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# URBAN ENERGY AND MICROCLIMATE: WIND TUNNEL EXPERIMENTS AND MULTISCALE MODELING

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## ABSTRACT

An urban microclimate model including air flow, heat and moisture transport in porous urban surfaces and solar and longwave radiation is presented, validated with wind tunnel experiments and used to study the effect of evaporative cooling on the thermal comfort in a street canyon.

## INTRODUCTION

A major part of the final energy consumption in our nowadays society is due to buildings and cities. For the future, we have to find new urban energy concepts based on the integration of renewable energy supply, conversion, storage, distribution and management on neighbourhood or urban scale, where buildings will become interconnected, harvesting, exchanging and storing energy. The objective might be that local neighbourhoods become energy self-regulating, minimizing the additional supply from national or international energy systems. This challenging new concept has the potential to substantially decentralize the energy sector. The energy demand of neighbourhoods depends not only on their building energy systems, but also on the microclimate created around the buildings, which can differ substantially for rural, suburban and urban areas.

The development and analysis of these new urban energy scenarios has to be supported by advanced multiscale simulation methods covering the urban microclimate (UMC), including urban heat island effects and building energy systems on city quarter level. Even for buildings in an urban context, common practice in detailed building energy simulation (BES) still relies on stand-alone building configurations, not accounting for the influence of neighbouring buildings, except perhaps for shading. However, the urban climate and microclimate can strongly affect the building energy demand. Compared to stand-alone buildings, buildings in urban context experience higher ambient temperatures due to urban heat island effects and local heat rejection from other buildings, an altered radiation balance, due to the presence of surrounding buildings, and changed convective heat exchange, due to the different wind flow pattern. Thus, BES has to be coupled with an UMC model.

The urban microclimate is modeled using a computational fluid dynamics (CFD) model for the urban air domain, a radiation model including solar radiation and longwave radiative exchange between urban surfaces (figure 1). This urban microclimatic model interacts with building energy simulation models and heat and moisture (HAM) transfer models for evaporative cooling processes situated at the porous building envelope and porous urban surface. The UMC model has to be linked to a regional meteorological meso-scale model to cover urban heat islands.

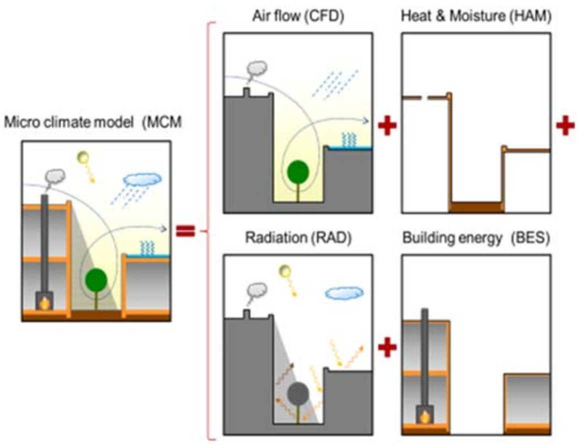


*Figure 1. The Urban Microclimate Model (UMC) consists of an air flow model solved by CFD, a heat and moisture transport model taking into account evaporative cooling effects by porous urban surfaces, a radiation model and a building energy simulation model.*

A detailed study regarding the influence of the urban microclimate in street canyons on the energy demand for space cooling and heating of buildings can be found in Allegrini et al. (2012). It was shown that the space cooling demand for the stand-alone buildings is much lower compared to the buildings situated in the street canyons, while the heating demand decreases for the urban case. In Allegrini (2012), the UMC model including the urban heat island effect is explained in detail and the reader is referred to this work. In this paper, we focus on two aspects related to the urban microclimate model on street canyon scale: the influence of buoyancy on the flow field in a street canyon and the influence of evaporative cooling on the thermal comfort in a street canyon. In the first part of the paper, wind tunnel measurements of buoyant flow in a scaled street canyon are presented. These measured results are later used to validate the CFD simulations. In the second part of this paper, the thermal comfort in a street canyon is studied by coupling CFD with a HAM transfer model and a radiation model.

