NUMERICAL STUDY OF EVAPORATIVE COOLING AS A CLIMATE CHANGE ADAPTATION MEASURE AT THE BUILDING AND STREET SCALE: CASE STUDY FOR BERGPOLDER ZUID

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ABSTRACT

Adaptation to climate change on an urban scale is important, as increases in temperature will be inevitable according to future climate scenarios. In this study, Computational Fluid Dynamics (CFD) simulations are performed for the Bergpolder Zuid district in Rotterdam, the Netherlands. The simulations take into account wind flow, solar radiation, heat transfer and evaporative cooling. Two validation studies are performed; one for the surface temperatures and one for the evaporative cooling model. In the final stage, three water ponds are added to the domain and a comparative study is performed. It is concluded that evaporative cooling can reduce the air temperature at pedestrian height (1.8 meter) by 0.9°C to 2.0°C.

INTRODUCTION

Based on different emission and climate scenarios, several assessment reports have been published by the Intergovernmental Panel on Climate Change (IPCC). According to these reports, the global mean temperature is likely to rise by 1.1°C to 2.9°C for the lowest emission scenario and by 2.4°C to 6.4°C for the highest emission scenario (worst case for the 21st century) (IPCC, 2007). These climate change scenarios are used to assess the possible consequences in the future and according to the report by the ClimateCOST Project, the consequences can be very severe for people and infrastructure (ClimateCOST, 2011). Higher temperatures as a result of climate change, but moreover heat waves, which are periods of excessively hot weather, can cause an increase in morbidity and mortality, which is a serious issue discussed in various studies (Garssen et al., 2005; Robine et al., 2007).

As large cities and metropolises release more heat to the atmosphere than their suburban and rural surroundings, local temperatures rise accordingly. These regions with higher temperatures than their surroundings are called urban heat islands (UHI). The increase in temperature inside the urban regions depends, among other factors, on how dense the built area is (Oke, 1982). In addition to the temperature increase due to climate change, the temperature is therefore even higher in urban areas compared to the rural regions, and possible health problems might rise accordingly (Tan et al., 2010; Moonen et al., 2012).

Considering all these factors affecting urban temperatures, excessive heat will be an even more important issue for human health and energy consumption in the near future. In order to reduce local temperature rise and to avoid possible health problems, adaptation measures (e.g. evaporative cooling, vegetation) can be implemented. In the recent past, there have been various studies concerning evaporative cooling (Nishimura et al., 1998; Robitu et al., 2006; Krüger and Pearlmutter, 2008; Narumi et al., 2009; Spanaki et al., 2011; Saneinejad et al., 2012) and about vegetation (Saito et al., 1991; Akbari et al., 1997; Dimoudi and Nikolopoulou, 2003; Zhang et al., 2010) in urban areas. The majority of these studies used field measurements to assess the influence of the adaptation measures. However, deterministic analysis of the climate change adaptation measures can also be performed with the use of Computational Fluid Dynamics (CFD) (Blocken et al., 2011; Moonen et al., 2012).

This research has been conducted as a part of the Climate Proof Cities (CPC) research programme, which is studying the effect of climate change adaptation measures in the Netherlands. This paper presents a numerical study in which the effect of evaporative cooling on the outdoor air temperature is assessed for the Bergpolder Zuid district in Rotterdam, the Netherlands.

METHODOLOGY

For this study, a computational model of Bergpolder Zuid and its surroundings is created (Figure 1). Special care is given to the generation of a high-quality grid based on CFD best practice guidelines (Franke et al., 2007; Tominaga et al., 2008; van Hooff and Blocken, 2010). The CFD simulations take into account wind flow, solar radiation (both shortwave and longwave), heat transfer and evaporative cooling. The simulations are performed using the 3D Reynolds-averaged Navier-Stokes (RANS) equations.

Model validation is performed for the urban surface temperature values and for the evaporative cooling model used in this study. The experimental data for the validation of the urban surface temperatures are acquired from Klok et al. (2012) whereas data for the evaporative cooling validation is from the study of Iskra & Simonson (2007).

