Simulation of indoor temperature and humidity conditions in the suburban and urban area over a hot summer

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Abstract. Urban areas are already suffering from the heat island effect. In the context of climate change, there will be higher temperatures and longer, more severe, and more frequent heat waves. The balance of indoor air temperature and relative humidity is very important for health and comfort of the occupants, building energy consumption and durability of the building envelope. In this study, a numerical model that incorporates building envelopes, indoor environment, indoor moisture and heat generation is developed. This model is validated with an analytical solution and with the BESTEST cases. We apply the whole building simulation model to study indoor temperature and humidity conditions in urban and suburban areas in Zurich, Switzerland in the summer of 2018. Indoor air temperature and relative humidity will not be accurately simulated when moisture transport in the building envelopes is not considered. There is a large difference of indoor temperature in the urban and suburban area during heat wave. The effect of moisture transport in the building envelopes on indoor temperature and relative humidity is important. Moisture transport could sometimes have a large influence on indoor thermal conditions. There is a potential of using hygroscopic material to lower indoor air temperature during heat waves.

1. Introduction
An urban area is usually much warmer than its surrounding rural areas, which is known as urban heat island (UHI) effect. The temperature difference between urban and rural areas is much larger at night than during the day. The urban area will be even warmer in the future due to the influence of climate change [1]. The global average surface temperature at 2090-2099 will likely be 1.7-4.4 °C higher than at 1980-1999 according to the A1B emission scenario whereas it will likely be 2.0-5.4 °C higher according to the A2 emission scenario [2]. The frequency, severity and duration of heat waves will increase significantly in the future.

Whole building simulations have been used to calculate indoor air temperature [3]. However, most whole building simulation models such as TRNSYS consider only heat transport in wall envelopes while moisture transport in wall envelopes is not considered. In reality, heat and moisture transport are coupled. Vapor transport in building envelopes is associated with sensible and latent heat flux. Omitting moisture transport may lead to incorrect simulation of indoor air temperature.

The capability of hygroscopic materials to moderate indoor humidity levels has been extensively studied. They could greatly increase perceived air quality in buildings by damping indoor humidity fluctuations. Furthermore, the moisture buffering effect of hygroscopic materials could greatly affect
indoor thermal condition. There may be possibilities to use hygroscopic materials to lower indoor temperature during heat waves.

The objective of this work is to study indoor temperature and humidity conditions in the suburban and urban areas during a hot summer. A whole building heat and moisture model is developed to simulate temperature and humidity conditions in the building envelope and indoor air. The influence of moisture transport in the building envelope on indoor air temperature is analyzed. The effect of hygroscopic materials on lowering indoor air temperature during heat waves is studied.

2. Development of whole building heat and moisture model
In this study, a building envelope model and an indoor model are coupled together to build a whole building heat, air and moisture transfer model. Heat and moisture transport in the building envelope is described with a one-dimensional hygrothermal model [4]. The hygrothermal model accounts for capillary liquid transport, moisture transport by vapor diffusion, vapor adsorption and desorption, heat conduction, transfer of sensible heat with capillary liquid transport and vapor diffusion, transfer of latent heat with vapor diffusion and heat conduction. The indoor air is assumed to be a well-mixed zone. The moisture and heat balance of the indoor model considers moisture and heat transfers with the envelope surfaces, air exchange via natural and mechanical ventilation, inner heat and moisture sources or sinks. The building envelope model and indoor model are coupled through moisture and heat exchange between building envelope and indoor air.

The whole building heat and moisture model is solved using Coefficient Form PDE from the finite element solver COMSOL. The developed numerical model is validated by two benchmarks: analytical solution for moisture buffering effect study from Bednar and Hagentoft [5] and BESTEST 600FF and 900 FF cases [3].