## WIND TUNNEL EXPERIMENTS AND VALIDATION

### Wind tunnel setup

This study is conducted in the ETHZ / Empa atmospheric boundary layer wind tunnel in Dübendorf, Switzerland. The flow in an urban street canyon is modelled by building up a cavity of 0.2 x 0.2 x 1.8 m (W x H x L; W: width; H: height; L: length) in the wind tunnel test section (Figure 2).

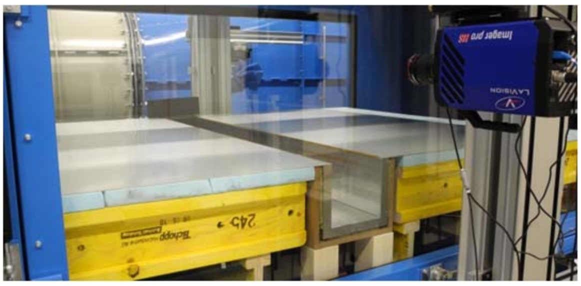

*Figure 2: Street canyon model installed in the ETH / Empa wind tunnel*

For the measurements, the wind tunnel floor and the street canyon surfaces are made out of aluminium plates, thus forming a low roughness surface. With such low roughness, low-Reynolds number modelling can be applied for the validation study (see below). This low roughness can be accepted here, because the aim of this study is to validate the CFD simulations and to study the general flow field in an urban street canyon. To study the boundary layer close to a building façade, a higher surface roughness is needed. Heating mats are attached at the back of each aluminium plate forming the street canyon to increase the surface temperatures. Due to the high thermal conductivity of aluminium, the temperature is uniform over the whole heated surface.
The flow field in a cross-section of the street canyon is measured with particle image velocimetry (PIV). 300 double frame images are recorded at a frequency of 4 Hz and time averaged temperature and turbulent kinetic energy (TKE) fields are determined. For some specific cases, the air temperatures inside the street canyon are measured with thermocouples on an equidistant grid of 10 x 10 measurement points. The flow direction is normal to the street canyon axis and the inflow temperature is 23 °C. Table 1 gives the different surface temperatures and Reynolds numbers at which the measurements are conducted, together with the corresponding Froude numbers. To reach the same Froude numbers in wind tunnel as in full-scale, rather high surface temperatures are needed for the wind tunnel measurements. More details can be found in Allegrini et al. (2013).

*Table 1*
*Surface temperatures and Reynolds numbers with corresponding Froude numbers*

| RE | 70 °C | 90 °C | 110 °C | 130 °C |
|---|---|---|---|---|
| 9000 | 1.49 | 1.04 | 0.80 | 0.65 |
| 14200 | 3.68 | 2.58 | 1.99 | 1.62 |
| 19200 | 6.75 | 4.74 | 3.65 | 2.97 |
| 24600 | 11.11 | 7.79 | 6.00 | 4.88 |
| 30700 | 17.29 | 12.13 | 9.34 | 7.59 |

### Wind tunnel results

Time averaged streamlines for isothermal cases and cases with windward wall and leeward wall heating are given in Figure 3 for three different Reynolds numbers.

