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Coupled simulations for hygrothermal investigation of subterranean car parks and similar spaces

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To investigate the hygrothermal conditions in subterranean car parks a two-dimensional simulation procedure has been used, based on coupling the transient heat transfer programme HEAT with the dynamic thermal building simulation program TRNSYS. The likelihood of condensation and the rate of water deposition on surfaces were calculated with a new moisture model KOND. To estimate the consequence of moisture adsorption in materials in the hygroscopic range below saturation, the TRNSYS moisture capacitance model (buffer storage model) was used. A parametric study of the internal temperatures and the annual hours of condensation risk in underground car parks were conducted using German and UK climate data. The simulations indicate the relative risk of condensation occurring for different earth conditions, levels of insulation and air change rates, in spaces covered by earth and spaces covered by a heated building. It is shown that increased ventilation rates in summer can reduce condensation risk in underground car parks below heated buildings.

1 Introduction

The reasons for moisture damage to buildings, with or without mould formation, are reasonably well known for many building types.[1,2] In situations where heat fluxes are multi-dimensional and nonstationary, and where heat- and moisture-transport processes strongly interact, hygrothermal design problems are difficult to analyse. The control of moisture movement is particularly important in buildings, which are in intimate, and extensive, contact with the ground.

The rate of heat loss through subterranean walls can often be improved by insulating the inner surface. However, the resulting moisture content, and risk of interstitial condensation, depends on the time varying temperature conditions in the adjacent earth, and this can only be assessed with difficulty. A lack of understanding of the hygrothermal behaviour of such walls has led to problems in the past, especially with regard to whether or not a vapour barrier is needed.[3,4]

In the design of cellars, storerooms and underground car parks, etc., it is important to know whether condensation is likely to occur, how much moisture is likely to accumulate and whether such an accumulation could lead to damage of either the building or its contents; for example, droplets of moisture falling onto cars in an underground car park. The designers of underground spaces need to know whether insulation measures or ventilation control is necessary, or indeed, whether such measures are likely to increase, rather than decrease, the risk of moisture problems.[5] It is widely believed that unheated cellars and basements should be ventilated at night when the moisture content of the air is

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assumed to be low.[6] However, the truth of such a statement is unclear since the incidence of condensation at surfaces not only depends on the water content of the air (which rarely displays a strong dependence on the time of day) but also on other effects such as the room and surface temperatures.

The wintertime temperature conditions in underground car parks below heated buildings are of particular interest when assessing the problem of heat-bridges at the pillars and walls which support the overlying building. Design guidelines, however, contain only general statements concerning the wintertime temperature in such rooms.[7,8] In addition, the occurrence of condensation and subzero temperatures could result in the icing of surfaces, which would have severe health and safety implications for people and could potentially lead to accidents in which vehicles are damaged.

It is because the interactions between the conditions in the subterranean room and the ground, which include both temperature and moisture effects, are so complex, that design questions such as those noted here are difficult to resolve. The aim of this paper is to illustrate the way in which existing models can be coupled in order to address these problems and to provide an indication of the sensitivity of condensation risk to the way in which spaces below a building, or below ground surface, are constructed.

The design of subground rooms is clearly a greater issue in those countries where such spaces proliferate. In Germany, for example, most domestic buildings are provided with a cellar for storage purposes. Commercial buildings also have such spaces, which are used either for storage, or for building services equipment, etc. In the UK, modern houses are rarely constructed with a cellar. However, in Germany and in the UK, the growing traffic problems in towns and cities are increasing the occurrence of underground car parks.

In this paper, the thermal and moisture issues are investigated, using both German and UK climate data. The paper builds on previous work, in which the question of vapour barriers was studied.[9,10] More recently, through collaboration between the University of Applied Sciences, Coburg (Germany) and De Montfort University, Leicester (UK), the work was extended to consider broader design issues. This required the coupling of simulation methods (Sections 2 and 3), so that an extensive parametric study of the thermal and moisture conditions in earth contacted underground car parks could be conducted (Sections 4–7).

2 Previous work

Simplified models of the temperature conditions in the ground have been developed to quantify the heat losses from rooms to the surrounding earth. The temperature field in the earth is approximated by multi-dimensional but steady-state numerical calculations which neglect heat storage.[11] Analytical calculation models are also available, which use simplified geometrical assumptions and boundary conditions.[12] A more sophisticated model, described by Kreč,[13,14] considers both the multi-dimensional heat transfer and storage processes in the earth. The method assumes that the boundary temperatures vary sinusoidally and so it cannot consider realistic boundary conditions based on measured weather data or step changes in ventilation rates or heat input due to the operation of environmental control systems. Based on such calculations DIN EN ISO 13370[15] contains simplified algorithms for the heat loss of a room to the earth. This standard does not, however, consider unheated subterranean spaces and the algorithms do not give hourly temperature information which is needed for detailed humidity calculations.

More complex, and potentially more accurate, multi-dimensional heat transport programs have recently been developed and are available commercially e.g., HEAT2/3.[16] Such programs offer the possibility of calculating the time-dependent temperatures within the constructions and on the surfaces. In addition, programs for calculating heat transfer and moisture transport, by both water vapour and capillary liquid transfer, as well as the rate of moisture storage in materials, already exist.[17–19] However, these, and similar programs, usually only consider the hygrothermal processes within the construction. The boundary conditions, in terms of temperature and moisture content of the adjacent airspace, need to be specified by the program user. Therefore, the time varying boundary conditions have first to be calculated, and there is no back coupling between the moisture simulation program and the boundary conditions e.g., to account for the influence of condensation and evaporation in the construction on the moisture content of the adjacent air.

Thermal simulation programs of buildings are able to calculate the time-varying air temperatures and humidities, which can provide the boundary conditions to detail the moisture transport and multi-dimensional heat flow models. Such models have been available since the early 1980's and have now reached a high level of sophistication e.g., TRNSYS, ESP-r, Energy-Plus. Whilst some of these programs themselves contain models for predicting multi-dimensional heat flow and moisture transport,[20] these submodels are less sophisticated than those available in stand-alone dedicated programs, such as HEAT, and cannot be used for highly complex problems such as unheated subterranean spaces.

By combining dynamic thermal models of buildings, which calculate boundary conditions, with detailed models of multi-dimensional heat transport and with moisture movement models, so that the programs interact, rather than operate in a sequential fashion, it is possible to investigate rather rigorous conditions in earth-contacted or subterranean rooms. Work has been conducted to develop such links in order to calculate the heating or cooling loads of heated or cooled earth-contacted rooms:[21] multi-dimensional simulation-studies of unheated subterranean rooms were not reported. For the studies reported here, a two-dimensional simulation procedure was developed, based on linking the commercially available transient heat transfer programme HEAT, the dynamic thermal building simulation program TRNSYS and a new moisture-model KOND.

3 Simulation model

3.1 Thermal model

The research project concentrated on the commercial transient simulation programs HEAT2 (two-dimensional).[16] This program permits the prediction of the transient, multi-dimensional temperature fields in the earth as a result of defined climate conditions such as hourly values of the weather data. In addition, HEAT2 is able to simulate ventilated air-cavities and considers the longwave (IR) radiation exchange between the cavity-surfaces.[22] Using this capability it was possible to use HEAT2 as a two-dimensional dynamic simulation program for unheated subterranean rooms. However, the room simulation had some limitations: it was not possible to vary the room ventilation rate with time; it was also not possible to model other control mechanisms e.g., a temperature dependent ventilation rate; and HEAT2 does not include moisture modelling.

To overcome the limitations, the simulation model based on HEAT2 was extended by connecting the dynamic building simulation program TRNSYS.[23] Within this combined calculation system, HEAT2 still simulates the whole earth-contacted room with walls, floor and ceiling but additionally records the hourly temperatures at the earth-contacted outer surfaces of the room at particular points (five points at the wall between concrete and earth and one point under the floor slab near the symmetry plane, see Figure 1). These temperatures form boundary conditions for the TRNSYS simulation of the hourly air temperatures inside the room considering ambient conditions, ventilation rates and roof, floor and wall constructions. The air temperatures are then passed back to HEAT2, which again calculates the hourly temperatures of the earth and earth-contacted surfaces. To account for thermal coupling, the simulations operated iteratively until a sufficiently consistent solution was obtained for the air and construction temperatures.