After the surface temperatures and evaporative cooling model are successfully validated, a comparative study is performed. The comparative study evaluates the effect of evaporative cooling under the meteorological conditions of 16th of July 2003, which was the hottest day in Rotterdam during the 2003 European heat wave and it can be considered as representative of future climate conditions. For the evaluation, three water ponds are added inside the simulated Bergpolder Zuid region (two in courtyards and one on a rooftop). In order to assess the effectiveness of evaporative cooling, the simulations are performed with and without the implementation of water ponds.

Description of urban area

The region Bergpolder Zuid in Rotterdam is subject to renovation and one of the aims of the CPC consortium is to apply adaptation measures to avoid problems caused by possible excessively high temperatures.

The region has little vegetation and negligible open waters (see Figure 1a). Common materials used in the region are dark coloured bricks for building blocks and asphalt for the paved roads. Because of the densely built urban structure, this region shows the basic symptoms of the UHI effect (Klok et al., 2012).

CFD SIMULATIONS: COMPUTATIONAL MODEL AND PARAMETERS

In this study CFD simulations are performed with 3D RANS equations and combined with the standard k-ε turbulence model (Jones and Launder, 1972) to provide closure and standard wall functions (Launder and Spalding, 1974).

As described in the best practice guidelines by Franke et al. (2007) and Tominaga et al. (2008), the maximum building height (H) of the area of interest is important for the dimensioning of the whole computational domain. The highest building in the Bergpolder Zuid region is 51 meters. The region of Bergpolder Zuid and its surrounding buildings are situated inside a circle. The complete domain has the dimensions of L x W x H = 1900 x 1754 x 400 m^3.

The inlet boundary of the domain is defined as a velocity inlet where a logarithmic mean wind speed profile is imposed:

$$U(z) = \frac{u^*}{\kappa} ln(\frac{z+z_0}{z_0})$$

Where U(z) is mean wind speed over height z (m/s), u^* is the atmospheric boundary layer friction velocity (m/s), κ is the von Kármán constant (= 0.40), z is the height (m) and z_0 is the aerodynamic roughness length (m), which is 0.5 m or 1.0 m depending on the wind direction. It is determined based on the updated Davenport roughness classification (Wieringa, 1992).

Inlet profiles are also defined for the turbulence parameters k and ε. The turbulent kinetic energy k (m^2/s^2) is described by:

$$k(z) = \alpha\, (I_u(z)U(z))^2 \quad (\alpha = 1)$$

Where I_u is the streamwise turbulence intensity, and α is a parameter in the range of 0.5 to 1.5. In this study, α is chosen as 1.0 as recommended in previous studies (Tominaga et al., 2008; Ramponi and Blocken, 2012).

The turbulence dissipation rate ε (m^2/s^3) is:

$$\varepsilon(z) = \frac{(u^*)^3}{(\kappa(z+z_0))}$$

Zero static pressure is imposed at the outlet. The top and lateral sides of the computational domain are modelled as a slip wall (zero normal velocity and zero normal gradients of all variables).

The standard wall functions by Launder & Spalding (1974) are used in this study as in combination with the sand-grain based roughness modification as shown by Cebeci and Bradshaw (1977), which is used for building and ground surfaces. In order to have an accurate description of the flow near the ground surface the equivalent sand-grain roughness height k_S (m) and the roughness constant C_S need to be in accordance with the aerodynamic roughness length z_0 (m). According to Blocken et al. (2007), for ANSYS Fluent software, this condition is:

$$k_s = \frac{9.793\, z_0}{C_s}$$

The radiation model P-1 is used for solving the radiation equations (ANSYS Inc., 2009) and the Boussinesq approximation is used to take into account buoyancy effects. At the inlet and outlet boundaries, constant temperatures are specified according to the data from the Royal Dutch Meteorological Institute (KNMI). Exact dates for the validation study are shown in Table 1. For the comparative study, the selected date is the 16th of July 2003, which was the hottest day in Rotterdam during the 2003 European heat wave.

