Urban physics simulation for climate change adaptation of buildings and urban areas

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Introduction

Climate change, mitigation and adaptation

Climate observations and analyses by the Intergovernmental Panel on Climate Change (IPCC) and national meteorological organizations show that climate change is occurring. The global temperature has increased by 0.56–0.92 °C in the last century and is expected to increase by 1.1 to 6.4 °C until the year 2100, depending on the greenhouse gas emission scenario (van den Hurk et al. 2006; Pachauri and Reisinger 2007). It is therefore important to apply both climate change mitigation and climate change adaptation.
Climate change mitigation is defined by the IPCC as “an anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases.” For the built environment, this includes reducing the amount of energy necessary to heat, cool and illuminate buildings and urban areas. In addition, renewable energy sources such as wind and solar energy can help to reduce the emission of greenhouse gases. Climate change adaptation is defined as “adjustments in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities” (IPCC 2001).

People spend around 90% of their time indoors (Awbi 2003), while most residential buildings in many western, central, eastern and northern European countries often do not have air-conditioning systems or any other active cooling systems to reduce the indoor air temperature during warm periods (Entranze 2010; van Kempen 2000). However, the number and the intensity of heat waves are expected to increase due to climate change (van den Hurk et al. 2006). It is undesirable to install this type of active cooling system on a large scale, as these will only increase energy consumption and will also increase climate change if fueled by non-renewable resources (Li et al. 2012). Climate change adaptation measures for buildings but also for urban areas are therefore important in order to minimize the exposure of people to excessively high air temperatures and hence to limit the negative impact of climate change on health, comfort, productivity and energy consumption.

**Heat waves and the urban heat island**

A heat wave is defined as a prolonged period of exceptionally hot weather. The increased frequency of heat waves can be considered an indicator of climate change. In the period between 1901 and 2009, 38 heat waves have been recorded in the Netherlands, seven of which took place in the last decade of this period (1999–2009) (Salcedo Rahola et al. 2009). The frequency and the intensity of heat waves are expected to increase throughout the current century as a result of climate change (van den Hurk et al. 2006).

Inside urban areas, the higher air temperatures due to climate change can be aggravated by a series of processes that give rise to the urban heat island (UHI) effect. These processes were described by Oke (1982) as follows (Figure 22.1): (1) Urban areas have amplified short-wave radiation gain due to the multiple reflections in the urban environment in combination with the relatively high short-wave absorptivity of urban surfaces. (2) Urban areas are characterized by amplified long-wave radiation gain mostly due to increased air pollution in and above urban areas. (3) The urban geometry often blocks the outgoing long-wave radiation due to small view factors to the sky, keeping part of this long-wave emission trapped inside street canyons, resulting in higher temperatures. (4) Urban areas also exhibit increased anthropogenic heat sources, including transport, industry and building heating, cooling and air-conditioning. (5) The construction materials in the urban environment (pavement, asphalt, concrete, stone, etc.) usually have a high heat capacity and high thermal conductivity, resulting in increased heat storage in urban areas, which is mainly released during nighttime. (6) Urban areas are characterized by limited evapotranspiration due to the relatively low number or even absence of water bodies and vegetation. (7) The urban geometry decreases convective heat transfer due to lower wind velocities in street canyons and courtyards and the resulting reduced ventilation rates of urban areas. The globally rising temperature, the increased frequency and intensity of heat waves and the amplification of heat waves by the above-mentioned seven processes all contribute to higher air temperatures in urban areas and demonstrate the importance of climate change adaptation of buildings and urban areas in the context of heat waves.
Climate change adaptation of buildings

Introduction

Due to the changing climate with rising temperatures, buildings will need to adapt in order to provide a healthy and comfortable indoor environment with a minimum or no increase in energy consumption. Several studies have been performed on the climate change adaptation of buildings with different simulation tools. Porritt et al. (2011, 2012) employed the building energy simulation programs IES VE and EnergyPlus to investigate a wide range of passive climate change adaptation measures for terraced houses. Both programs have been extensively validated (Henninger and Witte 2011; Zhai et al. 2011) and have an airflow network to investigate natural ventilation. EnergyPlus also allows for a large number of parametric simulations to be run in batch configuration and showed a very good agreement with analytical solutions and other airflow network models (Gu and Crawley 2009). Porritt et al. (2011, 2012) found that one or multiple adaptation measures can reduce the number of overheating hours by 32%–99%. In addition, a study by Coley et al. (2012) showed that behavioral adaptation measures (opening/closing windows, shifting work hours) can be just as efficient as (costly) structural adaptation measures (increasing thermal mass, adding shading). By painting the roof surface of a building in California white, Akbari et al. (1997) reported that the short-wave reflectivity increased from 0.18 to 0.73 resulting in cooling savings of 69% in the following period. Most of these studies were performed for only one building type and construction period. Therefore, a new study was set up by van Hooff et al. (2014) to study the effectiveness of six passive climate change adaptation measures applied to three generic residential buildings with characteristics of two different construction periods. This study is reported in the next subsections.

Figure 22.1 Seven physical processes leading to the urban heat island effect and the amplification of heat waves in urban areas
Building construction types and adaptation measures

Van Hooff et al. (2014) studied the effectiveness of six passive climate change adaptation measures applied to three generic residential buildings: a detached house, a terraced house and an apartment (Figures 22.2–22.4).

For these buildings, two reference case construction periods and types were considered: a construction typical of the 1970s, which is characterized by a low thermal resistance of the building envelope, and a construction according to the 2012 building regulations, with much higher insulation levels. The construction characteristics of both reference cases are listed in Tables 22.1 and 22.2.

The following adaptation measures were contemplated (Table 22.3): (1) Increasing the thermal resistance of the building envelope to $R_c = 5.0$ (RC50) and $6.5 \text{ m}^2\text{K/W}$ (RC65). (2) Lowering the thermal capacity by replacing the reference case limestone inner leaf and concrete materials with wooden constructions (TM_low). (3) Increasing the short-wave reflectivity (albedo value) of the external surfaces from 0.3 to 0.6 (SWR06) and 0.8 (SWR08). (4) Increasing natural peak ventilation by opening the windows when the indoor air temperature is both above 24 °C and higher than the outdoor temperature. This is done for either the entire day (NV_all) or for the situation where the windows can only be opened during the day between 8:00 and 20:00 (NV_day). (5) Adding vertical exterior solar shading devices with a short-wave reflectivity of 0.9 and where the solar shading is engaged starting from 150 W/m² radiation on the window. (6) Employing an extensive vegetated roof (VR) with a leaf area index (LAI) of 5.

Figure 22.2 Facades, floor plans and dimensions of the detached house (modified from (AgentschapNL 2013)). Triangles in windows and doors indicate operable windows/doors for the additional ventilation measure. Dimensions in mm.

Source: van Hooff et al. 2014, ©Elsevier, reproduced with permission
Figure 22.3 Facades, floor plans and dimensions of the terraced house (modified from (AgentschapNL 2013)). Triangles in windows and doors indicate operable windows/doors for the additional ventilation measure. Dimensions in mm.

Source: van Hooff et al. 2014, ©Elsevier, reproduced with permission

Figure 22.4 Facades, floor plans and dimensions of the apartment (modified from (AgentschapNL 2013)). The light gray area in the floor plan indicates the zone with the bedrooms. The dashed boxes in the figures of the total facade and total floor plan indicate the apartment under study. Triangles in windows and doors indicate operable windows/doors for the additional ventilation measure. Dimensions in mm.