Iteration can be performed by passing information between the programs at each time-step or by repeated annual simulations. The latter strategy was adopted as this did not require modification to the HEAT2 program—the researchers did not have access to the source code. The necessary number of iterations was highly dependent on the chosen starting conditions. When the temperature field of an earlier similar simulation was used as the starting conditions, temperature predictions, which changed by less than 0.1 K in successive steps, required less than 10 iterations. Since one iteration (e.g., the simulation of a 3-year period) takes only a few minutes on a modern Pentium PC, the whole calculation can be performed in a reasonable time.

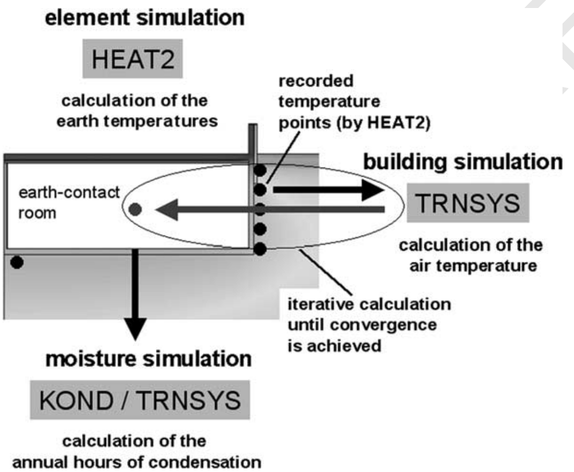

Figure 1 Calculation method for earth-contact rooms by thermal coupling of different simulation models

3.2 Moisture model

The linked thermal models provide the air and room temperatures in the unheated earth-contacted room. Neglecting the influence of the latent heat transfer, which occurs during water condensation or evaporation on the room surfaces, the moisture calculation can be independently conducted after the thermal simulations have iterated to a steady result. There is no iterative coupling between the moisture and thermal model.

Since TRNSYS does not offer a model for calculating condensation effects and moisture storage above saturation, a new moisture model 'KOND' was developed. Based on the differential equation for the room-moisture balance, the model calculates the partial water-vapour pressure inside the room as a function of the partial water-vapour pressure of the outside air as follows:

$$p_{i,t} = p_{e,t} + (p_{i,t-1} - p_{e,t}) \cdot e^{-n \cdot \Delta t} - \frac{\Delta p_{t-1}}{n \cdot \Delta t} \times (1 - e^{-n \cdot \Delta t}) \quad (1)$$

- $p_{i,t}$: actual partial water-vapour pressure of the inside air in Pa at time-step t
- $p_{e,t}$: actual partial water-vapour pressure of the outside air in Pa at time-step t
- $p_{i,t-1}$: last partial water-vapour pressure in Pa of the inside air at the time-step $t-1$
- n: air change rate in 1/h
- Δp_{t-1}: increase or depression of the partial water-vapour pressure in Pa caused by condensation or evaporation at the room surfaces during time-step $t-1$ (see later)
- Δt: duration of the time-step in h (in the study 1 h was used).

Knowing the water-vapour saturation pressures at the room surfaces, which themselves depend on the surface temperatures (calculated by the thermal model), the amount of condensation (or evaporation) at the surface 'j' can be calculated as follows (see e.g., Klopfer[24]):

$$\Delta W_j = \beta \cdot (p_{i,t} - p_{s,j,t}) \cdot A_j \cdot \Delta t \qquad (2)$$

ΔW_j: amount of condensation (when positive) or evaporation (when negative) in kg
β: moisture transfer coefficient (0.3×10^{-4} kg/(m$^2 \cdot$h$\cdot$Pa), see e.g., Klopfer[24])
$p_{s,j,t}$: water vapour saturation pressure at the surface j at the time-step t
A_j: Area of the surface j.

For the next time-step ($t+1$), the depression (or increase) of the partial water-vapour pressure of the air, Δp_t, is needed and can be predicted using the ideal gas equation of state:

$$\Delta p_t = \frac{\sum_j \Delta W_j \cdot R_S \cdot T}{V} \qquad (3)$$

R_S: specific gas constant of water vapour 462 J/(kg·K)
T: absolute temperature of inside air in K
V: volume of the air space in m^3.

To account for moisture storage, the amount of water at each surface is added up:

$$W_{j,t} = W_{j,t-1} + \Delta W_j \quad (W \geq 0) \qquad (4)$$

$W_{j,t}$: stored water at the surface j at time-step t in kg
$W_{j,t-1}$: stored water at the surface j at time-step $t-1$ in kg.

The model assumes unlimited moisture storage at the room-surfaces, i.e., as a film, as droplets or in material crevices and pours. The model does not consider moisture run-off, falling droplets or absorption and desorption in materials. Therefore, the model best represents modest condensation on impermeable surfaces, or, for example, on materials such as concrete, which are covered with impermeable paint.

To estimate the consequence of adsorption of moisture in materials in the hygroscopic range below saturation, the TRNSYS moisture capacitance model (buffer storage model) was used.[25] Within this model, the moisture storage of the building material is represented by surface buffer storage and deep buffer storage. Only the moisture exchange by water-vapour diffusion is considered, the effect of capillary condensation in the upper hygroscopic range (above 80% relative humidity in the material) as well as the moisture storage above saturation is neglected. The consequences of this limitation are not yet known, but could be investigated in future studies.

The KOND model was used for all the simulations, except for the limited sensitivity study where the moisture storage by materials was studied (see Section 6.7). It should be noted that KOND has been developed to study a subterranean room with a particular geometry. It is not a fully flexible stand-alone moisture simulation program which could be used for any room situation.

3.3 Validation

The individual simulation programs, TRNSYS and HEAT2, have been validated by the program authors using various methods, such validation includes the TRNSYS, below saturation, buffer storage model.[25] Other previous validation work is not discussed here, but see, for example, Blair and Moist.[26] The accuracy of the new, coupled simulation approach is of interest. Since in some cases HEAT2 offers an independent simulation (e.g., fixed ventilation rate, see Section 3.1), there is the possibility of comparing predictions from the coupled simulation HEAT2/TRNSYS with predictions from HEAT2 operating in isolation. Such a comparison is interesting because the calculation of air temperature in the earth-contacted room by TRNSYS is quite different from the method used in HEAT2. In addition, HEAT2 reproduces the room-surface temperatures at many points using a two-dimensional model, whilst TRNSYS is limited to a one-dimensional approach with a course numerical grid.

The annual simulations of an underground car park with a heated building above (base case, see Section 4) using mid-German (TRY05) climate data showed that the two methods (HEAT2 and HEAT2/TRNSYS) predict air temperatures to within 0.1 K of each other.

As well as the detailed buffer storage model, TRNSYS offers a simplified moisture model which neglects any moisture storage. The predictions of the new moisture model KOND (with moisture storage turned off, $\Delta W_j = 0$ in Equation (2)) were tested by comparison against the TRNSYS model. For the base-case situation (see Section 4) both models predict very similar internal relative humidities (the maximum difference in the predicted percentage relative humidity values was 7.5 percentage points with, on average, a difference of just 0.9%).

The moisture storage option within the program KOND could not be easily validated. However, the effect of the moisture storage on the moisture conditions in the earth-contacted subterranean room is of second order importance.

4 Modelling assumptions

As underground car parks must be ventilated, they are a more interesting problem to analyse than, for example, underground cellars and storerooms. By considering the performance of a car park, either below a building or below the earth, at various ventilation rates, the performance of other types of subterranean structure (e.g., including storerooms and cellars) can be inferred.

A two-dimensional model of an underground space was developed, this implicitly assumes a space that is relatively long and narrow. A symmetry plane down the centre of the section was assumed, and so a two-dimensional model of only half a space was necessary. As recommended in DIN EN 10211,[27] the earth surrounding the space was modelled up to a distance of 20 m from the outer surface of the building envelope neglecting any influence of other surrounding buildings. The vertical end was defined to be adiabatic. At the depth of 20 m it was assumed that the earth temperature corresponded to the average annual air temperature. The impact of ground water and its movement was neglected, although the sensitivity to the earth capacitance and conductivity was considered. It was assumed that the roof of the earth covered car park was covered to a depth of 30 cm, which is a typical depth necessary for the growth of grass and plants.