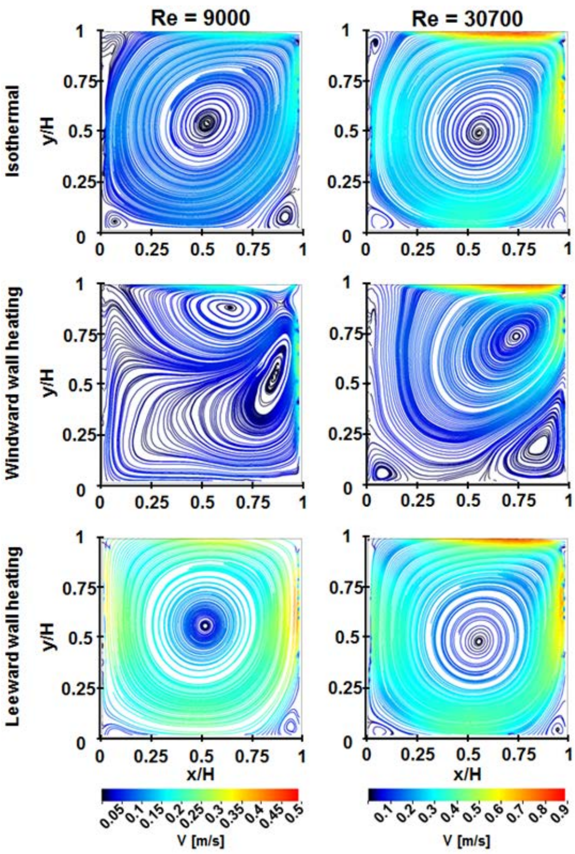


*Figure 3: Streamlines for isothermal cases and cases with windward wall and leeward wall heating.*

If no surface is heated, one main vortex in the centre of the street canyon and corner vortices in the bottom corners are formed. With leeward wall heating the structure is the same, but the velocities inside the street canyon are increased, because buoyancy strengthens the main vortex. For windward wall heating with low Reynolds numbers the flow structure changes significantly. Instead of one main vortex, two vortices with similar size can be found inside the street canyon. For higher Reynolds numbers the flow structure is similar to the structure of the isothermal case (forced convection). The velocities in the street canyon with windward wall heating are significantly lower compared to the other cases. The changes of the flow field, caused by buoyancy, show the importance of studying the detailed flow fields in urban areas for the determination of the convective heat transfer at building facades.

For the cases with windward wall heating, buoyancy significantly changes the vortex structure. Streamlines for the five different Reynolds numbers are presented in Figure 4 (windward wall temperature: 130 °C). Besides the main vortex a second counter rotating vortex is formed. This secondary vortex is located in the lower part of the street canyon and has a similar size as the main vortex at lower Reynolds numbers. For high Reynolds numbers (>24600) the size of the secondary vortex decreases and at the highest Reynolds numbers (30700) the flow structure becomes similar to the vortex structure of the isothermal case.

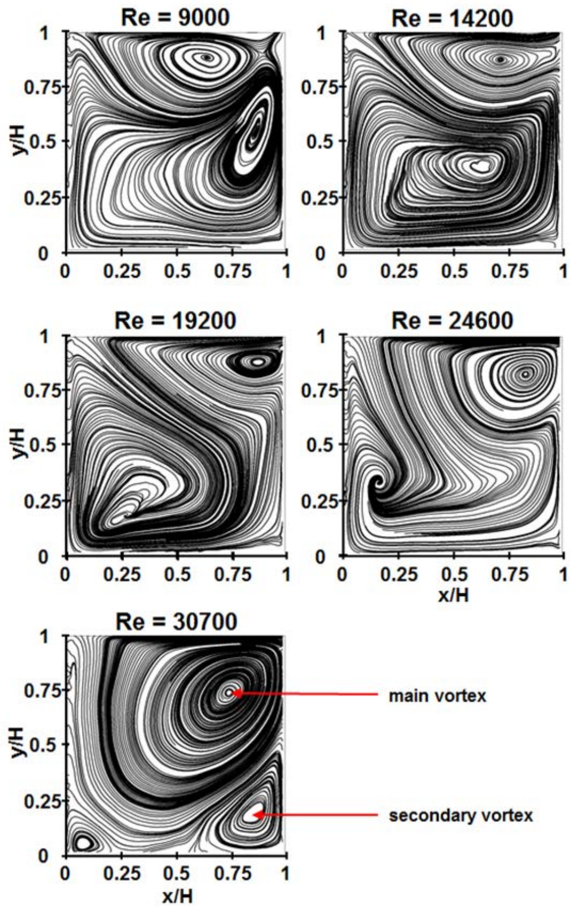


*Figure 4: Streamlines for cases with windward wall heating and five different Reynolds numbers.*