Source: van Hooff et al. 2014, ©Elsevier, reproduced with permission
### Table 22.1 Overview of construction characteristics for the reference case building from the 1970s

<table>
<thead>
<tr>
<th>Element</th>
<th>Details</th>
<th>$R_c$ value (m²K/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>External walls</td>
<td>Cavity walls with (inside to outside): limestone inner leaf, air cavity, brick outer leaf</td>
<td>0.4</td>
</tr>
<tr>
<td>Internal wall</td>
<td>Limestone wall</td>
<td>−</td>
</tr>
<tr>
<td>Roof (pitched)</td>
<td>Inside to outside: wooden sheeting, insulation layer, air cavity, roof tiles</td>
<td>0.8</td>
</tr>
<tr>
<td>Roof (flat)</td>
<td>Inside to outside: concrete, insulation layer, roofing material</td>
<td>0.8</td>
</tr>
<tr>
<td>External floor</td>
<td>Concrete</td>
<td>0.17</td>
</tr>
<tr>
<td>Internal floor</td>
<td>Concrete</td>
<td>−</td>
</tr>
<tr>
<td>Windows</td>
<td>Single pane glazing. Solar transmittance coefficient 0.7.</td>
<td>$U$-value: 5.2 W/m²K</td>
</tr>
</tbody>
</table>

### Table 22.2 Overview of construction characteristics for the reference case building from 2012

<table>
<thead>
<tr>
<th>Element</th>
<th>Details</th>
<th>$R_c$ value (m²K/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>External walls</td>
<td>Cavity walls with (inside to outside): limestone inner leaf, insulation, air cavity, brick outer leaf</td>
<td>3.5</td>
</tr>
<tr>
<td>Internal wall</td>
<td>Limestone wall</td>
<td>−</td>
</tr>
<tr>
<td>Roof (pitched)</td>
<td>Inside to outside: wooden sheeting, insulation layer, air cavity, roof tiles</td>
<td>4</td>
</tr>
<tr>
<td>Roof (flat)</td>
<td>Inside to outside: concrete, insulation layer, roofing material</td>
<td>4</td>
</tr>
<tr>
<td>External floor</td>
<td>Inside to outside: concrete, insulation</td>
<td>3.5</td>
</tr>
<tr>
<td>Internal floor</td>
<td>Concrete</td>
<td>−</td>
</tr>
<tr>
<td>Windows</td>
<td>Double pane glazing. Solar transmittance coefficient 0.7.</td>
<td>$U$-value: 1.65 W/m²K</td>
</tr>
</tbody>
</table>

### Table 22.3 Overview of adaptation measures

<table>
<thead>
<tr>
<th>Adaptation measure</th>
<th>Description</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased thermal resistance</td>
<td>The thermal resistance of all external building surfaces is increased to $R_c = 5.0$ m²K/W and $R_c = 6.5$ m²K/W, for cases RC50 and RC65, respectively. This measure is implemented by increasing the thickness of the insulation layers.</td>
<td>RC50, RC65</td>
</tr>
<tr>
<td>Changed thermal capacity</td>
<td>The thermal capacity is lowered, since the reference case is a heavy building. The thermal capacity is changed by replacing the limestone inner leaf by an inner leaf of wooden sheeting. In addition, concrete ceilings are replaced by wooden constructions.</td>
<td>TM_low</td>
</tr>
<tr>
<td>Increased short-wave reflectivity (albedo)</td>
<td>The short-wave reflectivity of the external surfaces is increased from the default value of 0.3 to 0.6 and 0.8, for cases SWR06 and SWR08, respectively.</td>
<td>SWR06, SWR08</td>
</tr>
</tbody>
</table>
Urban physics simulation for climate change

<table>
<thead>
<tr>
<th>Adaptation measure</th>
<th>Description</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additional natural ventilation</td>
<td>Additional natural ventilation is provided by opening (parts of) the windows. The windows will be opened when the indoor air temperature is above 24 °C, but only when the indoor air temperature is higher than the outdoor air temperature. In one case (NV_all), the windows can be opened the entire day (24 hours); in the other case (NV_day), the windows can only be opened between 08:00 and 20:00.</td>
<td>NV_all, NV_day</td>
</tr>
<tr>
<td>Vegetated roof</td>
<td>The default roof constructions are extended to incorporate a vegetated roof with a leaf area index of 5.</td>
<td>VR</td>
</tr>
<tr>
<td>Solar shading</td>
<td>Exterior solar shading is applied for all windows on the east, south and west side of the facades. The solar shading is automatically lowered when the solar radiation on the window is equal to or above 150 W/m².</td>
<td>SH</td>
</tr>
</tbody>
</table>

**Building energy simulations**

Dynamic thermal simulations were performed with the software EnergyPlus. The simulations were performed with a 10-minute time step, except for the vegetated roof where a time step of 1 minute was needed for accurate simulations. The simulations were conducted for four different building orientations, with the front facade facing the cardinal wind directions. The buildings all have an exhaust ventilation flow rate of 0.7 dm³/sm² and an infiltration flow rate of 0.2 ACH according to the Dutch building regulations. The KNMI weather data from De Bilt, the Netherlands, during July 2006 were used. This year was an exceptionally hot year with multiple heat waves (see Figure 22.5 for the air temperature during the month of July) and can represent a shape of things to come in future years. The adjusted adaptive temperature limit for residential buildings was used as a thermal comfort indicator (Peeters et al. 2009). Two different temperature limits were defined, for the living room (occupied between 06:00 and 23:00) and for the bedrooms (occupied between 23:00 and 6:00), respectively. The resulting number of overheating hours and degree hours (level of overheating) were used to compare the results for the reference case and the cases with the adaptation measures.

**Results: detached house**

Figure 22.6 shows the results of the adaptation measures for the detached house with the 1970s construction characteristics. By increasing the thermal resistance (RC50/RC60), the number of overheating hours and degree hours increase significantly compared to the reference case. The reason is that the short-wave solar radiation passes through the glazing and is then absorbed by the indoor surfaces and emitted as long-wave radiation, which cannot pass through the glazing. The related heat is therefore trapped to some extent, cannot be removed by radiation and needs to be removed by convection and conduction, i.e. the so-called greenhouse effect. Heat removal by conduction is a very slow process, particularly when insulation levels are high. As a result, increasing thermal insulation will increase the indoor temperature. When the thermal mass is reduced (TW_low), the number of overheating and degree hours increase for the ground floor and decrease for the first floor. This can be attributed to
the larger temperature fluctuations during the day, which is characteristic for a low thermal mass building. Therefore, compared to the reference case, there is a higher temperature during the day (when occupants are present on the ground floor) and a lower temperature during the night (when occupants are on the first floor). Increasing the short-wave reflectivity (SWR06 and SWR08) decreases the number of overheating hours, as it leads to lower exterior surface temperatures. Opening the windows during the day (NV_all) and applying exterior solar shading (SH) are the most effective adaptation measures for the detached house from the 1970s. The addition of a vegetated roof only provides a relatively small reduction (up to 17%) in the number of overheating hours. The vegetated roof increases the thermal resistance, which was already shown to have a negative effect as an adaptation measure. This effect appears to counteract to a large extent the benefit obtained by the lower surface temperature of the vegetated roof.

Figure 22.7 shows the results of the adaptation measures for the detached house built according to the 2012 building regulations. Due to the higher thermal resistance and the related amplified greenhouse effect, the number of overheating and degree hours for the reference case is significantly higher than that from the 1970s. This shows that newly built well-insulated buildings will have larger overheating problems if they are not properly equipped with measures to reduce this overheating. This increases the need for effective climate change adaptation measures for these buildings. By applying exterior solar shading or opening the windows for natural ventilation, the average number of overheating hours can be reduced to a very large extent. For the TM_low case, there is a significant increase in degree hours for the ground floor, while the number of overheating hours is only slightly higher. The lower thermal mass causes the indoor air temperature to reach very high temperatures, sometimes even above 40 °C. The results also show that increasing the short-wave reflectivity has less effect for buildings with a higher thermal resistance. This is because the heat flow through the building envelope is much lower due to this higher thermal resistance, regardless of the short-wave reflectivity value. The effects of the other measures effects are similar as for the detached house from the 1970s.
Figure 22.6 Number of overheating hours (a, c) and degree hours (b, d) for different cases of the detached house with construction characteristics from the 1970s. (a, b) Ground floor. (c, d) First floor.