The walls, roof and floor of the car park consisted of 20 cm of heavy concrete. In the case of the car park below a heated building, the ceiling of the car park was assumed to be covered with a 10 cm thick layer of insulation (conductivity 0.04 W/(m·K)). The outside wall of the building above was also insulated to a thickness of 10 cm and this insulation was continued to a depth of 1 m below the ground (Figure 2). The air in the building above the

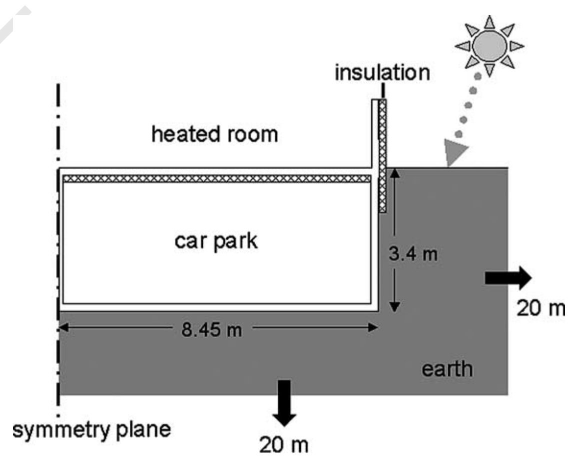

Figure 2 Model of the built-over car park (not true to scale)

car park was fixed at 21.5°C. (Analysis in which this air temperature was allowed to vary through the year, from 20°C in winter to 23°C in summer, showed little change in the predicted conditions in the car park).

For the built-over car park, it was assumed that the earth surrounding the building was completely shaded from solar radiation and that there was no infrared exchange between the earth's surface and the surroundings. This approximates to a 'worst case' assumption, as ground temperatures will be lower than for sun-warmed earth and so the risk of surface condensation will be greater. It also represents the most common situation, in which buildings above car parks cause significant shading. In contrast, for the earth-covered car park, it was assumed that the horizontal ground was exposed to solar radiation and that infrared radiation exchange occurred with the sky (Figure 3). This is the more typical situation for horizontal surfaces which are not permanently shaded by other surrounding obstructions.

It was assumed that there was no internal heat production in the car park i.e., a worst case for condensation. In practice, especially in a busy car park, the heat input from vehicles could be considerable. On the other hand, the

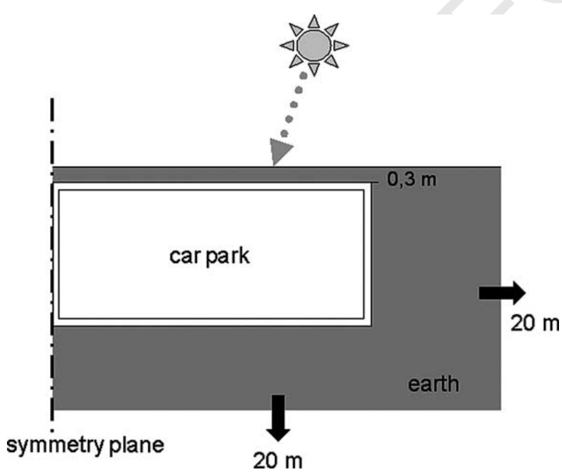

Figure 3 Model of the earth-covered car park (not true to scale)

assumption ignores the possible occurrence of moisture sources e.g., due to wet cars.

For the chosen building geometry, in accordance with German Building Regulations (Garagenverordnung GaVO),[28] air change rates of 0.25 (for car parks with low traffic volume e.g., domestic buildings) and 0.5 (for other car parks) were used. The thermal effects of heat storage in the earth are more evident at these low air change rates. However, simulations were also conducted with ventilation rates up to 4, per h.

Simulations were conducted using climate data representative of that for the middle of Germany i.e., the test reference year (TRY) for Würzburg, Franken and northern Baden-Württemberg.[29] In addition, simulations for a space below the heated building were conducted using TRY data for London, Manchester and Edinburgh as well as for measurement values of weather conditions in London between 1976 and 1995.

When conducting the thermal simulations, it was necessary to use a preconditioning time of at least 6 years, in order to overcome the thermal inertia of the large volume of surrounding earth (to a depth of 20 m). This effort could be reduced in the parametric studies because the temperature field resulting from an earlier simulation could be used as the starting values.

The sensitivity of predictions to the meshing strategy used in the HEAT2 program was studied. Additionally, a sensitivity study was conducted of the impact of the convective heat transfer coefficients at the internal surface of the space. This paper does not describe these studies, but, in the simulations conducted a grid with 1800 cells was used. The convective heat transfer coefficients in the earth-contacted room were set to a constant value of 3.07 $W/(m^2 \cdot K)$.

The combination of construction, earth properties and ventilation rates, which represent the base case for each room, are given in Table 1. The corresponding base-case climate file was the Würzburg, TRY. The lowest and

Table 1 Main design characteristics of the basic version (called base case) of the built-over and earth-covered car parks

Base case for the built-over car park	
Half internal room width in m:	8.25
Internal height in m:	2.9
Solar and infrared radiation onto earth:	no
Conductivity of the earth in W/(mk):	2.0
Heat capacity of the earth in MJ/(m^3K):	2.0
Thickness of ceiling insulation, (conductivity = 0.04 W/mK) in cm:	10
Thickness of wall insulation, upper 1 m below ground-level, (conductivity = 0.04 W/mK) in cm:	10
Thickness of wall insulation, whole wall-area, (conductivity = 0.04 W/mK) in cm:	0
Thickness of floor insulation, (conductivity = 0.04 W/mK) in cm:	0
Air-change rate in 1/h:	0.25
Base case for the earth-covered car park	
Half internal room width in m:	8.25
Internal height in m:	2.9
Solar and infra-red radiation onto earth:	yes
Conductivity of the earth in W/(mK):	2.0
Heat capacity of the earth in MJ/(m^3K):	2.0
Thickness of roof insulation (conductivity = 0.04 W/mK) in cm:	0
Thickness of wall insulation (conductivity = 0.04 W/mK) in cm:	0
Thickness of floor insulation (conductivity = 0.04 W/mK) in cm:	0
Air-change rate in 1/h:	0.25

highest annual air temperature in the car park, and the number of hours in the year during which surface condensation could occur, are given in Tables 2 and 3, for the built over and earth-covered car parks respectively. For the earth-covered car park, results are given for the base-case simulation and for each variation of insulation, earth cover and ventilation rate. Additionally, in the built-over car park, variations in the properties of the ground, the ventilation strategy and weather conditions were studied. When conducting these studies, all the parameters were held at their base-case value except for the one which was changed.

5 Lowest air temperatures in underground car parks

Before considering the moisture conditions in car parks it is useful to study the predicted air temperatures first. Knowledge of this value is important when assessing the problem of heat bridges in built-over car parks (at pillars and walls which support the overlying building) and as a worst-case indicator of the risk of hazardous conditions arising due to ice formation (during critical times in winter the floor temperature is slightly higher than the air temperature.) The predictions (Tables 2 and 3) represent typical temperatures in the centre of the car park. Near the entrance and exit the temperatures will be much closer to ambient.