On the ground region, mixed thermal settings are specified (taking into account conduction, convection and radiation) with a thickness of 20 meter and a free stream temperature of 10°C. The described ground region represents the material specifications of earth (density = 1450 kg/m^3, thermal conductivity = 1.5 W/mK and specific heat = 1260 J/kgK) whereas the reflective specifications of light coloured concrete are used (emissivity = 0.91 and solar absorptivity = 0.6). The aim of this selection is to represent the ground as a thick earth layer with concrete finishing at the top.

Building exteriors are specified as 0.3-meter thick brick walls and their thermal settings are defined as mixed, like for the described ground region. The temperature of the building walls has a free stream temperature of 23°C. The reason for this choice is to represent the building interiors as air-conditioned regions during summer.

In addition to air temperature, meteorological conditions as wind velocity (m/s), wind direction and solar radiation (W/m^2) are determined from the hourly statistics as acquired from the KNMI. Values from the hourly statistics are used as constant as the simulations are steady state.

For the evaporative cooling model, three different wall type boundaries are specified (one for each water pond). Two of these ponds are located inside courtyards where the wind velocity is low, causing high surface temperatures. The third pond is modelled on the top of a low-rise building as a roof pond. For calculating the moisture transfer, equations for species transport are activated. At these three boundaries, zero velocity injections are created. The calculations for injections take into account water volume inside the water pond and temperature. Therefore they obtain a certain thermal capacity and the water is subject to evaporation from the water pond surfaces.

For all the equations (energy, moisture transfer, momentum) the spatial discretization is defined as second order upwind and pressure-velocity coupling is performed with the SIMPLEC algorithm (ANSYS Inc., 2009).

CFD SIMULATIONS: MODEL VALIDATION

Two validation cases are set up. The first case is the validation of the CFD model under wind flow and solar radiation conditions with the focus on surface temperatures, using satellite measurements. The second case concerns the evaporative cooling model used in this research, by wind-tunnel measurements.

Validation of surface temperatures

The study of Klok et al. (2012) was performed to quantify the surface temperatures of heat islands inside Rotterdam. In the study, the surface temperature measurements for each region were used. The measurements were conducted during the July 2006 heat wave on different dates and times. The exact dates and times are specified in the full paper by Klok et al. (2012) and the weather conditions corresponding to these dates are acquired from the KNMI. The climate measurements are recorded at the KNMI station in Rotterdam.

As the satellite measurements have a resolution of 1 km x 1 km, the provided data in the study of Klok et al. (2012) are not available for every district of Rotterdam but rather for entire regions. As Bergpolder Zuid district in Rotterdam is located inside the Noord region, the satellite measurements for this region is compared with the simulations results.

In this validation study, 10 simulations are performed for different dates and times. Accordingly, air temperatures, solar radiation, wind speed and wind direction are also different for each case. For all these cases, Klok et al. (2012) present an average surface temperature value for the entire region of Noord. In the simulation results 25 arbitrary data points, positioned in streets and courtyards, provide surface temperature values. The data points are located around the Bergpolder Zuid region and there is at least one data point for every street. In Table 1 the complete data set with the meteorological conditions and results is provided. In Figure 2, the results of the first validation case are presented with a graph. It can be observed that the simulation results show a fairly good agreement with the satellite measurements and that the temperature differences are within 0.14°C to 2.28°C. It should be noted here that the larger differences in the last three simulations are caused by the varying climatic conditions on the 18th of July 2006. The measurements were reported by Klok et al. (2012) for a specific minute but the temperature data from the KNMI are hourly averaged. Therefore, when the variance of the climatic conditions is high for a specific time period, the dataset is not accurate which may have led to differences in the surface temperatures.