Legend: ■ = the average of the four orientations, ● = minimum value, ♦ = maximum value

Source: van Hooff et al. 2014, ©Elsevier, reproduced with permission
Figure 22.7 Number of overheating hours (a, c) and degree hours (b, d) for different cases of the detached house with construction characteristics from 2012. (a, b) Ground floor. (c, d) First floor.

Legend: ■ = the average of the four orientations, ● = minimum value, ♦ = maximum value

Source: van Hooff et al. 2014, ©Elsevier, reproduced with permission
Results: terraced house

Figures 22.8 and 22.9 show the results for the terraced house with construction characteristics from the 1970s and 2012, respectively. The largest difference compared to the detached house is the large spread between the minimum and maximum number of overheating and degree hours. This difference is attributed to the fact that the terraced house only has two building sides exposed to the solar radiation. The orientation of the front facade therefore plays a larger role in the number of overheating hours. A west or an east orientation has almost two times the overheating hours for a south- or north-orientated front facade. Another difference compared to the detached house is an increase of the number of degree hours on the first floor of the terraced house from 2012, when a lower thermal mass is used. Also the positive effect of increasing the short-wave reflectivity values is less pronounced due to the smaller surface area that is exposed to the outdoor environment and thus to solar radiation. As for the detached house, the two most effective measures are peak ventilation and exterior solar shading.

Results: apartment building

Figures 22.10 and 22.11 show the results of the adaptation measures for the apartment building with construction characteristics from the 1970s and 2012, respectively. Overall, the number of overheating and degree hours is higher for the living room and bedrooms than in the other building types. This is mainly attributed to the location of the living room and bedrooms directly below the roof construction. The effect of the other adaptation measures is similar to the other building types. Again, the two most effective measures are peak ventilation and exterior solar shading.

Overall, using peak natural ventilation and applying exterior solar shading are the most effective adaptation measures. Increasing the thermal resistance of the building has a negative effect on the overheating hours. Reducing the thermal mass in a building could have a positive effect for the indoor temperatures during the night, but only when the heat inside the building can be released either through the building envelope or by ventilation.

Climate change adaptation of urban areas: simulation and validation

Introduction

Several studies have been performed in the past decades on measures to reduce the air temperature in urban areas, especially during heat waves (e.g. Mochida and Lun 2008, Liu et al. 2012, Tominaga et al. 2015, Yang et al. 2017, Toparlar et al. 2018). One option is providing water facilities, which decrease the air temperature by evaporative cooling. Different possibilities include water ponds, fountains, waterfalls and mist spray. Nishimura et al. (1998) studied the effect of a water pond in a park and showed that the air temperature downwind of the water pond was reduced by 1–2 °C. The addition of waterfalls and fountains reduced the air temperature further (up to 4–5 °C) as the cooling effect by moving water is often greater due to a larger portion of the water’s surface area being exposed to air. However, in areas with water scarcity, this type of measure will often be difficult to implement. Other measures are vegetation (trees, green roofs and facades), increased short-wave reflectivity of urban surfaces, etc. However, before the effectiveness of such measures can be computationally assessed, it is important to assess the simulation approach itself by validation actions.
Figure 22.8 Number of overheating hours (a, c) and degree hours (b, d) for different cases of the terraced house with construction characteristics from the 1970s. (a, b) Ground floor. (c, d) First floor.

Legend: ■ = the average of the four orientations, ● = minimum value, ♦ = maximum value

Source: van Hooff et al. 2014, ©Elsevier, reproduced with permission
Figure 22.9 Number of overheating hours (a, c) and degree hours (b, d) for different cases of the terraced house with construction characteristics from 2012. (a, b) Ground floor. (c, d) First floor.

Legend: ■ = the average of the four orientations, ● = minimum value, ♦ = maximum value

Source: van Hooff et al. 2014, ©Elsevier, reproduced with permission
Figure 22.10 Number of overheating hours (a, c) and degree hours (b, d) for different cases of the apartment with construction characteristics from the 1970s. (a, b) Ground floor. (c, d) First floor.

Legend: ■ = the average of the four orientations, ● = minimum value, ♦ = maximum value

Source: van Hooff et al. 2014, ©Elsevier, reproduced with permission
Figure 22.11 Number of overheating hours (a, c) and degree hours (b, d) for different cases of the apartment with construction characteristics from 2012. (a, b) Ground floor. (c, d) First floor.

Legend: ■ = the average of the four orientations, ● = minimum value, ♦ = maximum value

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In order to assess heat waves, urban heat islands and climate change adaptation measures for urban areas, different simulation tools can be employed. Due to the complexity of the related physical processes, multiple simplifications are necessary in the simulations. Validation of the results is therefore important to ensure reliable results. Simulation techniques that have shown reliable outcomes to predict the temperature distribution for urban regions are the energy balance model (or urban canopy model) and numerical simulation with computational fluid dynamics (CFD) (Mirzaei and Haghighat 2010; Toparlar et al. 2017). The energy balance model was first suggested by (Oke 1982), and it applies the law of conservation energy for a control volume. Energy balance models generally have a short calculation time, as they use a limited number of nodes. The main weakness of these models is the absence of the velocity field, which is necessary to model the effects of wind flow and related processes and to accurately determine sensible and latent heat fluxes. This shortcoming can therefore substantially affect the temperature distribution, rendering the absence of the velocity field a major limitation of energy balance models.

CFD instead couples the temperature and velocity fields inside an urban area as it solves for both these variables. This generally results in a more accurate prediction of the temperature distribution. However, careful and high-resolution modeling with a high number of control volumes or finite elements is necessary in order to obtain accurate and reliable results, resulting in longer computation times. Several guidelines are available to help achieve accurate and reliable simulations of urban physics processes with CFD by limiting errors and uncertainties (e.g. Casey and Wintergerste 2000; Franke et al. 2007, 2011; Tominaga et al. 2008; van Hooff and Blocken 2010; Blocken et al. 2007, Blocken 2015). In order to investigate the ability of CFD to accurately reproduce surface temperatures in an urban area during a heat wave, Toparlar et al. (2015) conducted a case study for the Bergpolder Zuid district in Rotterdam. This study is described in the next subsections.

Bergpolder Zuid district

The Bergpolder Zuid district is composed of both residential and office buildings with several narrow streets and surrounded by large avenues (Figure 22.12). Here, the classification of streets is made with respect to the aspect ratio between the street width and the adjacent building height. In general, most of the streets are fairly narrow with an aspect ratio between 1:1 and 2:1.

The main color of the building walls is red and the rooftops are commonly gray or dark gray. Street materials generally have lighter colors (light gray) compared to the building materials. The vegetation levels of the region are fairly low as trees and green fields are mostly located in a few small courtyards. The only urban water source is the canal located in the north part of the region, and there are no additional water facilities within the district, hence the district has low evapotranspiration levels, which is typical of dense metropolitan cities.