At the air change rates that are typical of those which will be designed for i.e., 0.25 to 0.5 per h, the lowest air temperature for the German climate remained above freezing all year round. Even at much higher air change rates (up to 1.5 per h, see Figure 4) the temperatures remained above freezing. The predicted air temperature increased from 10.1°C to 11.0°C when the earth-contact walls were completely insulated and reducing the insulation to the heated building above raised the temperature even further (but this would be at the expense of the energy efficiency of the building). For the range of ground properties studied, the lowest temperature varied by about 2 K, from 9.1°C to 11.0°C. Under typical UK weather conditions the lowest temperature was somewhat higher than for the (base case) German weather conditions, varying from 11°C in Edinburgh to 12.8°C in

Table 2 Simulation results for the parametric study of the built-over underground car park

		Lowest air temp. °C	Highest air temp. °C	Dew at wall h per a	Dew at ground h per a	Dew in edge h per a
Base case		10.1	16.7	240	210	570
Influence of climate and solar/IR radiation						
V1.1	London TRY	12.8	16.9	160	150	300
V1.2	Manchester TRY	12.4	15.9	110	70	260
V1.3	Edinburgh TRY	11.0	15.1	150	110	320
V1.4[a]	Würzburg TRY	10.1	16.7	240	210	570
V1.5	Würzburg, with solar/IR radiation unshaded	10.4	17.5	30	60	230
V1.6	Würzburg, with solar/IR radiation shaded (without direct solar)	10.4	17.1	110	110	370
Influence of the thermal properties of the earth						
V2.1	Rock, conductivity = 3.5 W/(mK) capacity = 2 MJ/(m^3K)	9.1	16.0	350	530	970
V2.2[a]	Sand, conductivity = 2.0 W/(mK) capacity = 2 MJ/(m^3K)	10.1	16.7	240	210	570
V2.3	Dry sand, conduct. = 1.5 W/(mK) capacity = 2 MJ/(m^3K)	10.6	17.1	150	100	390
V2.4	Clay, conductivity = 1.5 W/(mK) capacity = 3 MJ/(m^3K)	11.0	16.8	220	140	490
Influence of insulation (conductivity = 0.04 W/(mK))						
V3.1	Without insulation at the wall	9.4	16.7	280	270	650
V3.2[a]	With 10 cm wall insulation 1 m below ground-level only	10.1	16.7	240	210	570
V3.3	With 10 cm wall insulation over the whole wall	11.0	16.9	80	120	420
V3.4	5 cm ceiling insulation wall insulation as V3.2[a]	12.0	17.9	30	20	120
V3.5	5 cm ceiling insulation and 10 cm wall insulation	12.8	18.2	10	10	60
V3.6	5 cm ceiling insulation 10 cm wall and ground insulation	12.5	19.3	0	0	0
Influence of air change rate (constant)						
V4.1[a]	Air change rate = 0.25 1/h	10.1	16.7	240	210	570
V4.2	Air change rate = 0.5 1/h	7.4	17.5	300	290	650
V4.3	Air change rate = 1.0 1/h	3.5	18.8	310	290	640
V4.4	Air change rate = 2.0 1/h	−1.1	21.0	300	260	590
V4.5	Air change rate = 4.0 1/h	−5.7	23.7	280	230	550
Influence of the ventilation strategy						
V5.1	Air change rate night 0.25 1/h/day 0.75 1/h	6.6	18.2	300	280	640
V5.2	Air change rate night 0.75 1/h/day 0.25 1/h	6.5	17.7	280	270	610
V5.3	Air change rate: 0.25 1/h or 2.0 1/h when ext. Temp. >7°C	10.3	21.5	110	90	290

Table 2 *(Continued)*

		Lowest air temp. °C	Highest air temp. °C	Dew at wall h per a	Dew at ground h per a	Dew in edge h per a
Base case		10.1	16.7	240	210	570
V5.4	Air change rate: 0.25 1/h or 2.0 1/h when ext. Temp. >11°C	10.5	21.6	70	60	220
V5.5	Air change rate: 0.25 1/h or 2.0 1/h when ext. Temp. >15°C	10.6	21.9	50	40	150
V5.6	Air change rate: 0.25 1/h or 2.0 1/h when ext. Temp. >19°C	10.6	21.9	60	40	200
V5.7	Air change rate: 0.25 1/h or 2.0 1/h when ext. Temp. >23°C	10.5	21.6	100	60	280
V5.8	Air change rate: 0.25 1/h or 2.0 1/h when ext. Temp. >int. Temp.	10.7	22.0	50	30	150
Influence of the room size						
V6.1	Half room width/height 2.5 m	9.7	16.2	340	390	780

[a]Corresponds to the base case.
The table contains the lowest as well as the highest annual air temperatures and the annual hours of condensation at the car-park wall, floor and the edge between them (rounded to the nearest 10 h).

London. Predictions for London were also undertaken for the 20-year period from 1976 to 1995 (using the CIBSE weather data[30]). The lowest temperature varied by less than 2°C during this period.

In earth-covered car parks without direct connection to heated rooms the air temperature is less important. It should however be noted that during very cold climate conditions in these rooms the air temperature as well as the surface temperature of the floor can fall below freezing leading to a risk of ice formation. This risk is clearly reduced, when the roof of the car park is insulated, or when the roof is covered with a thick earth layer.

Conditions, in partly covered car parks, will lie between the predicted temperatures for the two simulated cases, although the exact temperature will depend on the form of the partial covering. For more accurate information simulations must be made on a case-by-case basis.

6 Condensation in built-over car parks

6.1 Base-case predictions

The hourly saturation vapour pressures of the floor and walls in the built-over car park were compared with the partial vapour pressures of the internal and ambient air for the base-case building (Figure 5). It is evident that the partial pressure exceeds the saturation pressure at both surfaces during the summer months. As the floor and wall temperatures are similar, the total time for which condensation will occur will be similar for the two surfaces. As the water content of the outside air rarely depends on the time of day but on short- or long-term weather conditions, condensation can happen during the day as well as at night-time (Figure 6).

During the winter months the heat gain to the car park, primarily from the overlying building, but also from the surrounding earth, warms the air and surfaces. This keeps the surface temperatures, and thus the saturation

Table 3 Simulation results for the parametric study of the earth-covered underground car park, using mid-German climatic data

		Lowest air temp. °C	Highest air temp. °C	Dew at ceiling h per a	Dew at wall h per a	Dew at ground a per a	Dew in edge h per a
Base case		−3.9	22.5	100	230	150	120
Influence of insulation (conductivity = 0.04 W/(mK))							
V7.1	Insulation of the ceiling internal with 4 cm	1.0	18.4	30	140	200	490
V7.2	Insulation of the ceiling external with 4 cm	0.4	18.8	50	150	220	510
V7.3	Insulation of the wall external with 5 cm	−4.3	22.6	110	220	170	90
V7.4	Insulation of wall and ground external with 5 cm	−6.0	24.4	160	230	170	100
V7.5	Insulation of wall and ground external with 30 cm	−7.5	26.0	180	620	550	520
Influence of the ceiling earth cover							
V8.1	Earth cover thickness 130 cm	1.7	18.5	160	300	260	560
V8.2	Earth cover thickness 530 cm	7.3	13.2	1350	2010	1980	2340
Influence of air-change rate (constant)							
V9.1[a]	Air change rate $n = 0.25$ 1/h	−3.9	22.5	100	230	150	120
V9.2	Air change rate $n = 0.5$ 1/h	−4.3	22.5	160	250	190	150
V9.3	Air change rate $n = 1.0$ 1/h	−5.4	22.6	230	270	230	190
V9.4	Air change rate $n = 2.0$ 1/h	−7.1	23.3	290	300	280	270
V9.5	Air change rate $n = 4.0$ 1/h	−9.2	24.8	330	330	310	330

[a]Corresponds to the base case.
The table contains the lowest as well as the highest annual air temperatures which occur in the car-park and the annual hours of condensation at the car-park roof, wall and floor as well as in the edge between wall and floor (rounded to the nearest 10 h).

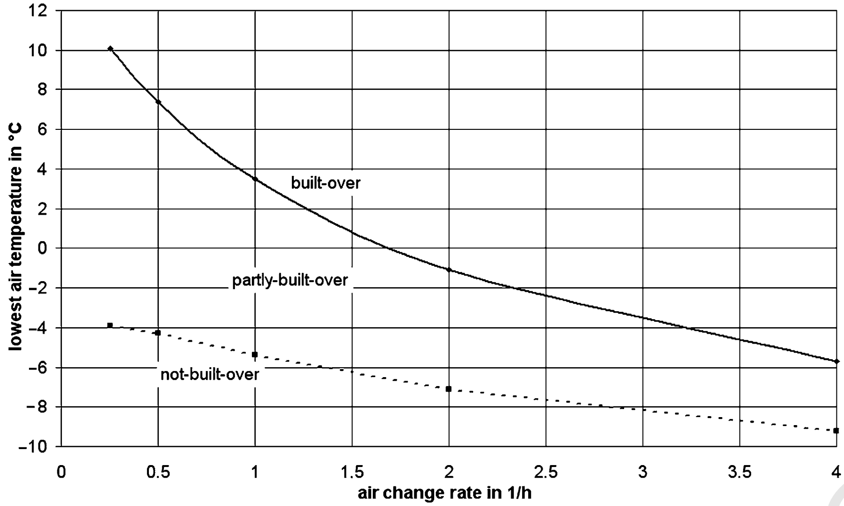

Figure 4 Influence of air change rate on the lowest air temperature in the built-over and earth-covered underground car parks for mid-German climate conditions. The space between both curves approximately represents the thermal conditions in a partially built-over car park

vapour pressures above the partial vapour pressure of the air and so avoids condensation. Thus, there is no risk of freezing surface moisture accumulating in winter to create a safety hazard.