Validation of the evaporative cooling model

The second validation case is performed to validate the evaporative cooling model used in this study. For the modelling of evaporative cooling, a region with a separate wall type of boundary is defined. At this wall, relative humidity is 100% and a zero velocity injection is imposed. A CFD model, which resembles the experimental model used in the wind tunnel study by Iskra & Simonson is created (see Figure 3). In the wind-tunnel study, the test setup considers a duct flow with a test region containing a water tray (depth of 0.03 m) filled with water, which is subject to evaporation. The evaporated species are carried away with the duct flow. There are two data points, one at the inlet and the other one at the outlet region of the duct. In these data points, temperature and relative humidity are measured and reported (Iskra and Simonson, 2007).

In the generated two-dimensional CFD setup, the duct has a height of 0.0205 m. The inlet region is 0.9 m long whereas the test section including the water tray is 0.6 m and the outlet (downstream) region is 0.9 m. Along the height of the duct, the domain is divided into 10 grid cells and in total 2900 cells are created. The flow in the duct is described by a parabolic Poiseuille velocity profile. The mean air velocity is 0.64 m/s whereas the highest air velocity (1.28 m/s) is measured at the middle of the duct. The airflow is solved by the 2D steady RANS equations and the standard k-ε turbulence model (Jones and Launder, 1972).

At the inlet, the same velocity profile as in the wind tunnel study is applied and zero static pressure is imposed at the outlet. Top and bottom sections of the duct are defined as no-slip walls. The duct walls have a constant temperature of 23°C. Duct walls inside the wind tunnel are aluminium and not porous. However, in order to obtain similar initial conditions with the wind tunnel study, CFD simulations assumed a constant 17% relative humidity on the walls, which was the initial relative humidity inside the wind tunnel. Water in the water tray has a temperature of 20°C and according to the evaporative cooling model used in this study, the relative humidity on the wall section, where the water tray is located, is 100%. The water tray has a width of 0.6 m and a height of 0.03 m.

Iskra & Simonson (2007) reported that the change in the relative humidity and temperature have become negligible after a certain time. Therefore, the aim in this validation case, as it is a steady simulation, to have similar results with the final values of temperature and relative humidity, where the system also behaves in a steady state.

At the outlet region, the average temperature obtained from the CFD simulations is 27.3%, whereas it is 27.9% according to the wind-tunnel measurements. At the same region, the average temperature obtained from CFD simulations is 20.7°C, whereas it is 20.5°C according the wind-tunnel measurements. After the relatively good agreement of simulation results and wind tunnel measurements for the given target variables, the evaporative cooling model used in this study is considered as reliable for the use in the following comparative study.

CFD SIMULATIONS: COMPARATIVE STUDY

The comparative study investigates the effect of evaporative cooling by modelling three water ponds (two in courtyards and one on a rooftop) in the Bergpolder Zuid district (see Figure 4).

The meteorological conditions in this comparative study are taken equal to those measured by the KNMI on the 16th of July 2003 in Rotterdam at 14:00h. This specific date and time is selected because it represents an excessive hot summer situation, which may also be considered as a representative future climate scenario. At this date and time the measured air temperature at rural regions of Rotterdam is 33.6°C, reference wind direction is 150° (south-southeast), the reference wind velocity U_{10} at 10 meter height (z_{ref}) is 3 m/s and the solar radiation is 900 W/m^2.

Dimensions of the water ponds are 30 x 25 x 0.3 m^3 (large water pond), 25 x 20 x 0.3 m^3 (small water pond) and 25 x 25 x 0.3 m^3 (roof pond) with a water temperature of 20°C. The water temperature is chosen same as the average daily (day and night) temperature. For the same date and time, simulations are performed with and without the water ponds. For the comparison, the target variable is the air temperature at 1.8 meters height inside courtyards. However, as it is not necessary to measure the air temperature at human height above the roof, the comparison of air temperature will be made at 0.5 m above the roof, only for the roof pond case. The number of data points around water ponds depends on the sizes of the corresponding courtyards. Therefore, the simulation results are recorded for:

- 10 data points around the large water pond at 1.8 meters height;
- 8 data points around the small water pond at 1.8 meters height;
- 12 data points around the roof pond at 0.5 meter height.

Comparison of the air temperatures with and without the large water pond is provided in Figure 5. With the application of the large water pond, the decrease in the air temperature inside the courtyard is between 1.4°C to 2.0°C.