Computational geometry

In order to create an accurate geometrical model of the region, official drawings and documents were acquired from the Municipality of Rotterdam and from the database of AHN. According to the database, the average height of the buildings is 12.6 m with the lowest and highest building having a height of 2.8 m and 51.0 m, respectively. Considering the surroundings of the Bergpolder Zuid district, south of it lies the central district of Rotterdam
Figure 22.12 (a) Location of Bergpolder inside the city of Rotterdam (modified from Wikipedia).
(b) Top view with the borders of Bergpolder and Bergpolder Zuid district (modified from Google Maps).
(c) Aerial view of Bergpolder Zuid district (view from south) (modified from Google Maps).

Source: Toparlar et al. 2015, ©Elsevier, reproduced with permission
and to the north, there are mainly green fields until the city of Delft (located in northwest of the district). Based on the updated Davenport roughness classification (Wieringa 1992), the aerodynamic roughness length ($z_0$) of the surroundings, which is necessary as input for the CFD simulations, is determined as shown in Figure 22.13. The $z_0$ value is determined as a spatial average of the $z_0$ values of the different patches of roughness (land use) of the terrain within a 10 km radius upstream of the urban area. A similar methodology was followed in previous CFD studies investigating urban wind flow (e.g. van Hooff and Blocken 2010; Blocken et al. 2012).

**Computational domain and grid**

The computational domain consists of a hexagonal with edges of 1200 m surrounding a circular subdomain with a diameter of 1200 m (Figure 22.14). The height of the domain is 400 m, resulting in a blockage ratio below the recommended value of 3.0% (Franke et al. 2007; Tominaga et al. 2008; Blocken 2015). It is important to model the surrounding buildings and neighborhood around the site of interest, as they might affect the local flow field as well as the advection and turbulent diffusion of heat. The buildings inside the subdomain are modeled explicitly (i.e. with blocks representing their actual shape and size) and divided into three categories: buildings in Bergpolder Zuid with a high resolution (details of 0.5 m), buildings in the rest of the Bergpolder region (1.0 m) and additional surrounding buildings, which are modeled
coarsely (4.0–8.0 m) and act as obstacles for the approaching flow (Figure 22.14). Elements like trees, cars, sidewalks and street poles are not modeled. The buildings and the urban terrain outside the circular domain are not modeled explicitly, but implicitly: their effect on the flow is implemented by means of appropriate values for the roughness height \( k_s \) and the roughness constant \( C_s \) in the wall functions. These roughness parameters are determined by the software dependent relationship with the aerodynamic roughness length \( z_0 \) at the bottom of the domain (Equation 22.1) (Blocken et al. 2007).

\[
k_s = \frac{9.793 \cdot z_0}{C_s}
\]  

Grid generation is performed with the surface-grid extrusion technique by van Hooff and Blocken (2010) with at least 10 cells along the building edges and by keeping the stretching ratio below 1.3. This results in a grid with a total of 6,610,456 hexahedral cells (Figure 22.15).

**Boundary conditions**

Depending on the wind direction, the wind flow is simulated with three hexagonal boundaries as velocity inlet and the other three as pressure outlet. The logarithmic mean wind speed profile \( U \) (m/s) is imposed with \( z_0 \) using Equation 22.2. Here \( u^* \) is the atmospheric boundary layer friction velocity (m/s), \( g \) is the von Karman constant (0.41) and \( z \) is the height coordinate (m).

\[
U(z) = \frac{u^*}{\kappa} \cdot \ln \left( \frac{z + z_0}{z_0} \right)
\]  

The turbulence kinetic energy \( k \) (m²/s²) and turbulence dissipation rate \( \varepsilon \) (m³/s³) of the neutrally stratified atmospheric boundary layer are imposed according to (Richards and Hoxey 1993) with Equations 22.3 and 22.4. Here \( C_{\mu} \) is a constant (0.09).
In the near-wall regions, low-Re number modeling or standard wall functions (Launder and Spalding 1974) can be used. Low-Re modeling requires a very high grid resolution close to the walls in order to have control volumes in the very thin laminar sublayer of the boundary layer. Even though wall functions might perform less well for calculating convective heat transfer, they are generally used for this purpose (Blocken et al. 2009). This method is therefore used to limit the computational load.

The air temperature is set as a spatially constant value at the inlet and like the reference wind speed and total solar radiation, it is acquired by the hourly weather data from the KNMI weather station in Rotterdam. The ground plane is modeled as a 10 m thick earth layer with a temperature of 10 °C at 10 m below ground and an absorptivity of 0.6. The buildings have 0.4 m thick brick walls with an absorptivity of 0.75. The internal air temperature of the buildings is set to 24 °C. Evapotranspiration is only applied to the ground plane with a sink value set to 80 W/m² during the morning and afternoon and 130 W/m² during noon.

**Solver settings**

The 3-D unsteady Reynolds-averaged Navier-Stokes (URANS) equations are solved with the realizable k-ε turbulence model (Shih et al. 1995) for closure. The radiation is solved with the P-1 radiation model (ANSYS 2009a), and the Boussinesq approximation is used to include buoyancy effects. A 1-D conduction equation is used for the ground and building walls, which calculates the heat transfer through the walls. The solar calculator of ANSYS Fluent is used to estimate the sun direction vector and the diffuse part of the total radiation. The SIMPLE algorithm is applied for pressure-velocity coupling. In addition, only second-order discretization schemes are used. A time step of 15 minutes and 60 iterations are chosen based on a time step and iteration number sensitivity analysis.
**Results and validation**

To evaluate the ability of the CFD simulation to reproduce some aspects of a heat wave, the results are validated/compared with experimental data from thermal infrared satellite imagery during a heat wave in July 2006 (Klok et al. 2012). The CFD simulations are performed for five consecutive days (480 time steps) to evaluate the diurnal variation of the temperature field. Ninety sampling points (based on a sensitivity analysis) are placed on the roofs and streets in the computational domain to obtain spatially average values that can be directly compared with the values from the satellite imagery. The comparison of the spatially averaged surface temperature obtained by CFD and satellite imagery is shown in Figure 22.16. Overall, there is a fairly good agreement. The CFD simulations are able to predict the surface temperatures with an average absolute temperature difference of 2.2 °C, generally due to a smaller amplitude of the diurnal variation of surface temperature. Some reasons for the surface temperature deviations are the use of a 1-D wall conduction equation instead of a 3-D one, as some heat is transferred in the planar direction. Second, the satellite data were recorded 42 times during the five days, while the simulations were based on hourly averaged meteorological data. This could cause a mismatch in average surface temperature results. In addition, the satellite data only records a single value for an entire district, of which 20% contains the Bergpolder Zuid region. Local temperature variations in the district might therefore influence the results. Finally, a simplification is made in the thermal stratification of the atmospheric boundary layer, as it was assumed to be neutral with a constant uniform temperature. In reality, the flow field might deviate from this assumption, especially during low wind speeds. Overall, the validation showed that CFD has the capability to accurately predict urban surface temperatures. However, future studies should focus on validation with data at higher spatial resolution.

Figure 22.17 shows simulation results of the wind velocity and surface temperature of the urban region at 10:00 on 15 July 2006. It can be observed that in regions with a low wind velocity (decreased convective heat transport), as in courtyards or street canyons, the surface temperatures are evidently much higher.  

![Figure 22.16 Comparison of spatially averaged surface temperature by CFD and satellite imagery for five days in July 2006](image-url)
Introduction

A promising climate change adaptation measure is the addition of vegetation to an urban area. The related evaporation and transpiration can help to limit high outdoor air temperatures. Vegetation can also provide shading and yield less heat storage. Examples of vegetation in urban...
areas are parks, green roofs and facades, urban farming and avenue trees. Many different studies have demonstrated the beneficial effects of vegetation on the temperature in urban areas (Taha 1997; Bruse and Fleer 1998; Dimoudi and Nikolopoulou 2003; Wong et al. 2003, 2010; Takahashi et al. 2004; Ali-Toudert and Mayer 2007; Alexandri and Jones 2008; Fröhlich and Matzarakis 2013).

