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Academic Article

Effect of trees and greening of buildings on the indoor heating and cooling load – microscale numerical experiment

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ABSTRACT

A three-dimensional microscale model is used to study the effects of trees and greening of buildings on the indoor heating and cooling load during a winter and a summer scenario. Shading by evergreen trees increases the heating load but also reduces the cooling load. The green roof and walls decrease the surface temperature in the summer scenario during daytime and increase it at nighttime. Overall is the cooling load decreased. An evergreen facade also improves the building insulation and causes a lower heating load during winter.

Key Words : indoor climate, trees, green roof, green wall, heating load, microscale simulations

1. Introduction

In developed countries, the average person spends most of their time in an interior location. During summer people stay in Germany and north America 79 % to 90 % of their time indoors and in winter even 88 % to 97 % [(1)(2)]. Especially in private households heating takes the largest amount of the total energy used there [(3)] and is most often provided by fossil fuels [(4)]. Whereas only 3 % of German households were using an air conditioning in 2015 [(5)], this number is rising since 1990 [(6)]. Regarding this, generating of a comfortable indoor climate during summer and winter without using more energy is very important and may reduce carbon emissions.

Urban greenery, such as green roofs, green facades and trees can have a positive effect on the local climate especially in summer by moderating the maximum temperatures [(7)(8)]. The effects of those green elements on the outdoor climate can be studied using a three- dimensional microscale meteorological models - for example with ENVI-met [(9)] or ASMUS [(10)]. Green walls and trees have also an effect on the indoor climate and can reduce the indoor temperature and cooling load during summer [(11) (12)].

The effects of those measures on the cooling and heating load during summer and winter conditions is investigated in the present study. A numerical microscale model is used to simulate the outdoor and indoor climate of a single building and analyze the effect of greenery and other measures on the energy consumption for different orientated and situated rooms. The simulation results for a building without green during a winter condition is compared to measurements made by Eiband [(13)].

2. Methods

The wind and temperature distribution is simulated with the micro-scale model ASMUS (Ausbreitungs- und Strömungs Modell für Urbane Strukturen). It is based upon the Navier-Stokes equations, the continuity equation, the first law of thermodynamics and an equation for specific humidity. Buildings and trees are represented by impermeable or semipermeable grid volumes. Their surface temperatures are calculated depending on their specific orientation and physical properties by a surface energy budget [(14)]. The model equations, boundary conditions for ground and building surfaces, including green roofs and trees are described by Gross [(10)].

The calculation of the latent heat flux is modified after Bruse [(15)] to take the soil water content and solar radiation via stomata resistance into account [(16)].

2. 1 Indoor Module

The walls, floors and roof elements of a building are divided in to multiple layers of different depth, thermal conductivity and thermal diffusivity. Windows have multiple layers of equal width and physical properties that sum up to the U-value (overall heat transfer coefficient) of real windows. A one-dimensional model is used to calculate the temperature within all layers.

Diffuse and direct shortwave radiation can partially transmit through windows in both directions. Longwave radiation is

absorbed by all surfaces. Each surface type can have a different albedo.
The temperature of the indoor surfaces is also calculated by an energy budget, but the diffusion coefficient for heat K to calculate the sensible heat flux by a flux-gradient relationship is empirically fixed to 0.08 m^2s^{-1} to match the heat transfer coefficient for indoor surfaces in DIN EN 6946 [17]

$$Q_H = c_p \rho K \frac{T - T_{Surf}}{\Delta z} \quad (1)$$

c_p is the specific heat, ρ the air density, Surf means Surface, T the temperature at the next air grid point and Δz is the distance between this grid point and the surface.
A room is heated or cooled by a single grid box where the temperature is decreased or increased and the heating or cooling power is calculated. An ideal air conditioning system is assumed for cooling that has an energy conversion efficiency of 1 like the numerical and experimental heating system.
Each room is ventilated through its outer walls to simulate typical leakage through window seams and doors and to take legal requirements for air exchange rates into account. The energy saving regulation EnEV (Energieeinsparverordnung) [18] requires a minimum exchange rate of 0.5 h^{-1} that is also used in these simulations.