3. Case study
The considered study site is the city of Zurich (Figure 1). Kaserne, located in the city center, is chosen to represent urban area and Affoltern, located in the suburban of the city, is chosen to represent the rural area. The summer of 2018 is one of the hottest summers since the beginning of the meteorological measurements. Figure 2 shows air temperature measured at the two stations during the heat wave period (Source: MeteoSwiss). During the period from 25th July to 9th August excluding 28th July, the maximum air temperature at Affoltern and Kaserne reaches above 30.0 °C. There are similar air temperature variations during the daytime at the two stations. However, large differences of the air temperature between Kaserne and Affoltern exist during the night time. Air temperature at Affoltern shows much lower values at night. The maximum temperature difference between the two stations at night is up to 5.65 K. During the heat wave period, the air temperature at Kaserne at night is mostly above 23.0 °C. By comparison, the air temperature at Affoltern at night is much lower.

A room facing east with geometry of $5 \times 3 \times 2.5 \text{ m}^3$ is selected for this study. Only one wall is an exterior wall. There is a window with a size of 3.0 m² on the exterior wall. The room is surrounded by other rooms, thus the ceiling (with floor above), floor and the other three interior walls are shared with the surrounding rooms. It is assumed that this room has the same condition as the surrounding ones. Therefore, adiabatic boundary conditions could be applied to the middle of the ceiling, floor and interior walls. Figure 3 shows the building components considered in the numerical model. The exterior wall has a thickness of 0.52 m and a U value of 0.23 W/m²K. For ceiling, floor and the interior walls, only half of their components are considered due to symmetry. The window has a U value of 0.70 W/m²K. The solar heat gain coefficient at normal incidence is 0.65. The shading coefficient is 0.25 in the hot period from 24th July to 20th August and 0.5 in the rest of the period from 1st June to 31st August.

The simulation period is from 1st June to 31st August, 2018. The room considered is a bedroom that is occupied by two persons from 22:00 to 7:00. The two occupants produce 148 W of sensible heat (ASHRAE Handbook) and 100 g/h of moisture. The air infiltration rate is taken as 0.5 ach. The following room ventilation rate is used: (1) in the hot period from 24th July to 20th August, the ventilation rate is 4.0 ach from 20:00 to 07:00. During the daytime from 07:00 to 20:00, no ventilation is allowed and the
ventilation rate is 0.0 ach; (2) in the other time from 1st June to 31st August, the ventilation rate is 2.0 ach when air temperature is above 15.0 °C. Hourly air temperature, relative humidity, wind speed, wind direction, solar radiation and horizontal rain from Meteoswiss stations at Kaserne and Affoltern are used to determine outdoor moisture and thermal conditions.

Figure 1. Selected rural and urban locations for study.

Figure 2. Outdoor air temperature at Affoltern and Kaserne over the heat wave period of 2018.

Figure 3. Geometry of the building components.
4. Results

4.1. Influence of coupled heat and moisture transport in building envelopes

The whole building simulation models that consider only heat transport in building envelopes tend to have different indoor air temperature and relative humidity compared to whole building simulation models that consider coupled heat and moisture transport in building envelopes. Figure 4 compares indoor air temperature at Kaserne with different model configurations. The indoor air temperature for coupled heat and mass transport model is mostly smaller than that of heat transport model. For example, during the hot period from 15th to 20th July, the indoor air temperature for coupled heat and mass transport model can be up to 1.3 K smaller than that of heat transport model. Indoor air temperature fluctuations in the coupled heat and mass transport model are also much lower than in the heat transport model. But during the hot period from 1st to 12th August, indoor air temperature is slightly higher from 1st to 5th August and slightly lower from 6th to 12th August as calculated by the coupled heat and mass transport model. This temperature difference is due to heat transport associated with moisture transport. Vapor adsorption in a hygroscopic porous material will release heat while vapor desorption in a hygroscopic porous material will absorb heat. The hygroscopic plaster has a significant moisture buffering effect. When the hygroscopic plaster absorbs water vapor from indoor environment, it leads to higher indoor air temperature. By comparison, when hygroscopic plaster releases water vapor into indoor environment, it results in lower indoor air temperature.