The effects of vegetation on momentum and heat transfer can be simulated with CFD by adding source and sink terms to the momentum equations, the energy equation and the equations of the turbulence model. This approach is briefly described in the next subsection. Based on this approach, Gromke et al. (2015) provided a validation study and a case study on the effects of avenue trees and green roofs and green facades on air temperatures for a street in Arnhem, which is described in later subsections.

**Vegetation effects: source and sink terms**

In order to model the effects of vegetation on the mean airflow and turbulence, vegetation terms can be added to the transport equations of momentum as in Equation 22.5, turbulence kinetic energy as in Equation 22.6 and turbulence dissipation rate as in Equation 22.7 for cells that contain vegetation (Green 1992; Liu et al. 1996; Sanz 2003):

\[ S_{u_i} = -\rho \cdot C_d \cdot LAD \cdot U_i \cdot U \]  
\[ S_k = \rho \cdot C_d \cdot LAD \cdot \left( \beta_p \cdot U^3 - \beta_d \cdot U \cdot k \right) \]  
\[ S_\varepsilon = \rho \cdot C_d \cdot LAD \cdot \frac{\varepsilon}{k} \left( C_{\varepsilon4} \cdot \beta_p \cdot U^3 - C_{\varepsilon5} \cdot \beta_d \cdot U \cdot k \right) \]

where \( \rho \) is the density of air, \( C_d (= 0.2) \) is the leaf drag coefficient, LAD is the leaf area density, \( U_i \) is the velocity component of direction \( i \), \( U \) the velocity magnitude, \( \beta_p (= 1.0) \) is the mean kinetic energy fraction that is converted into wake turbulence kinetic energy, \( \beta_d (= 5.1) \) accounts for short-circuiting of the eddy cascade, \( k \) is the turbulence kinetic energy, \( \varepsilon \) is the turbulence dissipation rate and \( C_{\varepsilon4} \) and \( C_{\varepsilon5} (= 0.9) \) are empirical coefficients.

**Vegetation effects on momentum: validation**

Validation of the vegetation effects on the mean airflow and turbulence is done by comparing the CFD simulation results with the measurement data by Amiro (1990) in a 12 m high black spruce forest. Equations 22.5–22.7 are implemented as user-defined functions (UDF) in the simulations (ANSYS 2009b). The computational domain has dimensions of 100 × 25 × 240 m (L × W × H) with coupled periodic boundary conditions for the inlet and outlet side (Figure 22.18). To obtain a streamwise wind speed of 2.6 m/s at 12 m height, an air mass flow rate of 35,000 kg/s is assigned at the inlet. For the ground plane, a no-slip condition is applied with an aerodynamic roughness length \( z_0 \) of 0.35 (\( k_S \) and \( C_S \) are calculated with Equation 22.1). Symmetry boundaries are applied for the sides and top of the domain to simulate a homogenous flow in an extended forest. The spruce forest is defined as a porous zone with the same vertical leaf area density profile (LAD(z)) as in the experiment by Amiro (1990). Cubical cells with a 1 m edge length are used to discretize the entire domain.

The comparison of the mean streamwise velocity (\( U \)) and the square of the shear stress velocity (\( <u'^2> \)) between the CFD results and the measurement data is shown in Figure 22.19. These results are normalized by height (z) at 10 m height and by the wind speed and the squared shear stress velocity at 12 m height. Overall, the simulation results exhibit a good agreement.
Figure 22.18  Computational domain of the black spruce forest validation study
Source: Gromke et al. 2015, ©Elsevier, reproduced with permission

Figure 22.19  Normalized mean wind speed (top) and normalized squared shear stress velocity (bottom)
Source: Gromke et al. 2015, ©Elsevier, reproduced with permission
with the measurement data. The largest deviations for the mean streamwise velocity occur at \( z/z_{ref} = 0.4 \). However, the wind speed at this location is still very small (0.1 m/s), the absolute difference is therefore quite small as well. For the squared shear stress, the maximum relative deviation is around 20% for the upper part of the canopy. This validation study shows that the CFD simulations with the implemented vegetation terms are capable of modeling the mean flow and shear stress velocity within a vegetation canopy.

Vegetation effects on heat transfer: validation

When air flows through vegetation, it will be cooled by transpiration mostly from the leaf surfaces. A more detailed microscale approach to model this would therefore be to consider the latent heat flux that leaves through stomata with convective heat/mass transfer coefficients (CTCs) (Defraeye et al. 2012, 2013). To reduce the associated computational costs, the volumetric cooling power of vegetation \( (P_c) \) per unit volume vegetation \( (V) \) can be used to model the vegetation effect on the change in air temperature \( (\Delta T) \) by transpirational cooling with Equation 22.8. Here, \( \dot{H} \) is the heat transfer rate, \( c_p \) the specific heat capacity and \( \dot{m} \) is the mass flow rate.

\[
\frac{\dot{H}}{V} = P_c = c_p \cdot \dot{m} \cdot \Delta T = \frac{1}{V} \Rightarrow \Delta T = P_c \cdot \frac{1}{\dot{m}} \cdot \frac{1}{c_p}
\]

(22.8)

In order to determine an appropriate value of \( P_c \), a validation study is performed by steady-state 3-D RANS CFD simulations for a bare and vegetated courtyard and by comparing the simulated air temperature with the experimental data of a field study by Shashua-Bar et al. (2009, 2011). The edges of the building are discretized by cubical cells of 0.15 m length, while outside the courtyard an unstructured grid with an increasing size towards the domain boundary is created. This results in a computational domain of 670,000 hexahedral cells (Figure 22.20).

Meteorological data are used to obtain boundary conditions for three periods on 7 July 2007. The roughness length \( z_0 \) is assumed as 0.03 m for the ground and building walls. The vegetation terms in Equations 22.5–22.7 are used to model the aerodynamic effects of the trees inside the courtyard (Figure 22.20). Different \( P_c \) values are then assigned to cells that contain vegetation until an agreement in air temperature is achieved with the experimental data. The comparison between measured and simulated air temperature in a bare and vegetated courtyard at 1.5 m height for different \( P_c \) values is shown in Figure 22.21. The bare courtyards show a small deviation of only 0.4 °C on average. The average deviations for the \( P_c \) values of 250, 500 and 700 W/m² are 1.1, 0.5 and 0.0 °C, respectively. Since the bare courtyard has an average deviation of 0.4 °C, a \( P_c \) value of 500 W/m² is assumed for the courtyard trees with a LAD of 2.0 m²/m³. This translates to a volumetric cooling power \( P_c \) of 250 W/m³ per unit LAD. This corresponds well to the data of Rahman et al. (2011), who reported a volumetric cooling power of 284 and 335 W/m³ per LAD for deciduous trees during the summer. However, different values might be obtained for trees that suffer from limited water supply.

Vegetation effects in an urban area: case study

Gromke et al. (2015) investigated the transpirational cooling effect of various vegetation measures applied in an existing urban street canyon in order to reduce the air temperature during a heat wave. Three different vegetation measures are studied for the case study of the street J.P. van Muijlwijkstraat in Arnhem, the Netherlands (Figure 22.22(a)). These vegetation measures are avenue trees, green facades and green roofs. CFD simulations are carried out to model the
heat wave of 16 July 2003 with a wind direction aligned along the canyon street (east wind). The effects of vegetation on the mean flow, turbulence and transpirational cooling were validated in the foregoing sections. The simulations can therefore be considered as a reliable estimate for the flow and microclimate in an actual urban environment. However, the outcomes are dependent on the site, modeling technique and meteorological boundary conditions.
A similar computational domain and grid and similar numerical settings and vegetation terms are used as described in foregoing sections. The computational domain has a total size of $1200 \times 950 \times 500$ m ($L \times W \times H$), where the buildings and 350 m long canyon street in an inner area of $900 \times 600$ m are explicitly modeled. An aerodynamic roughness length $z_0$ of 0.03 m and 0 m is used for the ground and building surfaces, respectively. Outside the inner area, where no buildings are modeled, a roughness length of 0.5 m is used to represent the urban terrain (Wieringa 1992). The computational grid has a total of 35 million hexahedral cells (Figures 22.22(b)–(d)).