It is also evident (Figures 5 and 6) that the peak daily partial vapour pressure of the internal air is lower than that of the ambient air and the minimum daily value is higher. This is because of the moisture storage capacity of the room air. The influence of the adsorption and desorption of moisture into, and out of, the concrete walls of the car park is not regarded within this simulation

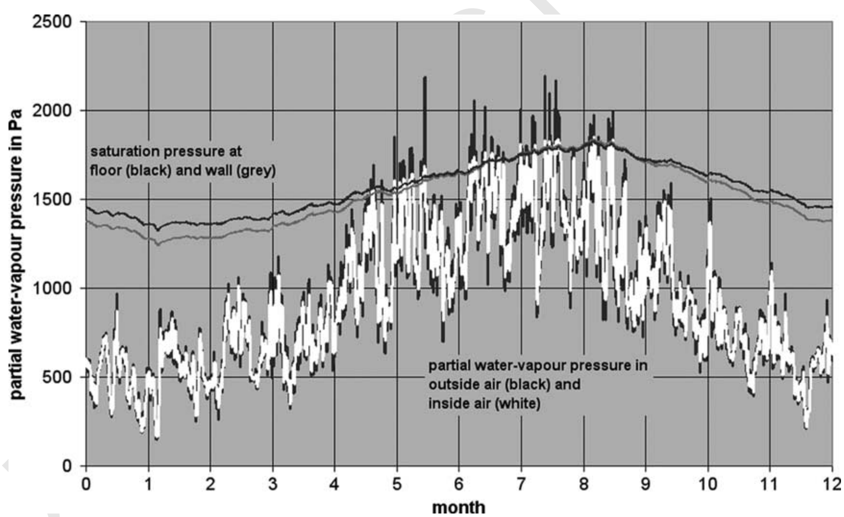

Figure 5 Annual variation of the partial water-vapour pressure of the outside air and the inside air compared to the saturation pressures at the car-park floor and the car-park wall (for the base case version of the built-over car park). The relationship between the vapour pressure of the inside air and the saturation pressures describes the relative humidity at the corresponding room surfaces

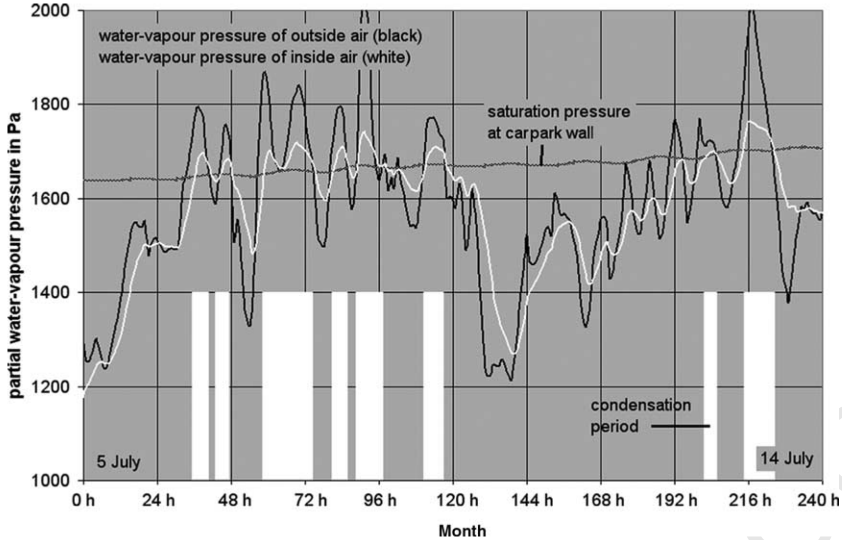

Figure 6 Variation of the partial water-vapour pressure of the outside air and inside air compared to the saturation pressures at the car-park wall, for a 10-day period between 5 and 15 July (for the base-case version of the built-over car park). Condensation occurs when the saturation curves are exceeded by the inside air vapour pressure (white blocks)

(see Section 6.6). One might expect therefore, that as the rate of ventilation increases (i.e., more ambient air is introduced) the amount of condensation will also increase (see Section 6.5)—because the condition of the internal air will approach that of the ambient air.

The length of time during the year for which condensation might occur, also called the 'risk of condensation' in this paper, was calculated by adding up the number of hours for which the saturation vapour pressure of the wall, floor and corner was lower than the partial vapour pressure of the air (Table 2). This value was very sensitive to the precise temperature predicted for the surface—which underlines the need for a robust analysis method. Because of this sensitivity, predicted values (Table 2) have been rounded to the nearest 10 h.

Because the temperature of the corner of the room is lowest, due to the multi-dimensional heat flow, the number of hours for which condensation might occur is high, about 570 h compared to 240 h and 210 h for the wall and ground surface, respectively.

The accumulated volume of water due to condensation at the surfaces was calculated using a typical moisture transfer coefficient of 0.3×10^{-4} kg/(m$^2 \cdot$h$\cdot$Pa) see e.g., Klopfer.[24] In the base-case car park the value never exceeds 40 g/m^2. This water could be stored in the capillaries of a porous material or it could be held on the surface as a film or as droplets. These factors are highly dependent on the hygroscopic properties of the surface material, coatings or paint and so were not investigated in detail.

6.2 Influence of climate and radiation

The risk of condensation in the UK is lower than in central Germany e.g., 150, 110, and 160 h of condensation on the walls in Edinburgh, Manchester and London respectively, compared to 240 h in central Germany (Table 2). This lower risk of condensation is because the air temperature in UK car parks tends to be higher, because the ground is not cooled as much in winter and because it remains warmer during critical times in spring and autumn. In addition, there also tends to be fewer extreme warm and humid days than in Germany. The year-on-year variation in the condensation risk in London was large, varying from 50 h (at the wall) in 1976 to around 350 h in 1982. The 25-year average was almost identical to the value, of 160 h, predicted using the TRY.

The extent to which the ground around the building was exposed to solar radiation (and was free to radiate to the night sky) had a big impact on the risk of condensation. The hours of condensation at the wall, for the mid-German climate, reduced from 240 h to 30 h when the earth was totally exposed and to 100 h when it was subject to diffuse radiation only (night-time long-wave losses to half of the sky-vault). This effect can be explained by the summer solar-heating of the earth, which increases the temperatures of the earth-contacted car park surfaces. When designing moisture sensitive subterranean rooms therefore, greater care needs to be exercised when they face north, or are shaded, than if they face south.

6.3 Influence of earth thermal properties

The thermal properties of the earth depend on many factors e.g., density, water content, material etc. Four different earth thermal properties, as described in DIN EN ISO 13370,[15] were compared. It was found that the condensation risk clearly increases with the thermal conductivity of the earth and tends to increase with its heat capacity. The highest number of annual condensation hours occurred for high-conductivity rock (V2.1), the lowest for dry sandy soil (V2.3). The base case (V2.2) considers damp sandy soil (thermal conductivity of 2.0 W/(m·K) and heat capacity of 2.0 MJ/(m^3·K)), which leads to a condensation risk midway between that for the other soils.

6.4 Influence of insulation

In the base-case simulation it was assumed that there was 10 cm of insulation on the car park ceiling, and outside the vertical walls to a depth of 1 m below the ground surface. When all the wall insulation was removed the risk of condensation increased slightly, from 570 h at the edge (base case) to 650 h. By increasing the depth of insulation to cover the whole car park wall, the condensation risk was reduced to 420 h at the edge. Clearly, the risk of condensation remains high.

Introducing heat into the car park, by reducing the ceiling insulation to only 5 cm, reduced the risk of condensation and this measure, together with external insulation to the whole of the car park wall and floor, entirely eliminated the risk of condensation (0 h). Under these circumstances the car park is effectively part of the heated volume of the building. The reduction in condensation risk is thus gained at the expense of additional energy use for heating the overlying building (as heat 'leaks' out to the car park below).