For leeward wall heating, the main vortex becomes strengthened by the buoyancy effect (Figure 3), mainly for low Reynolds numbers. In Figure 5 normalised velocity profiles are given on the vertical centreline of the street canyon for different Reynolds numbers and different leeward wall temperatures. At low Reynolds numbers a strong increase of the velocities with increasing leeward wall temperature can be observed. For a leeward wall temperature of 130 °C the velocities inside the street canyon are more than double compared to the isothermal case. For high Reynolds numbers no strong dependency of the velocity profiles on temperature can be noticed, because the flow is in a forced convective flow regime.

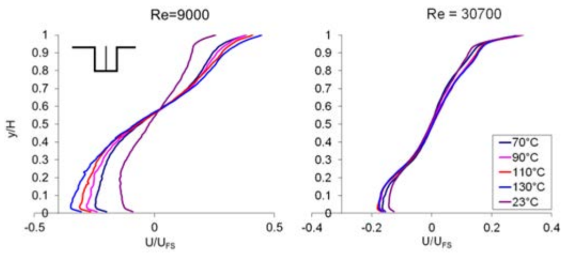


*Figure 5: Normalised velocity profiles on the vertical centreline of the street canyon for different Reynolds numbers and different leeward wall temperatures.*

**CFD models and simulations**

For this validation study, steady 2D RANS CFD simulations using ANSYS-Fluent 12.0 are conducted with the standard and the realizable k-ε model. At the near-wall regions the boundary layers are either resolved with low-Reynolds number modelling (LRNM) or modelled with wall functions (WFs) (Allegrini et al. 2012b). The dimensions of the computational domain are set according to the wind tunnel dimensions (Figure 6). The grid is built based on a grid sensitivity analysis and consists of 5500 cells. It is refined towards the walls. The same mesh is used for simulations with LRNM and WFs.

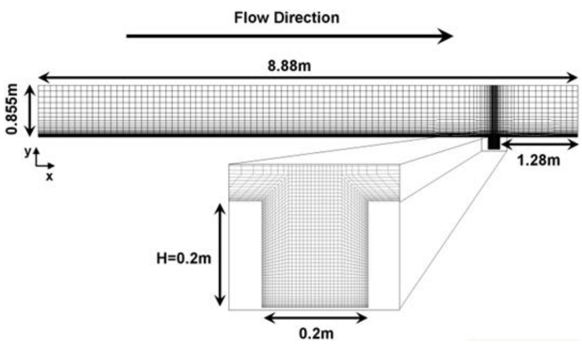


*Figure 6: Computational domain.*

At the inlet, the measured boundary layer profiles for the velocity and turbulent kinetic energy (TKE) are imposed (Figure 6). All surfaces are modelled without roughness, because no roughness can be defined with LRNM. This may be justified since the wind tunnel model was made out of aluminium with a very low surface roughness. For the surfaces inside the street canyon, the surface temperatures obtained from the experiments are used as a temperature boundary condition. The surfaces outside the street canyon are modelled adiabatic. Symmetry boundary conditions are imposed at the top boundary and outflow boundary conditions at the outlet. To account for buoyancy the density, the specific heat, the thermal conductivity and the viscosity are approximated with polynomial functions as a function of the temperature in the Navier-Stokes equations. Radiation is not considered in the CFD simulations, because for the wind tunnel measurements the surface temperatures were kept constant with heating mats and therefore radiation did not influence the flow field.