The current situation (reference case – status quo) and the effect of five different vegetation scenarios on the air temperature are investigated (Figure 22.23). The current situation (status quo) consists of a few small deciduous trees in the street canyon and a 600 m$^2$ triangle patch of trees eastwards of the canyon street. Scenario 1 is a situation with no vegetation at all. Scenario 2 applies avenue trees in the street canyon together with the trees from the current situation. Scenario 3 is a situation with the trees from the status quo together with facade greening. Scenario 4 uses the status quo together with roof greening. Finally, scenario 5 has all vegetation measures and status quo applied together.

The scenarios are simulated for 16 July 2003 at 15:00 local time with a wind speed of 5.1 m/s at 10 m height. The approach flow from the east had an air temperature of 34.5 °C. The four blue lines in Figure 22.23 indicate cross-sections where the effects of the vegetation measures on the air temperature are analyzed in more detail.

For the current situation only, the leaf area density (LAD) is set to 0.55 m$^2$/m$^3$. This corresponds to a volumetric cooling power of 137.5 W/m$^3$ according to the validation study. The simulation results (air temperature at 2 m height) for this scenario are shown in Figure 22.24. The average air temperature at this height is 36.11 °C. The cooling effect of the eastern patch of trees is clearly visible with cooler temperatures inside the patch of trees and downstream of it, partly inside the J.P. van Muijlwijkstraat. However, there seems to be no noticeable cooling effect of the row of small trees inside the street canyon.
Figure 22.25 shows the air temperature results at the four cross-sections inside the J.P. van Muijlwijkstraat. The air temperatures at ground level and at the building facades are generally higher. In addition, the average temperature slightly increases from the first to the fourth cross-section. Also there are slightly lower air temperatures at the north side of the street (right side in cross-section), except for cross-section 1. The reason for this is the presence of trees at the north side of the street canyon, which start leeward of cross-section 1. At cross-section 1, the effect of the eastern patch of trees is more pronounced.

The air temperature results of scenario 1 with no vegetation at all are shown in Figure 22.26 (2 m above ground) and Figure 22.27 (cross-sections 1 and 2) to see if the existing trees provided a noticeable cooling effect. The average temperature at 2 m height for scenario 1 is 36.28 °C (0.17 °C higher than current situation), which shows that the existing trees do not provide a significant cooling effect. The temperatures at the eastern patch of trees do however show a temperature difference of around 1 °C compared to scenario 1. This is also shown in the temperature difference in cross-section 1 as depicted in Figure 22.27, indicating a difference up to 0.5 °C at the south side close to the ground. For cross-section 2, there is a temperature difference at the north side of the street canyon, related to the absence of trees in the canyon and the flow from the eastern patch of trees.

Scenario 2 consists of the existing vegetation together with additional avenue trees with the same LAD and volumetric cooling power as the existing trees. The air temperature results are shown in Figure 22.28 (2 m above ground) and Figure 22.29 (cross-sections). The additional
Figure 22.25 Air temperatures in the four cross-sections for the current situation
Source: Gromke et al. 2015, ©Elsevier, reproduced with permission

Figure 22.26 Air temperatures at 2 m height in the J.P. van Muijlwijkstraat for scenario 1 (no vegetation)
Source: Gromke et al. 2015, ©Elsevier, reproduced with permission

Figure 22.27 Air temperature differences in cross-sections 1 and 2 for scenario 1 (no vegetation)
Source: Gromke et al. 2015, ©Elsevier, reproduced with permission
trees show a significant transpirational cooling effect for almost the whole north side of the street with temperature differences of 1–2 °C. The total average temperature reduction compared to the current situation is 0.43 °C. The air temperature at cross-section 1 is not yet affected by the avenue trees. For the other cross-sections, the air temperature does show a significant difference, especially close to the position of the avenue trees (dashed square). At cross-section 2, the air temperature between the avenue trees and building wall shows the highest temperature reduction, which suggests a flow through the trees towards the building wall here. For cross-sections 3 and 4, the whole width of the canyon street is affected by this vegetation measure.

The facade greening in scenario 3 is defined by adding a vegetation zone in all cells next to the building facades in the J.P. van Muijlwijkstraat. A LAD value of 0.75 m²/m³ (\( P_c = 187.5 \) W/m³) is assigned to these cells, assuming a vegetation coverage of 50% (Susorova et al. 2013). Figure 22.30 shows the temperature difference compared with the reference case for
cross-sections 2 and 3. The simulation results show that the cooling effect is only present in the close vicinity of the building facades. The average temperature at 2 m above ground is also only 0.04 °C lower than the existing situation.

Roof greening (scenario 4) is defined with a LAD value of 1.5 m²/m³ for the cells adjacent to the roof surfaces of the buildings surrounding the street canyon. Normally higher values are present for roof greening (Barrio 1998). However, only a coverage of 25% is assumed because of obstacles such as antennas and PV cells. The air temperature differences between the existing situation and scenario 4 for cross-sections 2 and 3 is shown in Figure 22.31. Overall, the cooling effect is very small with no noticeable changes of the air temperature at 2 m height. A reason for this is that the air cooled by the roof greening is convected over the rooftops due to the eastern wind, with only a small portion entering the canyon street.

Finally, for scenario 5, all vegetation measures are applied together to investigate possible interactions. The air temperature differences between the existing situation and scenario 5 for cross-sections 2 and 3 are shown in Figure 22.32. The temperature reduction is dominated by the addition of avenue trees at the north side and green facades at the south side. The average air temperature at 2 m height is 35.59 °C (0.52 °C lower than the existing situation), which is the highest reduction in air temperature of all vegetation scenarios.
Overall, there seems to be little interaction between the different vegetation measures, when they are applied together.

**Discussion**

Concerning the indoor environment of buildings, building energy simulation (BES) is considered to be the most straightforward and appropriate simulation tool. In this chapter, BES was applied to three types of buildings with construction characteristics from the 1970s (low insulation levels) and 2012 (high insulation levels). Overall, applying natural ventilation throughout the day and applying exterior solar shading emerged as the most effective adaptation measures, and this was the case for all three building types with both sets of construction characteristics. Increasing the thermal resistance of the building actually had a negative effect on the overheating hours. Reducing the thermal mass in a building can have a positive effect for the indoor temperatures during the night, but only when the heat inside the building can be released either through the building envelope or by ventilation. In terms of costs (installation and maintenance), natural ventilation and exterior solar shading are considered less expensive than several other measures, such as reducing the thermal mass and providing green roofs and green facades.

Concerning the outdoor environment of buildings, energy balance models or computational fluid dynamics (CFD) can be used. For high-resolution information at the level of individual streets, CFD should be preferred over energy balance models. The validation study for the Bergpolder Zuid district showed that CFD simulations based on the 3-D unsteady Reynolds-averaged Navier-Stokes equations could reproduce the temporal evolution and the magnitude of the surface temperatures with a satisfactory accuracy.