It is important to maintain indoor relative humidity at optimal levels. When the indoor air relative humidity fluctuates too much, it can lead to discomfort and health problems. Figure 5 compares indoor air relative humidity at Kaserne with different model configurations. The model that considers only heat transport in the building envelopes works similarly as the coupled model with vapor-closed building envelope surfaces. The indoor air relative humidity for coupled heat and mass transport model shows much smaller variations than that of heat transport model. The indoor relative humidity for heat transport only model varies between 0.22 and 0.71, whereas relative humidity varies between 0.38 and 0.63 for the room with hygroscopic plaster.

![Figure 4. Indoor air temperature at Kaserne with different model configurations.](image)

![Figure 5. Indoor air relative humidity at Kaserne with different model configurations.](image)
4.2. Difference between Kaserne and Affoltern
The indoor air temperature at Kaserne shows much larger values than at Affoltern during the heat wave (Figure 6). For example, the maximum indoor air temperature during heat wave is around 28.0 °C at Kaserne while it is below 26.0 °C at Affoltern. The number of hour above 26.5 °C at Kaserne is 243 hours whereas Affoltern never experiences such temperature. During the heat wave period from 25th July to 9th August, there is significant indoor temperature decrease at Affoltern at night due to night ventilation. By contrast, the indoor air temperature decrease at night at Kaserne is very moderate. High outdoor air temperature at Kaserne caused by urban heat island effect limits night cooling effect. The indoor relative humidity at Kaserne is between 0.4 and 0.6 while it is between 0.45 and 0.70 at Affoltern (Figure 6), due to the lower temperatures.

![Simulated temperature and relative humidity at Kaserne and Affoltern.](image)

4.3. Application of hygroscopic materials to lower indoor temperature during heat waves
Heat protection measures are needed to lower indoor air temperature for urban areas in Switzerland. There is also a possibility of using moisture buffering effect of hygroscopic material to lower indoor air temperature. When water is desorbed by the building surface material, cooling effect will take place. Under energy recovery mechanical ventilation system, humidity of incoming air could be controlled by transferring water vapor in the incoming air to the air that is leaving the house. The following controlling strategy is used to lower indoor air temperature during heat wave period from 31 July to 9 August: incoming air temperature is maintained the same as outdoor air temperature while relative humidity of incoming air is lowered to 60% of the relative humidity of the outdoor air. The indoor air temperature under controlled condition from 31st July to 9th August at Kaserne is much lower than the one with base condition (Figure 7). The indoor air temperature from 31st July to 9th August under controlled condition is mostly below 26.5 °C. The average air temperature from 31st July to 9th August is 1.3 °C lower than the base case air temperature. A side effect of the cooling effect from desorption by the hygroscopic material is much lower indoor relative humidity. The indoor relative humidity from 31st July to 9th August is between 0.3 and 0.4. Even though the indoor humidity is quite low under humidity controlled condition, it is still in the comfort zone according to ASHRAE 55-1992 as higher temperatures can be tolerated at low humidity. Cooling effect from desorption by the hygroscopic material could last for a certain period before moisture content in the hygroscopic plaster becomes too low. In the study here, the available amount of moisture in the hygroscopic plaster is capable to lower indoor air temperature for about 10 days.
5. Conclusions
A whole building heat and moisture transport model is developed to study indoor thermal comfort in urban and suburban areas in Zurich, Switzerland in the summer of 2018. There are similar outdoor air temperature variations during the daytime in urban and suburban areas. However, large differences of outdoor air temperature between urban and suburban areas exist during the night time. Due to cooling effect at night in the suburban area, indoor air temperature is much lower in suburban area than in the urban area. When moisture transport in the building envelopes is not considered, indoor air temperature and relative humidity will not be accurately simulated. Moisture transport could sometimes have a large influence on indoor thermal comfort. There is a potential of using hygroscopic material to lower indoor air temperature during heat waves.

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