Another comparative graph showing the air temperatures with and without the small water pond is provided in Figure 6. According to the simulation results, with the application of the small water pond, the air temperature in the corresponding courtyard had a decrease between 1.0°C to 1.5°C. Compared to the application of the large water pond, the cooling effect of the small water pond is smaller.

The cooling effect of the roof pond is evaluated at 0.5 m above the roof. A comparative graph showing the air temperatures with and without the roof pond is provided in Figure 7. According to the simulation results, with the implementation of the roof pond, the decrease in air temperature around the pond varies between 2.7°C to 3.9°C.

According to the results, it is clear that the size of the water pond is effective on the cooling potential of the implementation in a closed courtyard environment. Inside the courtyard, which contains the large water pond, the cooling effect is the highest.

Moreover, different air temperatures at different heights show that the cooling effect of water ponds is more profound when the data is collected at lower heights.

DISCUSSION

Urban geometry and grid

The generated urban geometry in this research is based on the drawings and data from the municipality of Rotterdam. Therefore, modelled buildings and dimensioning of these buildings with respect to each other are realistic enough to perform a study in the urban environment. However, there are elements in the real situation that are not taken into account in the CFD simulations. Trees, street poles, cars and all other obstacles or heat sources are neglected. The obstacles might change the wind flow on a local basis but the difference would not be significant considering the larger urban scale. A similar issue should be addressed for the cars as well, as they reflect the incoming sun light and avoid them from reaching to the surface. In other words, along with trees, they behave like artificial shading elements. Such elements are represented within the simulation domain by assigning a low solar absorptivity value and a higher surface reflectance to the ground plane.

A grid-sensitivity analysis is beneficial to make sure that the results have become independent of the grid resolution. In the validation study of the evaporative cooling model, a grid sensitivity analysis is performed and the grid is selected accordingly. However, such an analysis has not yet been performed for the computational model of the Bergpolder Zuid district. Therefore, future work will include a grid-sensitivity analysis to assess the grid-dependency of the simulation results of the Bergpolder Zuid domain.

Evaporative cooling model

A choice for modelling the evaporative cooling had to be made in the beginning of the study. It was chosen to perform steady simulations and to include a water film to include the ponds in the model. The other option was to model water ponds explicitly as water volumes inside the computational domain. If the latter option would have been chosen, a separate three-dimensional zone had to be created (rather than using water films with defined volumes) with water as the fluid in this region. In addition, a transient simulation had to be performed for this option because the level of water would drop after some time and there would be a secondary flow caused by temperature differences within the water pond. However, for a study performed on an urban region such an implementation might become too detailed and would increase the computational demand to a large extent.

CONCLUSION

Considering the future climate scenarios and the UHI effect, numerical studies about the evaluation of adaptation measures might be even more important. In this study, CFD is used for simulating climate change adaptation measures for an urban region. The simulations consider wind flow, solar radiation, heat transfer and evaporative cooling. Two separate model validations are conducted. First, the surface temperatures are validated by comparing simulation results with measurements by satellite images. Second, the evaporative cooling model used in this study is validated by comparing a separate set of simulations with wind-tunnel measurements. Both validation studies showed a fair to good agreement between the experimental data and the results of the CFD simulations. In general, CFD studies can provide fairly accurate results for the analysis of climate change adaptation measures. In the future, CFD can be used as an assessment tool for feasibility studies of adaptation measures and for the analysis of the urban heat island effect.

According to this study, the following conclusions can be made:

1) The studied evaporative cooling implementations in Bergpolder Zuid can decrease the temperature by 0.9°C to 2.0°C (at z = 1.8 m) inside the courtyards and 2.7°C to 3.9°C on rooftops (at 0.5 m above the roof);
2) The effectiveness of the evaluated water ponds is positively linked with their sizes.
3) The cooling effect of water ponds is more profound when the data is collected at lower heights.

ACKNOWLEDGEMENT

The authors are grateful to the Climate Proof Cities consortium for their collaboration and assistance during the formation of this study.