In CFD, the effects of vegetation can be modeled with source and sink terms in the momentum and energy equations and in the equations of the turbulence model. The cooling effect by avenue trees, green roofs and green facades was simulated with CFD and with appropriate sink and source terms for a street in Arnhem under the conditions of a heat wave. Overall, the cooling effect by the avenue trees appeared most pronounced. Under the conditions of the present study, the cooling effect by green facades and roofs was very limited. By applying avenue-tree rows (with large crowns) on both sides of a street canyon, a large vegetation volume could be achieved which should lead to an even more noticeable increase in transpirational cooling. To achieve a citywide temperature reduction during the summer, a densely
distributed arrangement of trees and other vegetation measures would be necessary, provided that the vegetation is regularly irrigated. However, adding avenue trees will decrease the wind speed in the street canyons, which can give rise to less ventilation and higher air pollutant concentrations due to traffic in these street canyons (Gromke and Ruck 2007).

The results found by the case study on vegetation showed some similar trends as in other studies with vegetation. Namely, the air temperature reduction of 1 °C within the first 10 m downwind of the avenue trees is in general agreement with a study by Dimoudi and Nikolopoulou (2003). Also, the air temperature reduction of the green facades up to a few meters away from the building surfaces was found by Wong et al. (2010). Finally, Alexandri and Jones (2008) also reported a similar weaker cooling effect by roof greening, compared to facade greening. Regardless of this, it is important to note that the findings in this study were obtained for a specific site and for very specific meteorological conditions. Care must therefore be taken in generalizing these results. A different wind direction might lead to less temperature reduction overall, but perhaps also to a higher cooling effect for the roof greening. Also, different wind speeds and LAD values might lead to different results for different vegetation measures. Furthermore, the vegetation was assumed to be subjected to unlimited water supply, as a limited water supply will lead to reduced volumetric cooling powers (Shashua-Bar et al. 2009, 2011). Other vegetation effects such as shading, trapping radiation and a low heat capacity were not taken into account in this study, which might have resulted in an underestimation of the air temperature reduction.

Synopsis

This chapter has presented simulations to analyze the effects of heat waves on buildings and urban areas and the effect of adaptation measures in terms of overheating hours and degree hours in buildings and surface and air temperatures in urban areas. Building energy simulation has been used to evaluate the effectiveness of a range of measures at the building scale to reduce indoor overheating. Computational fluid dynamics simulations for an urban area and for vegetative effects have been validated and subsequently applied to reproduce surface and air temperatures in two case studies.

Notes

2 Google Maps source: http://goo.gl/maps/zEziy
3 AHN: Actueel Hoogtebestand Nederland (Updated Height Data of the Netherlands) www.ahn.nl

References


Urban physics simulation for climate change


**Assignments**

**Assignment 1**

In this exercise, the effect of passive climate change adaptation measures on the building scale is studied. For this exercise we will use EnergyPlus (version 8.7), which is a freely available building energy simulation (BES) software package; however, other BES software can be used as well.

An arbitrary simple generic building is studied, with a floor plan of $5 \times 5 \text{ m}^2$ and a height of 3 m, resulting in an indoor volume of 75 m$^3$. There is one window present in the building, with a surface area of $2 \times 2 \text{ m}^2$, which is located in the middle of the south-oriented facade (middle of window located at (2.5 m; 1.5 m); see Figure 22.33).

The construction properties are shown in Table 22.4.
Table 22.4 Overview of different layers with required properties

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness [m]</th>
<th>Conductivity [W/mK]</th>
<th>Density [kg/m³]</th>
<th>Specific heat [J/kgK]</th>
<th>Short-wave absorptivity [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wall</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outer leaf (masonry)</td>
<td>0.1</td>
<td>0.8</td>
<td>2000</td>
<td>840</td>
<td>0.7 (default)</td>
</tr>
<tr>
<td>Air cavity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulation layer</td>
<td>0.14</td>
<td>0.04</td>
<td>35</td>
<td>1470</td>
<td>0.7 (default)</td>
</tr>
<tr>
<td>Inner leaf (bricks)</td>
<td>0.1</td>
<td>1</td>
<td>2000</td>
<td>840</td>
<td>0.7 (default)</td>
</tr>
<tr>
<td><strong>Floor (incl. soil layer)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil</td>
<td>1</td>
<td>1.28</td>
<td>1460</td>
<td>800</td>
<td>0.7 (default)</td>
</tr>
<tr>
<td>Insulation layer</td>
<td>0.14</td>
<td>0.04</td>
<td>50</td>
<td>840</td>
<td>0.7 (default)</td>
</tr>
<tr>
<td>Concrete floor</td>
<td>0.2</td>
<td>1.4</td>
<td>2500</td>
<td>840</td>
<td>0.7 (default)</td>
</tr>
<tr>
<td><strong>Roof</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roof covering</td>
<td>0.002</td>
<td>0.17</td>
<td>1400</td>
<td>1470</td>
<td>0.7 (default)</td>
</tr>
<tr>
<td>Insulation</td>
<td>0.2</td>
<td>0.04</td>
<td>35</td>
<td>1470</td>
<td>0.7 (default)</td>
</tr>
<tr>
<td>Concrete roof</td>
<td>0.2</td>
<td>1.4</td>
<td>2500</td>
<td>840</td>
<td>0.7 (default)</td>
</tr>
<tr>
<td><strong>Window</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simple glazing system</td>
<td>1.65</td>
<td>0.7</td>
<td></td>
<td>0.8</td>
<td></td>
</tr>
</tbody>
</table>

Figure 22.33 Front view of the south facade, depicting the 2 × 2 m² window located in the middle of the facade. Dimensions in m.
An ideal loads air system is present, without active cooling and with a heating setpoint of 20 °C throughout the day. The air exchange rate is equal to ACH = 0.8, and no infiltration is assumed. There are no internal heat gains present for this case. Ground temperature is assumed to be 10 °C below the 1 m thick layer of soil.

Questions

1. Perform a simulation using weather data of Amsterdam, the Netherlands (e.g. https://energyplus.net/weather-location/europe_wmo_region_6/NLD//NLD_Amsterdam.062400_IWEC) for the reference case. Export the hourly zone air temperatures and determine the maximum value. In addition, determine the heating load.

2. Change the albedo value (short-wave reflectivity) of the outer leaf of the wall and of the roof cover to 0.8 by changing the short-wave absorptivity to 0.2 (=1 − albedo). Rerun the simulation and determine the maximum occurring zone air temperature and the heating load.

3. Change the density of the inner leaf of the wall to 100 kg/m³ to simulate the influence of a less heavy material for the inner leaf. Rerun the simulation and determine the maximum occurring zone air temperature and the heating load.

4. Perform the simulations from Question 2 for a building with less thermal insulation for the roof and walls, i.e. a 0.1 m thinner layer of thermal insulation (wall: 0.04 m instead of 0.14 m; roof: 0.1 m instead of 0.2 m, etc.). What are the maximum occurring zone air temperature and the heating load for this case? Can you explain the reason for the observed differences?

Assignment 2

The effect of transpirational cooling of air by vegetation shall be explored by CFD. Create a simple U-shaped building and equip the inner courtyard with trees analogue to Figure 22.20 (see also Gromke et al. 2015 for more information). Assign the vegetation sink and source terms provided in Equations 22.5–22.7 to cells occupied by trees. Users of ANSYS Fluent can use the user-defined function described below.

Assign a volumetric cooling power $P_c$ to cells occupied by trees by implementing a constant value ($P_c = 200 – 400$ W/m³ per unity LAD) as a sink in the energy equation.

Perform a CFD simulation for a wind direction of your choice without taking into account the transpirational cooling effect of trees (reference scenario). Now, assign a volumetric cooling power $P_c$ to cells occupied by trees by implementing a constant value ($P_c = 200 – 400$ W/m³ per unity LAD) as a sink in the energy equation and run the simulation. Analyze the air temperatures in the courtyard and around the building (e.g. at 1 m above ground).