3 Setup of the numerical experiments

Eiband [13] has built a real size single 14 m² large and 2.5 m high room that has one south orientated window with a size of 2 m² and has a very effective insulation towards all "inner" walls, the floor and the roof. An artificial sun and a glass dome over the only exterior wall are used to simulate direct and diffuse shortwave radiation through the window as well as different outdoor temperatures. The room is ventilated through the south facade with an air exchange rate of 0.5 h^{-1} and is heated with a fan heater.
For the simulations, this room is copied and mirrored to create a full three-storey building with a flat roof and 6 rooms per floor. Half of them with a window to the south and the other half with a window to the north side (Fig. 1). The south orientated room in the center of the 2nd floor corresponds with the real size room from Eiband [13].
The rooms fulfill building insulation requirements in Germany from 2004. The thermal properties of the different wall layers are described in Table 1 (layer structure in detail in [13]).
For these simulations, an equidistant Cartesian staggered grid with a mesh size of 0.5 m was used. Therefore, the windows are 12.5 % larger and have a size of 2.25 m².

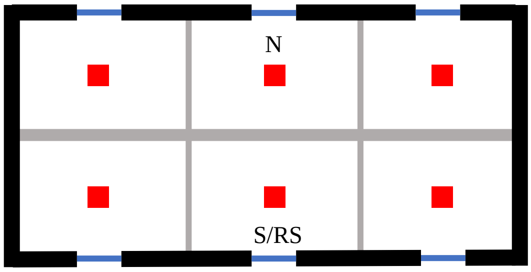

Figure 1: Floor plan of the simulated building. With window positions as small blue lines, heating grid points as red squares, centered north room on 2nd floor N, centered south room on 2nd floor and reference to measurements S, centered south room on 3rd floor under the roof RS.

Table 1: Albedo and calculated heat transfer coefficients of walls, ceilings and floors according to material parameters (after [13]).

	Albedo	U-value
Facade	0.3	0.44
Window	-	1.4
Side wall	0.6	0.9
Rear wall	0.6	0.65
Ceiling	0.6	0.52
Roof	0.3	0.52
Floor	0.3	0.52
Green wall	0.3	0.43
Green roof	0.3	0.50

3. 1 Meteorological and HVAC conditions

A winter and a summer situation is simulated. The winter situation was created by Eiband [13] and represents a typical sunny winter day in Munich, Germany at the 20th of February. The temperature outside varies between -5 °C and +5 °C with an average temperature of -0.53 °C and the sun is shining for 9 hours with a maximum shortwave irradiance of 480 W/m². The summer situation represents a clear hot summer day without clouds at the 20th of July. The outdoor temperature varies between 20°C in the early morning and 30°C in the early afternoon.
A room is heated in winter when its average temperature is lower than 20 °C. In summer a room is cooled when the room temperature is higher than 20 °C.

3. 2 Initialisation and Spin-up

It takes serveral days of simulation time for the temperatures inside the walls to reach a steady state under periodic outdoor conditions and the three-dimensional simulation is computationally very intensive. Therefore, a one-dimensional model is used for each building wall, roof and floor element that is forced on the outside with the diurnal cycle for the winter or summer situation and on the inside with a constant room temperature.

3. 3 Building scenarios

For both meteorological scenarios four different building setups are simulated: the basic building (B), a building with three close large evergreen trees on the south side (14 m high, 10 m crown diameter) (T), a building with a green roof (0.2 m growing medium and 0.2 m thick vegetation on top) and green facades (during summer and winter) on all surfaces except for the windows (0.2 m thick vegetation) (G) and a building where all windows are 66 % larger and have an area of 3.75 m² (W).

