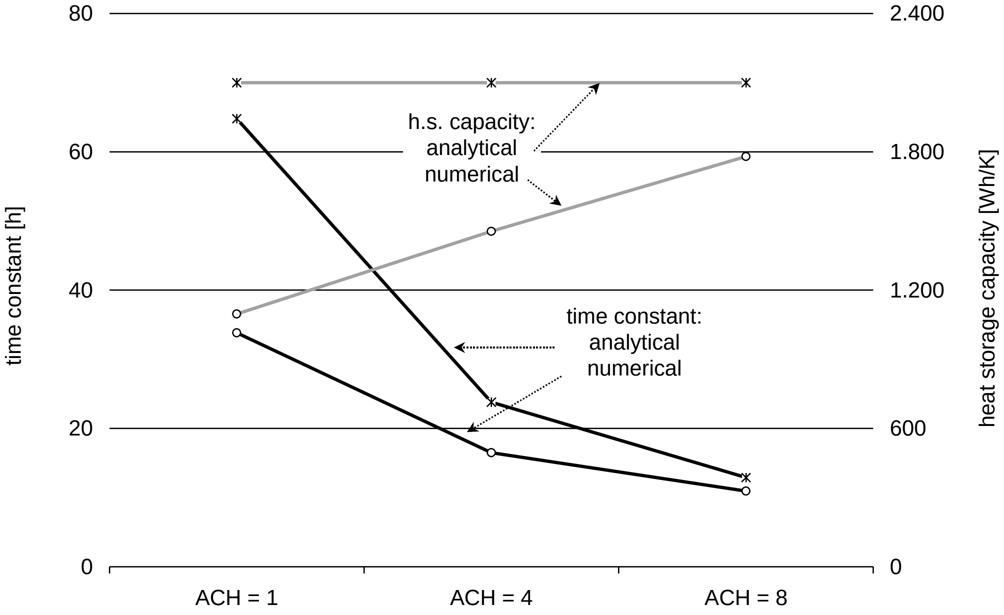

Fig. 17. Heat storage capacity and time constant dependent vs. change rate.

the simulation model can be used for data evaluation with standardised boundary conditions and operation.

As a single office room should be characterised, adiabatic boundary condition are introduced at the internal walls in order to prevent heat flux between adjacent rooms. The simulation has been carried out with separate fixed air change rates for day and night, sun protection on or off, no internal heat gains and climatic data from 28 July 2002, with $T_{\mathrm{a,m}} = 23.8\,^{\circ}\mathrm{C}$ and the vertical solar radiation on the South facade $I_{\mathrm{m}} = 160\,\mathrm{W/m^2}$.

Table 7 shows the input parameters (air change rate and *g*-value) and Fig. 18 the simulation results with (a) the effect of night ventilation and (b) sun protection shading on the indoor air temperature: in this case, night ventilation reduces the mean indoor temperature by 2–3 K dependent on sun protection, sun protection by 3–4 K dependent on night ventilation and both night ventilation and sun protection by 5.7 K.

This simulation is dependent on the thermal behaviour from the room but is independent of the operation. Thus, the building characteristics *G* and *H* can be derived from these simulation results, Table 7.

Noteworthy, there is a negative thermal loss factor, if the office room is cooled by night ventilation and the blinds are closed: in this case, the mean indoor air temperature is lower than the ambient air temperature. Eq. (2) demands a negative *H*-value, which is delivered by a negative, thermally effective air change rate from Eq. (8). A negative air change rate is thermodynamically impossible but mathematically correct in this context.

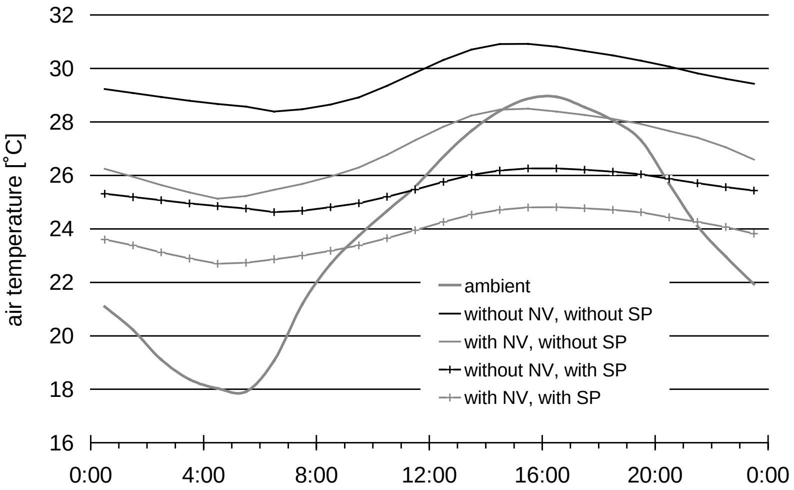

Fig. 18. Simulation with standardised inputs.

6. Conclusions

The building simulation provides accurate results, if the input parameters and boundary conditions are well known. However, user behaviour results in energy and temperature variations which are of the same order of magnitude as the effect of different design decisions and operation strategies, respectively. There are two ways to manage these variations with a probabilistic approach and uncertainty analysis:

- Macdonald and Strachan [29] provides an algorithm for both differential sensitivity analysis and Monte Carlo analysis: if an extensive building simulation is performed the effect of each varied parameter on the energy balance and the thermal behaviour can be deduced during the design phase.
- Herkel and Pfafferott [21] carried out a data evaluation using a Monte Carlo simulation.

Statistically distributed events (i.e. user behaviour) and transient phenomena affects the energy balance and the indoor temperatures in buildings. Thus, the data evaluation of measurements in buildings under ordinary operation is difficult. The presented parametric model focuses on main building characteristics and provides a simplified thermal model which can be used advantageously for data evaluation.

With this model, the thermal behaviour of a building and its energy demand can be characterised independently of user behaviour but dependent on day and night ventilation or operation (e.g. blind control).

An accurate parametric model can be deduced from a procedure in three steps:

1. Short-term measurements (weather, indoor air, surface and operative room temperatures, air change rate, sun protection, internal gains, occupancy).
2. The thermal behaviour is simulated by a sophisticated building simulation with the short-term measurements as input data and known material properties (g-value, U-value, thermal properties).
3. The main building characteristics are derived from the validated simulation model with standardised weather data, operation and user behaviour.

In the context of quality assurance, the presented method (measurement–simulation–building characteristics) can be used in order to check

- whether the original design ideas were realised or not,
- whether control strategies (i.e. night ventilation and/or sun protection) are realised properly.

Moreover, the simplified parametric model can be integrated into (predictive) controller for time and temperature controlled ventilation strategies.

During the design phase, different design decisions from a building simulation can be evaluated by these building characteristics in order to compare different techniques for avoiding over-heating in passively cooled buildings.

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SolarBau:Monitor [1] as the related accompanying project documents and analyses all SolarBau-projects. This data evaluation has been done in the sub-project MessISE under the reference O335006X.

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