Perform parameter variations:

1. double/halve the volumetric cooling power
2. double/halve the wind speed of the approach flow
3. change the direction of the approach wind
4. change value of LAD in the UDFs

Before looking at the simulation results, think about how the parameter variation will affect the air temperature. Is your expectation in qualitative/quantitative agreement with the simulation results? Explain the tendencies and observations.
User-defined function:

```
#include "udf.h"
#define Cd 0.2  /* usually between 0.1 - 0.3 ; lambda = Cd * LAD */
#define LAD 2.0

real A1t = 1.0; /* Betap */
real A2t = 5.1; /* Betad */
real A3t = 0.9; /* closure constant cepsilon4 */
real A4t = 0.9; /* closure constant cepsilon5 */

DEFINE_SOURCE(x_mom_source,c,t,dS,eqn)
{
  real x[ND_ND];
  real source;
  real U  = C_U(c,t);
  real V  = C_V(c,t);
  real W  = C_W(c,t);
  real VEL = sqrt(C_U(c,t)*C_U(c,t)+C_V(c,t)*C_V(c,t)+C_W(c,t)*C_W(c,t));
  real k   = C_K(c,t);
  real e   = C_D(c,t);
  real rho = C_R(c,t);
  C_CENTROID(x,c,t);
  source  = -Cd*LAD*rho*VEL*U;
  dS[eqn] = -Cd*LAD*rho*(U*U/VEL + VEL);

  return source;
}

DEFINE_SOURCE(y_mom_source,c,t,dS,eqn)
{
  real x[ND_ND];
  real source;
  real U  = C_U(c,t);
  real V  = C_V(c,t);
  real W  = C_W(c,t);
  real VEL = sqrt(C_U(c,t)*C_U(c,t)+C_V(c,t)*C_V(c,t)+C_W(c,t)*C_W(c,t));
  real k   = C_K(c,t);
  real e   = C_D(c,t);
  real rho = C_R(c,t);
  C_CENTROID(x,c,t);
  source  = -Cd*LAD*rho*VEL*U;
  dS[eqn] = -Cd*LAD*rho*(U*U/VEL + VEL);

  return source;
}
```
C_CENTROID(x, c, t);

source = -Cd*LAD*rho*VEL*V;
dS[eqn] = -Cd*LAD*rho*(V*V/VEL + VEL);

return source;
}

/*--------------------------------------------------------------------------------*/
DEFINE_SOURCE(z_mom_source, c, t, dS, eqn)
{
real x[ND_ND];
real source;
real U = C_U(c, t);
real V = C_V(c, t);
real W = C_W(c, t);
real VEL = sqrt(C_U(c, t)*C_U(c, t)+C_V(c, t)*C_V(c, t)+C_W(c, t)*C_W(c, t));
real k = C_K(c, t);
real e = C_D(c, t);
real rho = C_R(c, t);
C_CENTROID(x, c, t);

source = -Cd*LAD*rho*VEL*W;
dS[eqn] = -Cd*LAD*rho*(W*W/VEL + VEL);

return source;
}

/*--------------------------------------------------------------------------------*/
DEFINE_SOURCE(tke_source, c, t, dS, eqn)
{
real x[ND_ND];
real source;
real U = C_U(c, t);
real V = C_V(c, t);
real W = C_W(c, t);
real VEL = sqrt(C_U(c, t)*C_U(c, t)+C_V(c, t)*C_V(c, t)+C_W(c, t)*C_W(c, t));
real k = C_K(c, t);
real e = C_D(c, t);
real rho = C_R(c, t);
C_CENTROID(x, c, t);

source = Cd*LAD*rho*(A1t*pow(VEL, 3) - A2t*VEL*k);
dS[eqn] = Cd*LAD*rho*(- A2t*VEL);

return source;
}
/*--------------------------------*/
DEFINE_SOURCE(eps_source, c, t, dS, eqn)
{
    real x[ND_ND];
    real source;
    real U = C_U(c, t);
    real V = C_V(c, t);
    real W = C_W(c, t);
    real VEL = sqrt(C_U(c, t)*C_U(c, t)+C_V(c, t)*C_V(c, t)+C_W(c, t)*C_W(c, t));
    real k = C_K(c, t);
    real e = C_e(c, t);
    real rho = C_R(c, t);
    C_CENTROID(x, c, t);

    source = Cd*LAD*rho*(A3t*A1t*e/k*pow(VEL, 3) - A4t*A2t*VEL*e);
    dS[eqn] = Cd*LAD*rho*(A3t*A1t/k*pow(VEL, 3) - A4t*A2t*VEL);

    return source;
}

Answers
This section provides solution keys to the projects assigned.

Assignment 1

Q1:
Maximum zone air temperature: \( \approx 26.5 \, ^\circ\text{C} \)
Heating load: \( \approx 2,536 \, \text{kWh} \)

Q2:
Maximum zone air temperature: \( \approx 24.8 \, ^\circ\text{C} \)
Heating load: \( \approx 2,817 \, \text{kWh} \)

Q3:
Maximum zone air temperature: \( \approx 28.5 \, ^\circ\text{C} \)
Heating load: \( \approx 2,567 \, \text{kWh} \)

Q4:
Low albedo case (see Question 2):
Maximum zone air temperature: \( \approx 24.8 \, ^\circ\text{C} \)
Heating load: \( \approx 2,817 \, \text{kWh} \)

Low albedo case with less thermal insulation:
Maximum zone air temperature: \( \approx 23.8 \, ^\circ\text{C} \)
Heating load: \( \approx 5,081 \, \text{kWh} \)

The maximum air temperature decreases when thermal insulation is decreased by 10 cm. This trend is depicted in Figure 22.34 for six days in June. The air in the building with less thermal insulation cools down faster (and to lower temperatures) than in a building with more...
Indoor and outdoor air temperatures. Indoor air temperatures are depicted for the low albedo case with two different thicknesses of the thermal insulation layer in the building envelope.

Thermal insulation. In addition, the building with more thermal insulation heats up faster when solar radiation enters the building (e.g. on 4 June), resulting in indoor air temperatures above the setpoint while the outdoor air temperatures are below the heating setpoint. Of course, the indoor air temperatures depend on many other aspects as well, e.g. ventilation and infiltration rates, solar shading, internal heat gains, etc.

The heating load obviously increases (≈ 80% increase in this case) when thermal insulation is decreased by 10 cm. This is due to the resulting lower thermal resistance of the building envelope, resulting in higher thermal transmittance and thus a higher heating demand.

Assignment 2

1. The air temperature difference relative to the reference scenario ($P_c = 0 \text{ W/m}^3$) is, to a first approximation, double/halve in the cells occupied by trees if doubling/halving the volumetric cooling power and fades out with leeward distance from the trees. There should be hardly any noticeable difference in air temperature outside the courtyard.

2. The air temperature difference relative to the reference scenario ($P_c = 0 \text{ W/m}^3$) is, to a first approximation, halve/double in the cells occupied by trees if doubling/halving the wind speed of the approach flow and fades out with leeward distance from the trees. There should be hardly any noticeable difference in air temperature outside the courtyard.

3. The effect of tree-induced transpirational cooling on air temperature inside the courtyard is larger the more the U-shaped building arrangement shelters the courtyard from the approach flow, i.e. the lesser the ventilation of the courtyard is. There should be hardly any noticeable difference in air temperature outside the courtyard.

4. The effect of tree-induced transpirational cooling on air temperature inside the courtyard increases with increasing LAD. There should be hardly any noticeable difference in air temperature outside the courtyard.