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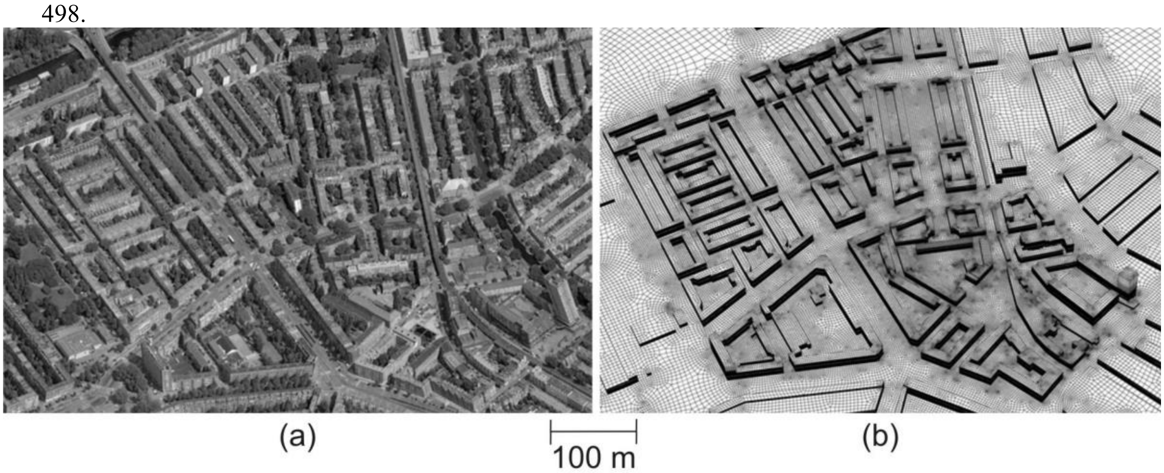

Figure 1: (a) Aerial view of Bergpolder Region (taken from south). (b) The view of grid on the building and ground surfaces within the computational domain (number of cells: 6,307,876). The intensity of the black lines represents regions with finer mesh and higher detail.

Table 1: Data table for the validation of surface temperatures.

Simulation #	Date/Time (all dates in 2006)	Air temperature (°C)(KNMI)	Radiation (W/m^2) (KNMI)	Wind speed (m/s) at 10 m (KNMI)	Wind direction (0°:North, 90°: East) (KNMI)	Surface temperature (°C) (Klok et al. 2012)	Surface temperature (°C) (simulations)
1	16.07 / 11:55	26.6	825	4.5	70	**36.8**	**37.4**
2	16.07 / 12:19	27.4	863.89	4.5	70	**39.0**	**39.0**
3	16.07 / 14:07	28.5	802.77	4.5	110	**38.5**	**38.9**
4	16.07 / 17:59	28.3	580.55	4.5	90	**32.5**	**32.3**
5	17.07 / 11:56	29.1	844.44	3	90	**38.9**	**40.7**
6	17.07 / 13:56	30.5	783.33	3	50	**43.0**	**43.1**
7	17.07 / 17:34	26.9	236.11	3	350	**33.2**	**31.9**
8	18.07 / 11:29	32	813.89	4	80	**39.0**	**41.3**
9	18.07 / 13:13	34.4	763.89	4.5	100	**39.6**	**41.4**
10	18.07 / 15:27	34.6	533.33	4	90	**38.9**	**40.7**