### Validation results

In Figure 7 normalized centreline profiles of the horizontal velocity and TKE are given for the case where all surfaces are heated inside the street canyon. The following two CFD model combinations are used: (i) LRNM with a realizable k-ε model (ii) non-equilibrium wall functions with a standard k-ε model. Further simulations are conducted with the same models as the simulations with NEWFs, but the extension of the upstream domain in front of the street canyon is only 0.25 H (NEWF short). With this short upstream domain, the boundary layer cannot develop and therefore the approach flow velocities do not decay as in the case with the long upstream domain. In short upstream domain case, the flow velocities at the entrance of the street canyon will be more accurate. In the boundary layer above the street canyon the simulation with NEWFs predict too low velocities.

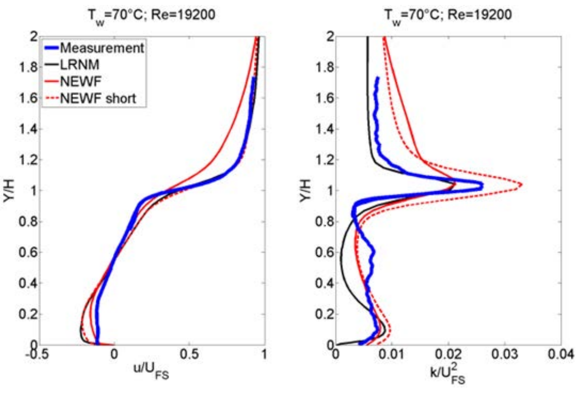


*Figure 7: Normalised centreline profiles of the horizontal velocity for cases with all surfaces heated inside the street canyon (70 °C).*

With LRNM and NEWFs with the short domain a very good agreement between the simulations and the measurements can be found. In the shear layer at the top plane of the street canyon the measured velocities are strongly decreasing and at H = 1 the slope of the profiles changes strongly. At this point the best agreement for the velocity can be found for the NEWFs, while the other two models overestimate the velocity. The same trend can be observed close to the ground of the street canyon. Therefore it can be concluded that the velocities inside the street canyon are mainly influenced by the velocities in the shear layer. Even with too low velocities above the street canyon the flow inside the street canyon can be predicted well (NEWFs). For the TKE all CFD models can capture the general trend. Inside the street canyon the NEWFs (long and short domain) perform better than LRNM that underestimates the TKEs.

For windward wall heating the vortex structure is strongly influenced by buoyancy. The information gained from comparing centreline profiles is rather limited, because already small changes of the centre of the vortices strongly change the profiles. Therefore here the trajectories of the centre of the main vortex are compared (Figure 8). As for the measurements also for the CFD simulations the centre of the main vortex is moving from the leeward wall side towards the windward wall side and then to the centre of the street canyon with increasing Reynolds numbers. The trajectories are similar for the simulations with LRNM and NEWFs. For LRNM the flow is more in the forced regime than for NEWFs for all simulations. It can be concluded that with CFD the general development of the vortex structure can be predicted for cases with windward wall heating.

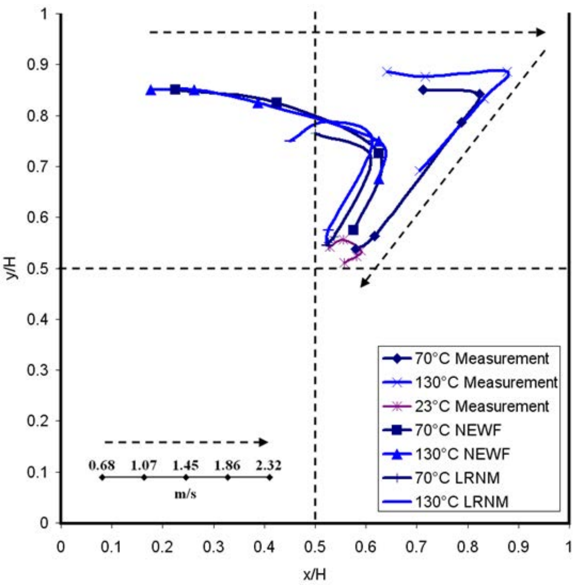


*Figure 8: Trajectories of the centre of the main vortex as a function of the freestream velocity for different windward wall temperatures.*