As the insulation standards for heated and cooled buildings are likely to become more, rather than less, stringent in the future. The risk of condensation in unheated subterranean spaces is likely to increase.

6.5 Influence of air change rate and ventilation strategy

As the air change rate was increased from 0.25 to 4.0, the risk of condensation in the car park varied by only a small amount. This was because, although the introduction of more ambient air increased the partial vapour pressure of air in the car park (at very high air change rates, it would equal that of the ambient air), this was counteracted by the warming effect, which increased the temperature of the surfaces. (The increase in maximum temperatures with air change rates can be seen in Table 2 i.e., V4.1 to V4.5).

The effect of daytime or night-time ventilation was tested by increasing the ventilation rate during the daytime (0.75 per h instead of 0.25 per h between 06:00 and 18:00, V5.1) or during the night-time (0.75 per h instead of 0.25 per h between 18:00 and 06:00, V5.2)—the daily average ventilation rate in both cases 0.5 per h. The calculated hours of condensation and temperatures are, for both cases very similar and comparable with those predicted with a constant ventilation rate of 0.5 per h (V 4.2). Since the time of condensation rarely depends on the time of day (Figure 7), increased daytime or night-time ventilation just leads to correspondingly increased daytime or night-time condensation. The annual hours of condensation are not obviously influenced by daytime-dependent ventilation. Hence, the commonly held view, that subterranean rooms should be ventilated at night-time, was not supported—at least for the car parks studied here.

It should be noted that increased daytime ventilation increases the air temperatures somewhat in the car park (as well as the temperatures of the earth-contacted car park surfaces) e.g., from a maximum of 17.5°C for a constant ventilation rate of 0.5 per h (V4.2) to 18.2°C for increased daytime and reduced night-time ventilation (V5.1).

When the ventilation is increased during times of high outside temperatures the heating-effect can significantly reduce the annual hours of condensation. The air change rate was increased from 0.25 per h to 2.0 per h when the outside air temperature exceeded different specified ventilation set points, which varied between 7°C and 23°C (V5.3–V5.7). The least condensation occurred for a ventilation set point of 15°C (V5.5)—which produced 50 h per year of condensation at the wall, 40 h on the floor at 150 in the edge. In a final study (V5.8) it was shown that very similar results could be achieved if the car park was always increasingly ventilated, at 2.0 per h, when the outside air temperature was greater than the inside air temperature.

The results indicate that a ventilation system with ambient temperature control can reduce condensation in built-over car parks. Since the resultant moisture conditions are quite insensitive to the chosen temperature limit, simple manual control, to increase ventilation rates during warm days in summer, could be a realistic option.

6.6 Influence of room size

To investigate the influence of room geometry and size, the width of the room was halved from 8.45 m to 4.27 m and the internal

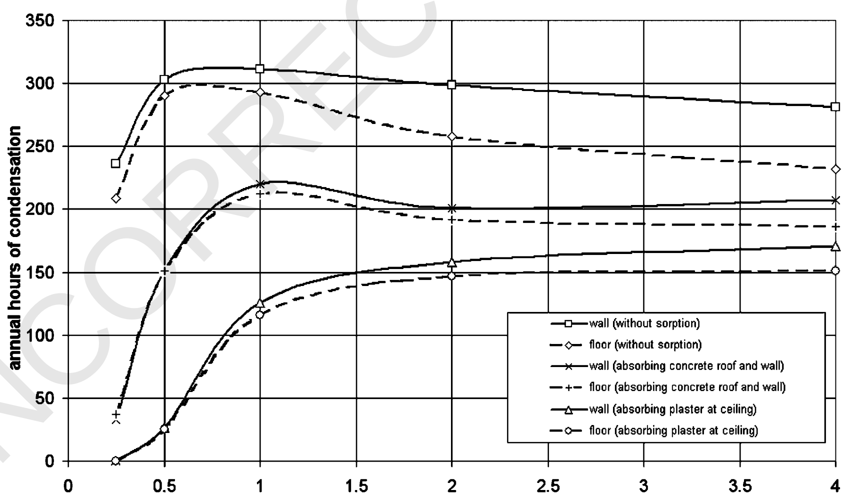

Figure 7 Annual hours of condensation in a built-over underground car park and the influence of the air change rate and the water-vapour adsorption of the room surfaces for mid-German climate conditions

ceiling height was reduced from 2.9 m to 2.5 m. The room was assumed to be infinitely longer in the third dimension. The surface area to volume ratio of the car park therefore increased from 0.8 to 1.0. One would expect, therefore, that the temperature of the surrounding earth would exert a greater influence on the internal conditions in the car park, and thus increase the risk of condensation. This expectation was borne out in practice.

The summer and winter temperatures in the smaller room were a little lower than those for the base case. The risk of condensation on the walls, ground and at the edge was increased (at the edge from 570 h to 780 h). It would appear, therefore, that the risk of condensation in underground spaces increases as the volume of space decreases. Further analysis is required before firm conclusions can be reached about the appropriate method of ventilating smaller spaces, and three-dimensional analysis may be required before firm conclusions can be drawn.

6.7 The influence of moisture storage in materials

In all the simulations discussed above, the KOND model was used, which ignores moisture movement into and out of materials i.e., the car park was assumed to have impermeable surfaces. All the moisture is purely stored on the surfaces.

To test whether or not surface permeability might have an impact on the results, the storage model available within the TRNSYS program was used (see Section 3.2). This model enables the consequence of vapour diffusion into and out of the materials, of which the car park is made, to be examined. Two variations of surface material were considered:

- Car park floor and wall of heavy concrete with diffusion resistance (μ-value) 105 and density 2000 kg/m^2; the insulation layer on the roof assumed to be impermeable.
- Car park ceiling with plaster of diffusion resistance (μ-value) 15 and density 1800 kg/m^2; wall and floor is assumed to be impermeable.

The variation of the risk of condensation (annual hours of condensation) with air change rate for both these cases and for the base-case are plotted in Figure 7.

As expected, the risk of condensation is much lower when the surfaces are able to absorb moisture vapour and this is particularly so when the car park has a low air change rate. With a plaster lining to the ceiling and a small ventilation rate of 0.25 per h, there is no condensation on either the walls or the floor. As the moisture absorbing capabilities of the materials is limited, the effect of the moisture absorbing characteristics diminishes as the air change rate in the car park increases.

As described in Section 3.2 the TRNSYS moisture model is limited to vapour diffusion between the room air and two storage layers in the material (surface buffer and deep buffer storage). In reality, liquid capillary water transport would certainly increase the water transport into the depth of the material and therefore increase the absorbing capabilities (thus reducing the negative influence of ventilation). This could however not be investigated.

It is clear from Figure 7, that at the air change rates which are common (recommended in Germany) there is a substantial difference in the risk of condensation between car parks with impermeable surfaces and those with moisture absorbing surfaces. It is therefore important to stress that the sensitivity analyses conducted earlier concerning climate conditions, insulation, room size and ventilation strategy applies only to car parks with impermeable surfaces.

Finally, it is worth noting that the absorption of water vapour into the materials reduces the peak vapour pressure of the air and therefore the risk of condensation.

The materials, although not saturated, nevertheless have high moisture content and so there remains potential for mould growth, which can occur at a relative humidity of around 80% or more.[7,31,32] To examine the risk of mould growth, the annual hours above 80% relative humidity, at surfaces of different moisture absorption, should be studied. This is a possible topic for further investigation.

7 Condensation risk in earth-covered car parks

In contrast to car parks below buildings, there is very little heat gain in winter to a car park covered by earth. The conduction heat losses to cold winter temperatures (despite small solar gains) lead to internal temperatures well below those for a built-over car park at the same ventilation rate (compare base case Table 3 with base case Table 2). In contrast, because it was assumed that the ground of the earth-covered car park is exposed to solar radiation, the summer temperatures in the earth-covered car park are much higher than in the car park below the building.

The consequence of the different thermal regime in the earth-covered car park is that the condensation risk in summer is low—the vapour pressure of internal air is less than that of the internal surfaces (Figure 8).