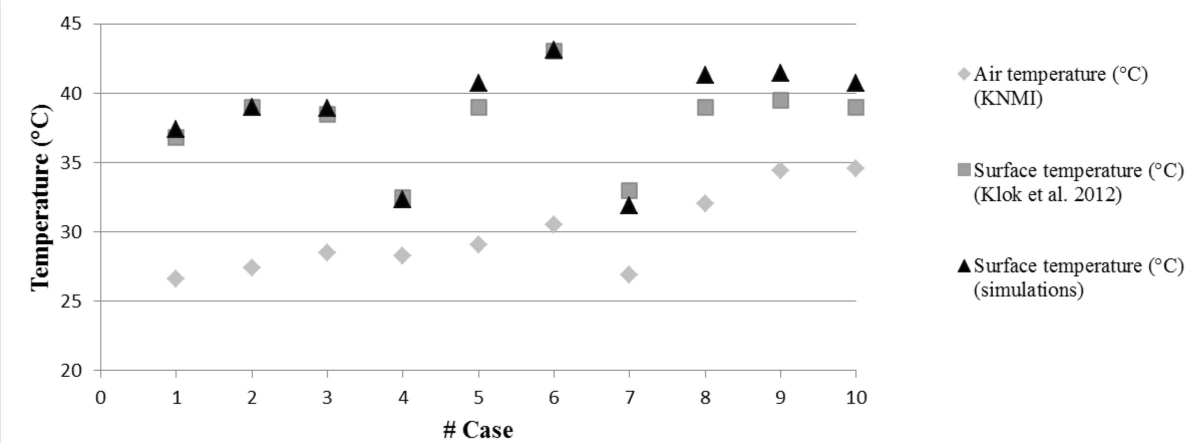

Figure 2: Comparison between the measurements by Klok et al. (2012) and the steady RANS CFD simulations as presented in this paper. Air temperatures are measured at 10 m height outside the city.

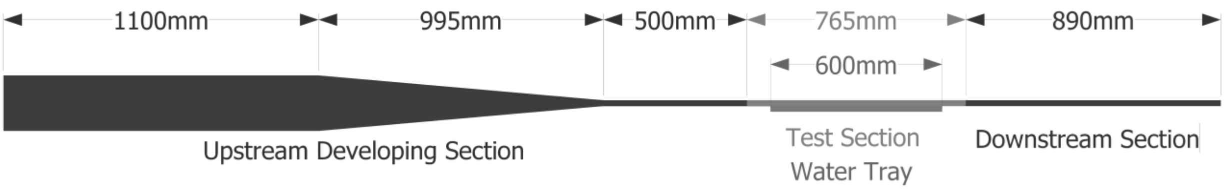

Figure 3: Representation of the experimental setup as used in the study by Iskra & Simonson (2007).

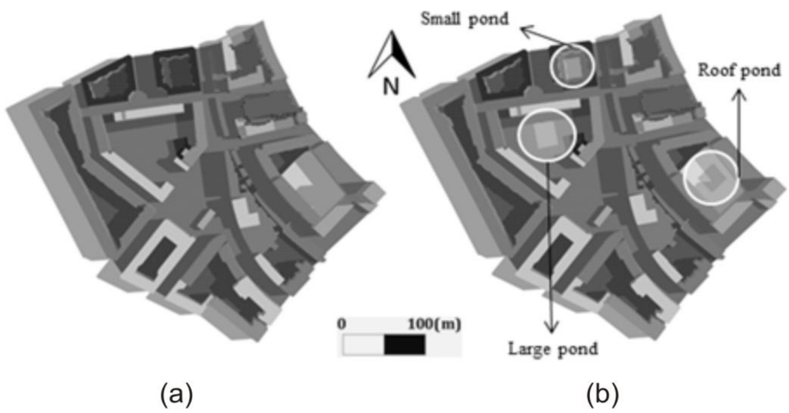

Figure 4: Representation of Bergpolder Zuid. (a) Current situation without any water ponds; (b) same region with the water pond implementations.