The simulated green roof is covered with gras with an leaf area index (LAI) of 6 and the green facades consist of ground-based ivy (LAI = 4). The water supply of the plants is optimal with a soil water content at field capacity. The evapotranspiration is mainly limited by the stomata resistance of the plants and its reaction to shortwave radiation.

4 Results

During the winter scenario, there is a strong change in power needed for heating and indoor temperature for unshaded south orientated rooms caused by short-wave radiation from the sun through the windows (Fig. 2).

Room S gains 5.7 kWh of energy per day by heating (Table 2) and about 2.0 kWh per day by incoming short-wave radiation through the window. The same total is lost by heat transfer through the outer façade (4.4 kWh per day) and due to the forced ventilation (3.3 kWh per day). In comparison to this room N gains almost no energy by short-wave radiation through the window but has a about the same losses through the façade and ventilation and therefore has higher heating requirements. Room RS has also energy losses through the roof and therefore also needs more energy for heating than the rooms S and N.

For the basic scenario, the heating power in room S and the indoor temperature is similar to the measurements by Eiband. The simulated reference room needs 8 % more energy than in the laboratory experiment.

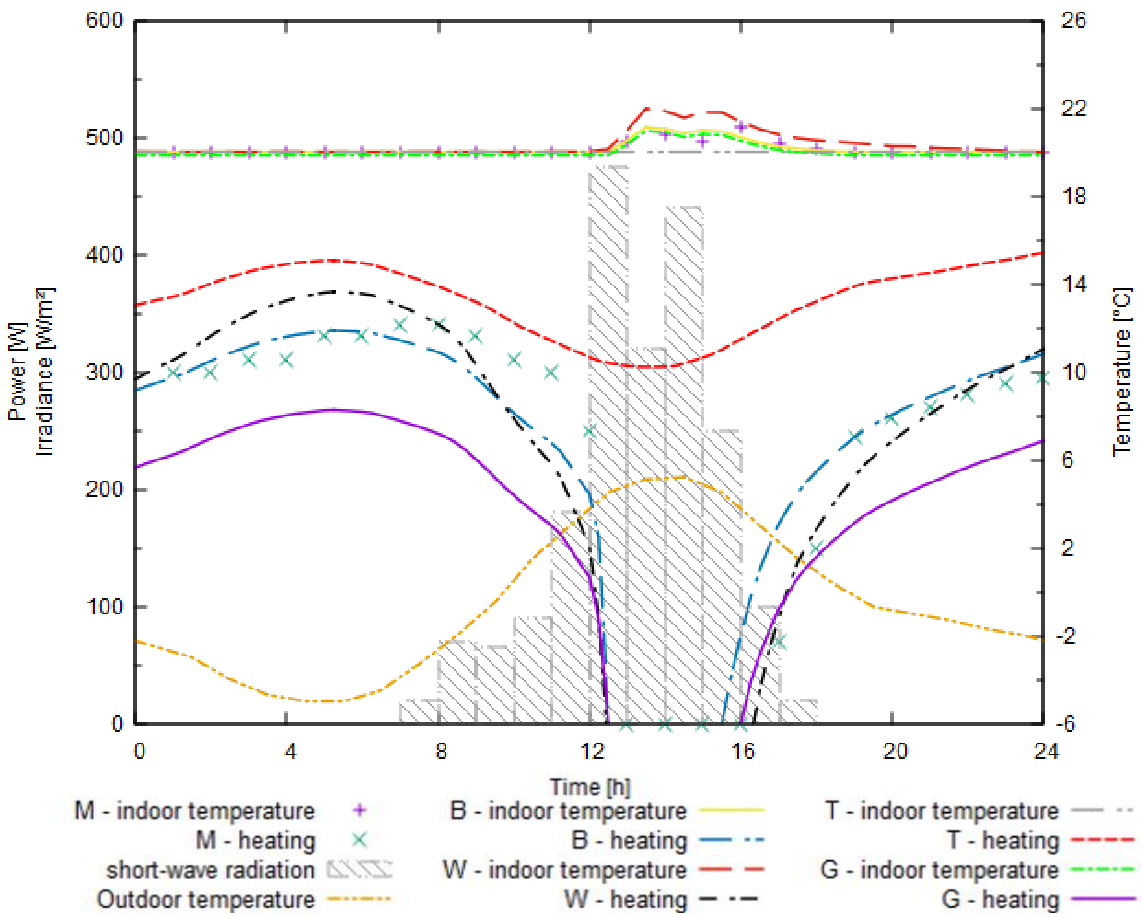

Figure 2: Outdoor temperature at 2 m height and short-wave radiation during the winter scenario, indoor temperatures and power needed for heating in room S for different building scenarios (Basic, big Windows, Trees, Green roof and facades)

Table 2: Energy for heating /cooling in different scenarios and rooms (see Figure 1)

Energy [kWh/d]	Eiband	Basic			Trees			Green			Windows		
	S	S	N	RS	S	N	RS	S	N	RS	S	N	RS
Winter	5.3	5.7	8.7	13.9	8.6	9.1	17.3	4.2	7.1	11.9	5.6	9.6	13.5
Summer	-	4.4	3.2	5.6	2.9	3.1	5.4	4.0	2.7	5.5	5.0	3.5	6.1