In Figure 9 horizontal profiles (measured, LRNM and NEWFs) of the temperature are given for the case with a Froude number of 6.75. It is expected that the most accurate results would be achieved by LRNM, where the boundary layer at the walls can be

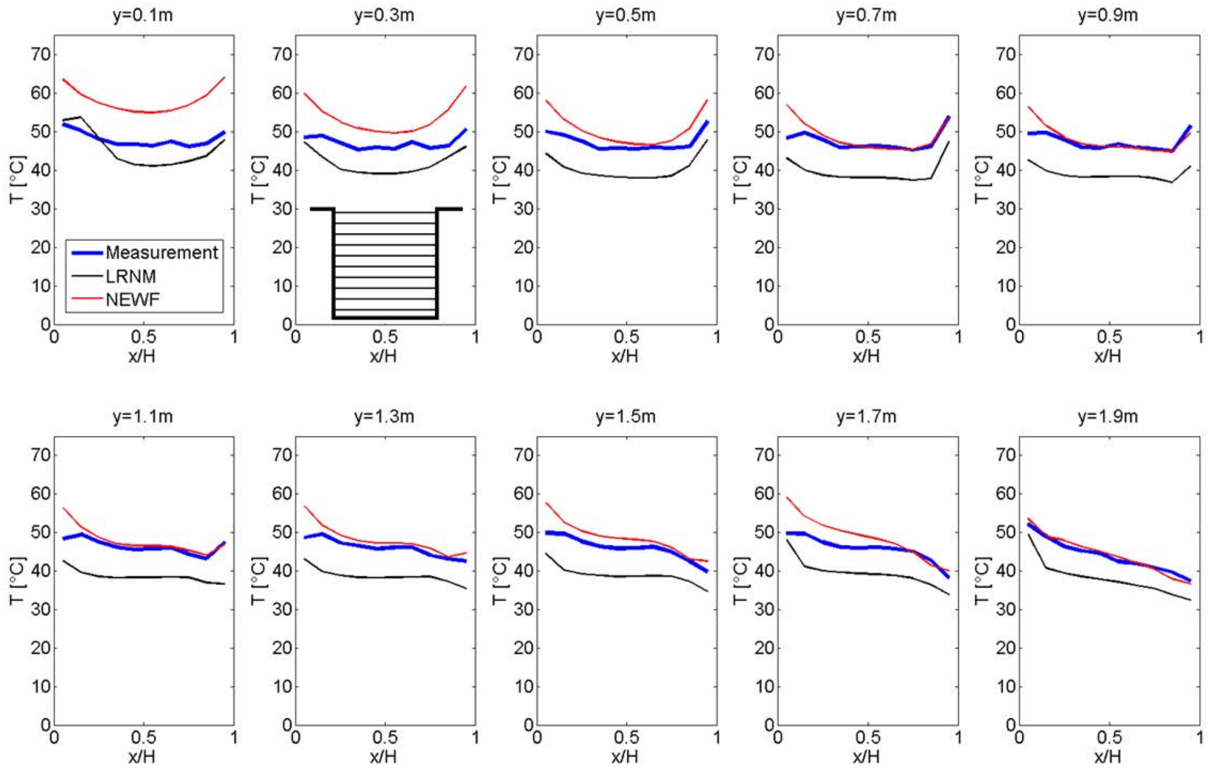


*Figure 9 Temperature profiles on horizontals lines at different y-positions inside the street canyon. Wind tunnel measurements and CFD simulations for cases where all surfaces are heated (Fr = 6.75) using two different turbulence models and different near-wall modelling approaches (LRNM: Low-Reynolds number modelling with realizable k-ε; NEWF: non-equilibrium wall functions with standard k-ε).*

accurately resolved. With LRNM the temperatures are underestimated for all profiles by about 10 °C. The results can be improved by using NEWFs. For the profiles at y < 5 cm and for most profiles close to the windward and leeward walls the temperatures are overestimated by NEWFs due to the overestimation of the thickness of the temperature boundary layer. In the centre of the street canyon a good agreement for the temperatures with NEWFs can be found. A reason for the better agreement of the profiles with NEWFs compared to LRNM could be that the velocities in the shear layer correspond better to the measured velocities and therefore the predicted air exchange rate is more accurate. Another possible reason is that the convective heat transfer predictions are more accurate due to a different near-wall treatment. This cannot be evaluated here, because the wall heat fluxes were not measured.