Between autumn and spring the saturation pressures of the ceiling as well as of the earth-contacted surfaces are below the partial vapour pressure of both the ambient and internal air on a number of occasions and thus surface condensation is likely to occur during the cold period. During autumn and early winter the ceiling tends to be the coldest surface whilst the earth-contacted surfaces are slightly warmer due to the warming effect caused by the seasonal heat storage of the earth. Therefore, during this time, more condensation occurs at the ceiling than at the other surfaces. During late winter and spring (and summer) the same heat-storage effect, in combination with increased solar radiation onto the ceiling, leads to the opposite

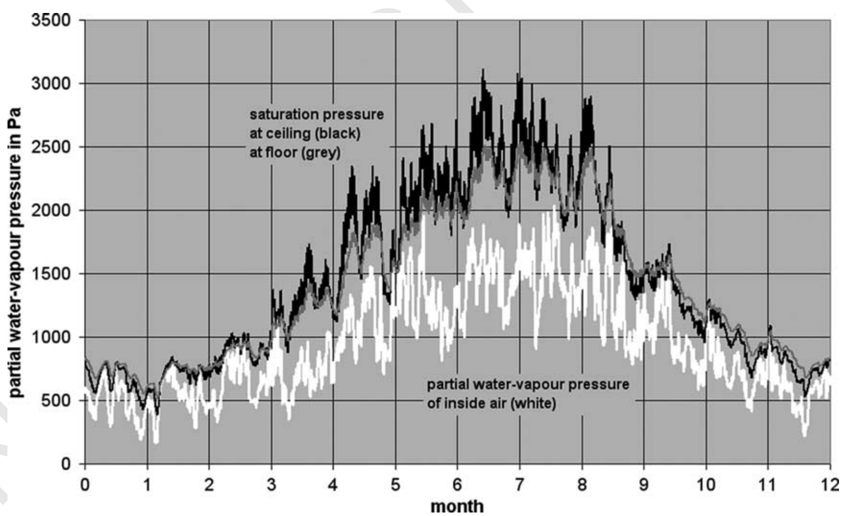

Figure 8 Annual variation of the partial water-vapour pressure of the inside air compared with the saturation pressure at the car-park ceiling and car-park floor (for the base case version of the earth-covered car park). The relationship between the vapour pressure of the inside air and the saturation pressure describes the relative humidity at the corresponding room surface

situation: higher ceiling temperature and lower temperatures at the earth-contacted surfaces. This results in condensation at the earth-contacted surfaces (Figure 9).

As for the room covered by the building, the number of hours in the year for which the partial vapour pressure of the air exceeds the saturation vapour pressure of each surface was calculated (Table 3) and, again, the risk of condensation was calculated for the middle point of each surface and at the edge between the wall and the floor. The values reached 100 h at the ceiling, 230 h at the wall, 150 h at the ground and 120 h at the edge for the base-case car park.

Since most of the condensation occurs during late winter or spring (during the warming period) the earth-contacted surfaces generally suffer more condensation than the ceiling. It can also be seen that, in contrast to the built-over car park, the risk of condensation is less at the edge than it is at the other earth-contacted surfaces, which stay in greater thermal contact with the space. This can be explained by the warming effect of the surrounding earth, which is mentioned above. This prevents condensation at the edge until the middle of February (Figure 10).

When considering the problem of water droplets falling onto cars, the ceiling is the most critical surface. However, the maximum amount of condensation that accumulated at the ceiling never exceeded 20 g/m^2 (also see Section 6.1). Again the risk of down-drop will mainly depend on the hygroscopic properties of the surface, which were not investigated in this study.

7.1 Influence of air change rate

As in the case of the built-over car parks, the introduction of more ambient air during times with high outside vapour pressures increased the partial vapour pressure of the air in the car park. In addition, as the earth-covered car park is warmed by conduction from the surrounding earth in winter, and heat is lost by conduction through the overlying earth and in the ventilation air, any

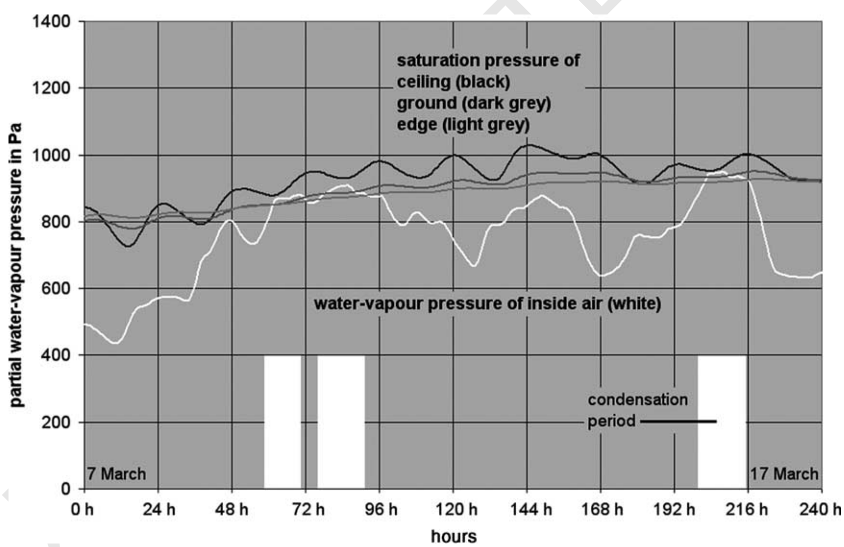

Figure 9 Variation of the partial water-vapour pressure of the inside air compared with the saturation pressures at the car-park ceiling, ground and edge for a 10-day period between 7 and 17 March (for the base-case version of the built-over car park). Condensation happens when the saturation curves are exceeded by the inside air-vapour pressure (white blocks)

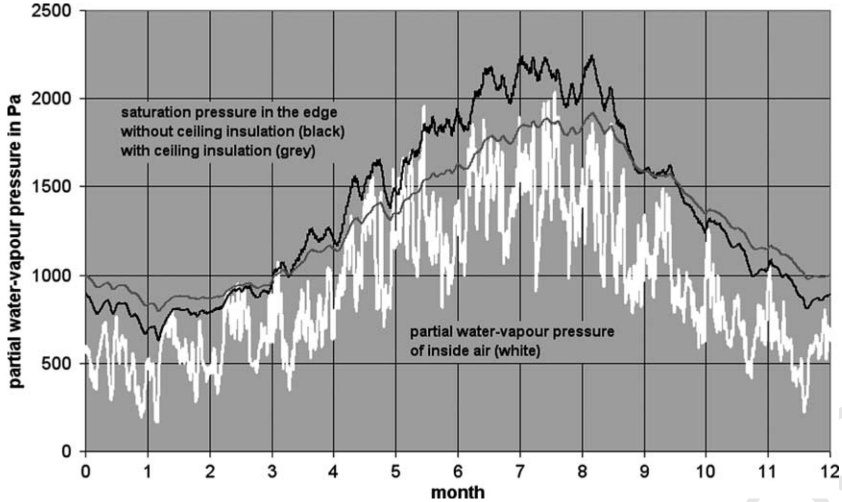

Figure 10 Annual variation of the partial water-vapour pressure of the inside air compared with the saturation pressure at the edge for a car park without insulation at the ceiling and with 4 cm insulation at the inner side of the ceiling. The relation between the vapour pressure of the inside air and the saturation pressure describes the relative humidity at the edge

increase in the ventilation rate results in a lowering of the internal air temperature, a lowering of the temperature to the surfaces adjacent to the air, and thus an increase in the risk of condensation (Figure 11). The decrease in the air temperature in the car park and the resultant increase in the risk of condensation on all surfaces can clearly be seen in Table 3.

For ventilation rates of 2.0 per h and higher, floor condensation was predicted for a short period when the temperature was below 0°C (results not shown here). This could lead to ice formation on the floor.