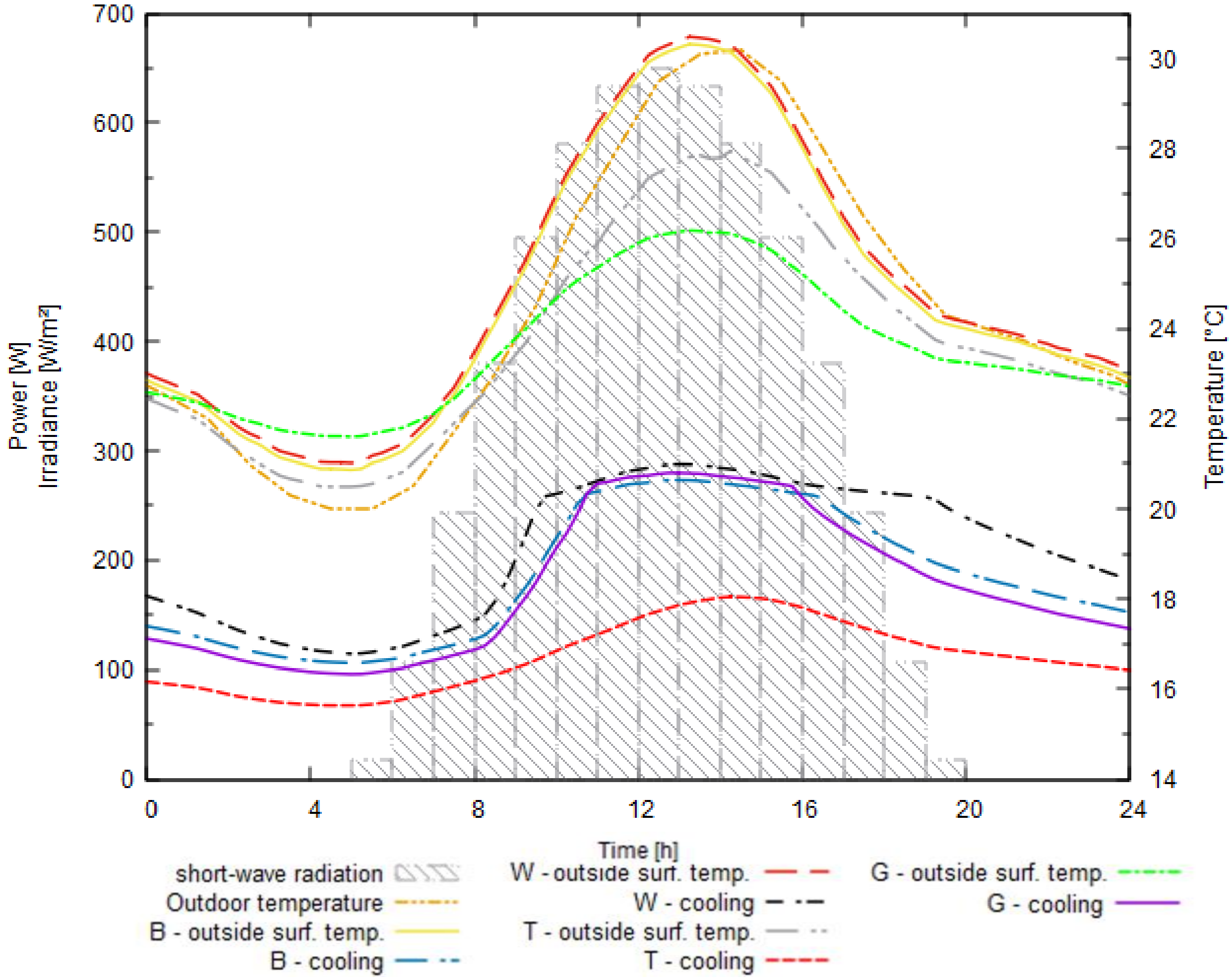

Figure 3: Outdoor temperature at 2 m height and short-wave radiation during the summer scenario, outside wall surface temperatures and power needed for heating in room S for different building scenarios (**B**asic, big **W**indows, **T**rees, **G**reen roof and facades)

Bigger windows reduce the time the heating is needed, increase the indoor temperature while the sun is shining but need more power at night due to the higher heat transfer coefficient of the window surfaces compared to the wall facade. Therefore room S and RS need about the same energy for heating than in the basic szenario.

Almost zero short-wave radiation enters the rooms S and RS in the scenario with trees and causes that more heating is needed there. The results and causes are very similar to the north orientated room N in the basic scenario.

The green scenario has a lower heat transfer coefficients caused by the additional green roof and facade layer. This results in lower heating requirements for all rooms.

During the summer scenario in the unshaded south rooms S and RS is most of the cooling power used while the sun is shining through the windows (Figure 3). The rooms gain less energy per day by ventilation (1 kWh) due to the lower differences between indoor and outdoor temperature and also through the facade. Incoming short-wave radiation is heating the southern rooms much more than in the winter szenario (3,3 kWh per day).

The trees reduce the cooling load very strong by blocking the short wave radiation from entering the south rooms. The surface temperature of the southern facades is also lower.

Bigger windows are increasing the cooling load by the same properties that affected the winter situation.

The green roof and walls cause lower outside surface temperatures during daytime by evapotranspiration and higher surface temperatures during nighttime because of the stronger heat flux from the underlying vegetation layer. Therefore, the overall effect on the cooling load is relatively small (Table 2).

5 Summary and Discussion

The different results of the laboratory experiment and the simulated reference room are probably caused by differences in the size of the window and the room itself due to the used grid resolution.

The room location and solar radiation cause the strongest effects in the simulations for the heating and cooling load. The ventilation of the room can have a strong impact on the heating and cooling load if there is a large differenze between indoor and outdoor temperature. In other meteorological szenarios ventlation could be used to lower the energy demand of the rooms. Overall the energy demand can be more than two times larger between different rooms.

The rooms in the green building need up to 16 % less energy in the summer and up to 26 % less energy in the winter scenario. This effect depends on the available soil water for evapotranspiration, the meteorological conditions and whether the green walls will lose their leaves during winter.

The simulated trees decrease the cooling load in the summer scenario by up to 34 % and increase the heating load during winter by up to 51 %. The negative effects during winter could be avoided by using deciduous trees.

The overall effects of the tree, green and window measures should be evaluated on a long-term yearly basis and effects of the micro-scale urban climate should be taken into account.

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