**Discussion**

Due to buoyancy there is a strong coupling between the flow field inside the street canyon and the heat fluxes at the boundaries of the street canyon. Therefore already small errors in the prediction of the fluxes of the flow field can significantly change the results of the CFD simulations. In the case of a street canyon the important fluxes are the convective heat fluxes at the three surfaces, the heat flux out of the street canyon and into the street canyon (red arrows in Figure 10). The main driver of all the fluxes is the heat exchange at the top plane of the street canyon. There is a strong coupling between the heat fluxes and the flow structures inside the street canyon. For example an increase of the leeward wall temperature can increase the heat exchange at the top plane due to increased buoyancy effects. This increase can lead to lower temperatures at the windward wall and a significant change in the whole flow structure inside the street canyon. Therefore it can be concluded that accurate flow predictions at the top plane of the street canyon (blue box in Figure 10) are needed to get accurate flow predictions inside the street canyon with CFD.

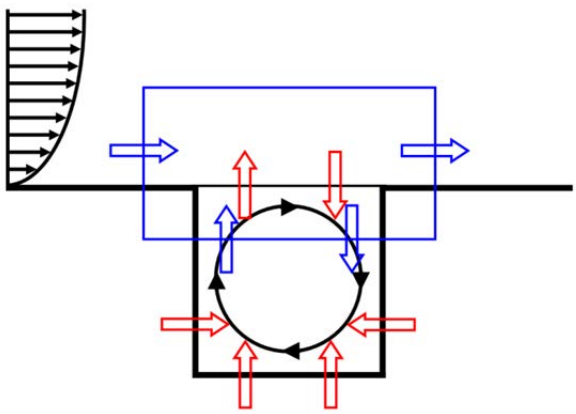

*Figure 11 Sketch of the heat fluxes in a street canyon.*

## EVAPORATIVE COOLING IN A STREET CANYON

A second example of the Urban Microclimate (UMC) model is the influence of evaporative cooling on the thermal comfort in a street canyon. The air flow due to forced convection and buoyancy, including heat and vapour transport in the air domain, is solved using CFD, the effect of solar and longwave radiation including multiple reflections is solved using a radiation model, while evaporative cooling in the porous urban materials is modelled using a heat and moisture transport model (Saneinejad et al. 2012). The 2D street canyon of 10 x 10 m is exposed to two days during June taken from a typical meteorological year (TMY) of Zürich. The air temperature varies between 13.5°C and 19°C and the relative humidity varies between 62% and 86%. The windward wall is assumed to be wet after a rain shower (RH ≈ 100%) while the other surfaces are dry. The walls of the canyon are made of ceramic brick (0.09 m tick) and have albedo of 0.4. The soil is covered with 0.1 m concrete layer, assumed to be dark colored with albedo of 0.1. The reference wind speed at 10 m height is 5 m/s.

To evaluate the effect of evaporative cooling, we compare the surface temperature at the top point (9.5 m), and bottom point (0.5 m) of the windward wall, as well as the average air temperature and relative humidity in the street canyon for two cases: (i) when the windward wall is initially wet, and (ii) when the windward wall is initially dry (Figures 11a-d). It can be seen that evaporative cooling results in a maximum drop of the wall surface temperature of 15°C at the top location(Figure 11a) and 13°C at the bottom location (Figure 11b) of the wall, during the first day of drying. The material at top and bottom is in its first drying phase, where water evaporates from the surface of the wall, and a lot of latent heat is extracted. On the second day the temperature difference at the top location (Figure 11a) is less because the wall at this location has reached the second drying phase, where the moisture front recedes into the material and therefore less energy is required for evaporation. The average air temperature in the street canyon (Figure 11c) is approx. 3°C lower in the case with the wet wall, due to evaporative cooling. The average relative humidity (Figure 11d) is approx. 15% higher, compared to the dry case, due to mixing of moisture evaporated from the wall with the air in the canyon.