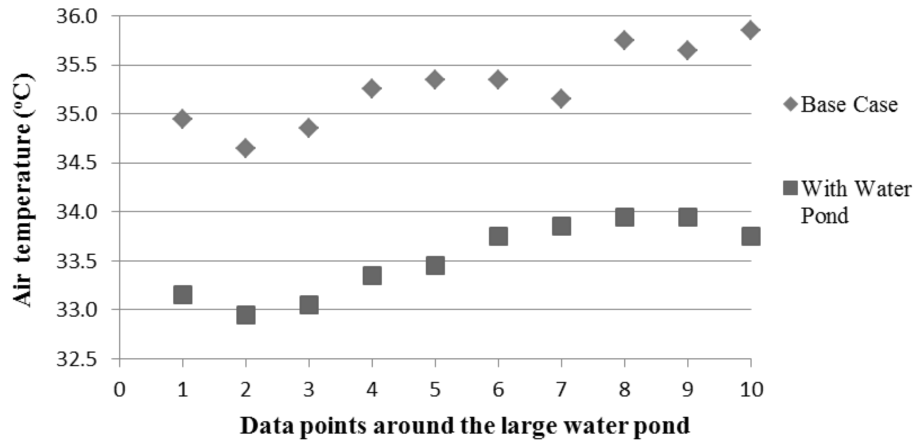

Figure 5: Comparison of air temperatures at z = 1.8 m for data points around the large water pond. The comparison is between the base case simulation and the case with the water pond implemented.

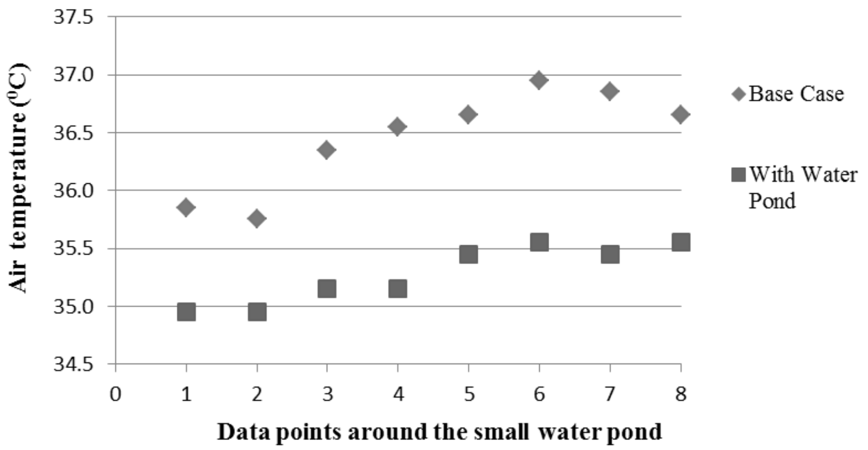

Figure 6: Comparison of air temperatures at z = 1.8 m height for data points around the small water pond. The comparison is between the base case simulation and the case with the water pond implemented.

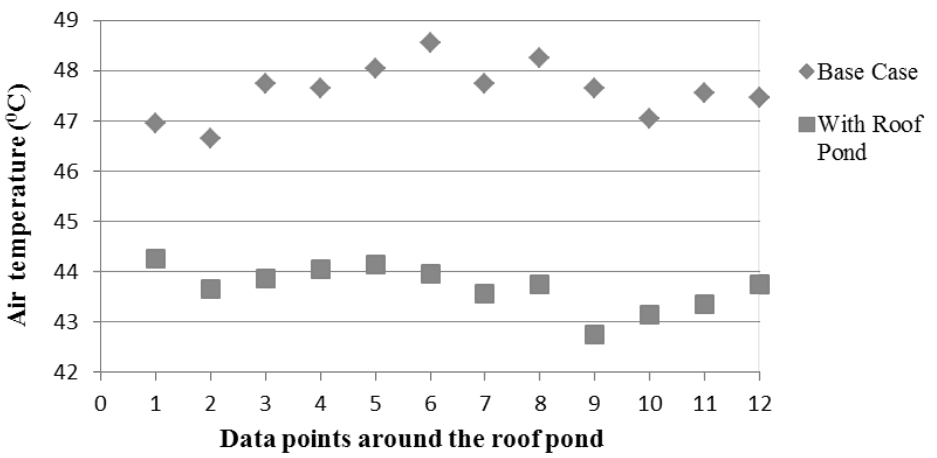

Figure 7: A comparison of air temperatures at 0.5 m above the roof height for data points around the roof pond. The comparison is between the base case simulation and the case with the roof pond implemented.