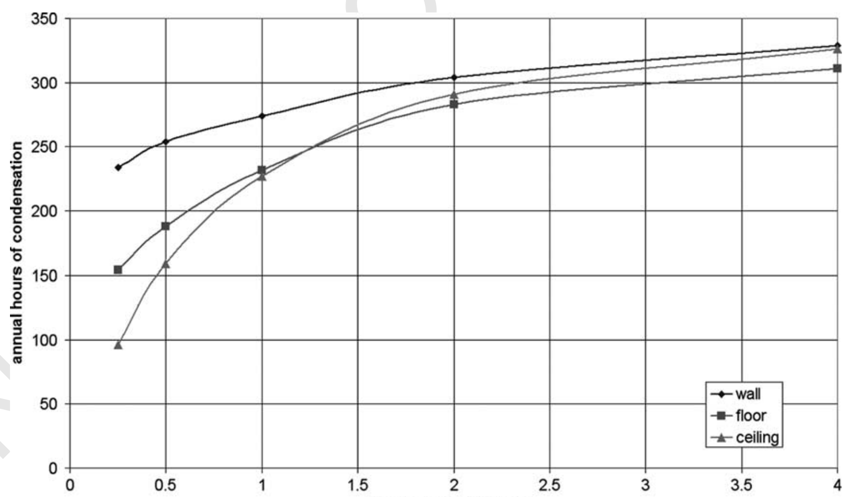

Figure 11 Influence of the air-change rate on the annual hours of condensation in the earth-covered underground car park for mid-German climate conditions. No water-vapour adsorption is considered

The design consequence of these predictions is that, to reduce condensation, ventilation rates should be kept to a minimum, especially during the winter, in earth-covered car parks.

7.2 Influence of insulation

The impact of insulating the ceiling and the surrounding walls and floor of the car park was examined. By placing 4 cm of insulation on either an inside or an external surface of the ceiling, the winter temperatures were raised (Table 3). As a consequence, the risk of condensation on the ceiling and on the walls was reduced. There was, however, a slight increase in the risk of condensation on the floor and a more pronounced risk at the edge. This was attributed to the decrease in summer temperatures, caused by the insulation i.e., the creation of a summer condensation problem. The shift in the time of condensation at the edge can clearly be seen in Figure 10, which compares the saturation pressures for both cases: with and without (base case) ceiling insulation. On balance it would seem that insulating the roof of the car park has no overall benefit with regard to the likelihood of condensation.

Insulating the wall and ground to a thickness of 5 cm or 30 cm reduces the winter earth warming effects and so the internal air temperature is decreased. The temperature of the surrounding surfaces is also diminished and therefore, compared to the base case, the risk of condensation on all surfaces (except of the edge for the 5 cm insulation) is greater. In addition, the time of condensation is shifted towards autumn and early winter while the condensation problem in spring is reduced. Since most of the condensation at the edge occurs in spring, a small amount of insulation reduces the condensation risk in this region. Thicker insulation however, results in the temperature of all the surfaces becoming similar and a higher condensation risk.

From a practical design point of view, the external insulation of all the surfaces of an underground space is usually prohibitively expensive.

7.3 Influence of the thickness of earth cover

As, in winter, heat is lost from the car park to the cold ambient air, one would anticipate that increasing the earth cover (and therefore the thermal insulation to the ceiling), would reduce the risk of condensation. In practice, this is not the case—the predicted hours of condensation at the wall increased from 230 h (base case) to 300 h (with an earth covering of 130 cm) and to 2010 h (with an earth covering of 500 cm).

The result can be explained by noting that the condensation problem shifts from winter to summer, when the thickness of earth is increased—note the decrease in the highest recorded air temperature (Table 3). With a covering of 530 cm of earth, the summer time temperature is reduced to 13.2°C and condensation occurs entirely during the summer period. The simulations suggest that it is preferable for earth-covered car parks to be covered to a minimum thickness, or, if they must be buried to a greater depth, increased ventilation during times with high outside temperatures is likely to be beneficial (see Section 6.5)

8 Conclusions

8.1 Numerical methods

Numerous methods are available by which the temperature and humidity conditions in buildings and building elements can be calculated. However, in general, they deal with a limited number of the hygrothermal problems which are encountered in practice. In unheated subground spaces, the internal conditions depend on the multi-dimensional heat transport in the adjacent earth, the prevailing climatic conditions and the construction and ventilation of the space. Numerical analysis of these problems requires highly-sophisticated multi-dimensional heat flow and moisture models.

To investigate the hygrothermal conditions in subterranean car parks a two-dimensional simulation procedure has been developed based on coupling the transient heat transfer programme HEAT2 with the dynamic thermal building simulation program TRNSYS. The likelihood of condensation and the rate of water deposition on surfaces were calculated with a simple model—KOND. To estimate the consequence of moisture adsorption in materials in the hygroscopic range below saturation, the TRNSYS moisture capacitance model (buffer storage model) was used.

The lowest and highest annual air temperatures in the underground car parks, and the number of hours in the year during which surface condensation could occur were investigated for built-over car parks (with a heated building above) and earth-covered car parks. Analyses were conducted using mid-German (base case) and UK weather data. For the earth-covered car parks, results are given for each variation of insulation, earth cover and ventilation rate. Additionally, in the built-over car park, variations in the properties of the ground, the ventilation strategy and weather conditions were studied.

8.2 Built-over car parks

At typically occurring air change rates i.e., those which will be designed for, 0.25 to 0.5 per h, the lowest air temperature in built-over car parks for the German climate remained above freezing all year round.

Under typical UK weather conditions the lowest temperature in the built-over car park was between about 1 K and 3 K higher than for the (base case) German weather conditions.

In built-over car parks, surface condensation usually occurred during the summer. For the base case (German climate, air change rate 0.25 per h) the annual hours of condensation were predicted as 240 h at the wall, 210 h on the floor and 570 h at the edge between them. The maximum accumulated volume of condensate at the surfaces was about 40 g/m^2.

The risk of condensation in the UK is generally lower than in central Germany and can be less than half (for Manchester). The year-on-year variation in the condensation risk in London was large, varying from 50 h to around 350 h (at the wall) between 1976 and 1995. The 20-year average was almost identical to the value predicted using the TRY.

The extent to which the ground around the building is exposed to solar radiation has a big impact on the risk of condensation in built-over car parks. When designing moisture sensitive subterranean rooms therefore, greater care needs to be exercised when they face north, or are shaded, than if they face south. In contrast, the thermal properties of the soil have less impact on the risk of condensation.

Reducing the thickness of ceiling insulation in built-over car parks reduces the risk of condensation and this measure, together with external insulation to the whole of the car park wall and floor, can eliminate entirely the risk of condensation. However this would lead to additional energy use for heating the overlying building. As the insulation standards for heated and cooled buildings are likely to become more, rather than less, stringent in the future, the risk of condensation in unheated and uninsulated subterranean spaces is likely to increase.

As the air change rate was increased, the risk of condensation in the built-over car park varied by only a small amount. In addition, the annual hours of condensation could not obviously be influenced by a simple time-dependent ventilation regime (e.g., by increased night-time or daytime ventilation). However, when the car park was ventilated at a higher rate during the time of high outside temperatures e.g., above 15°C, the temperature level in the car park was lifted and the annual hours of condensation were markedly reduced. It is suggested therefore that a ventilation regime with simple ambient temperature control can reduce the risk of condensation problems in built-over car parks.

There is a substantial difference in the risk of condensation between built-over car parks with impermeable surfaces and those with moisture absorbing surfaces. The risk of condensation is much lower when the surfaces are able to absorb moisture vapour below saturation and this is particularly so when the car park has a low air change rate.

8.3 Earth-covered car parks

In contrast to car parks below buildings, in earth-covered car parks with unshaded roofs, the summer temperatures are much higher whilst the temperatures in winter are clearly lower—in fact, below freezing on some occasions. Thus surface condensation is likely to occur during the winter period. For the base-case car park, the annual hours of condensation were, depending on the surface, 100 to 230 h. However, the maximum accumulated amount of condensation water at the ceiling did not exceed 20 g/m^2.

In earth covered car parks any increase in the winter ventilation rate resulted in a lowering of the internal air temperature, a lowering of the temperature on the surfaces adjacent to the air, and thus an increase in the risk of condensation. To reduce condensation, ventilation rates should be kept to a minimum, especially during the winter.

Insulating the ceiling of an earth-covered car park increases winter and reduces summer temperatures. As a consequence, the condensation problem is shifted from winter to summer. On balance, insulation seemed to give no overall benefit with regard to the likelihood of condensation.

Similarly, increasing the earth cover of a car park shifts the condensation problem to summer and clearly increases the condensation problem. The simulations suggest that it is preferable for earth-covered car parks to be covered to a minimum thickness, or, if they must be buried to a greater depth, increased ventilation during times of high outside temperatures (e.g., over 15°C) is presumably favourable.

Acknowledgements

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