Further we evaluate the effectiveness of evaporative cooling by studying the comfort conditions of a person standing in the street canyon. For this study, a 1.8 m tall person standing 1 m away from the windward wall is considered. To study the comfort of this person, we use the universal thermal climate index (UTCI) (Fiala et al, 2012). The parameters used for determining the UTCI are the air temperature, the vapor pressure, the wind speed and the mean radiant temperature.

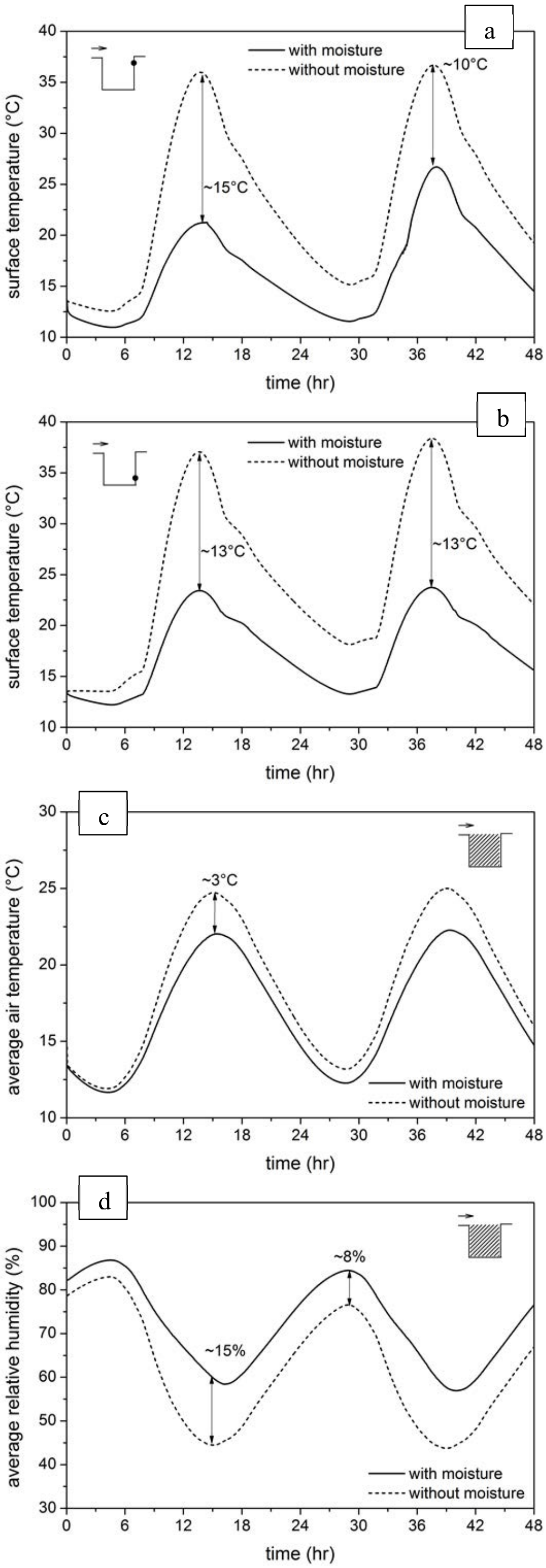


*Figure 12. Comparison of cases with and without moisture (a) surface temperature at the height of 9.5 m, (b) surface temperature at the height of 0.5 m on the windward wall, (c)average air temperature and (d) average relative humidity in the street canyon*

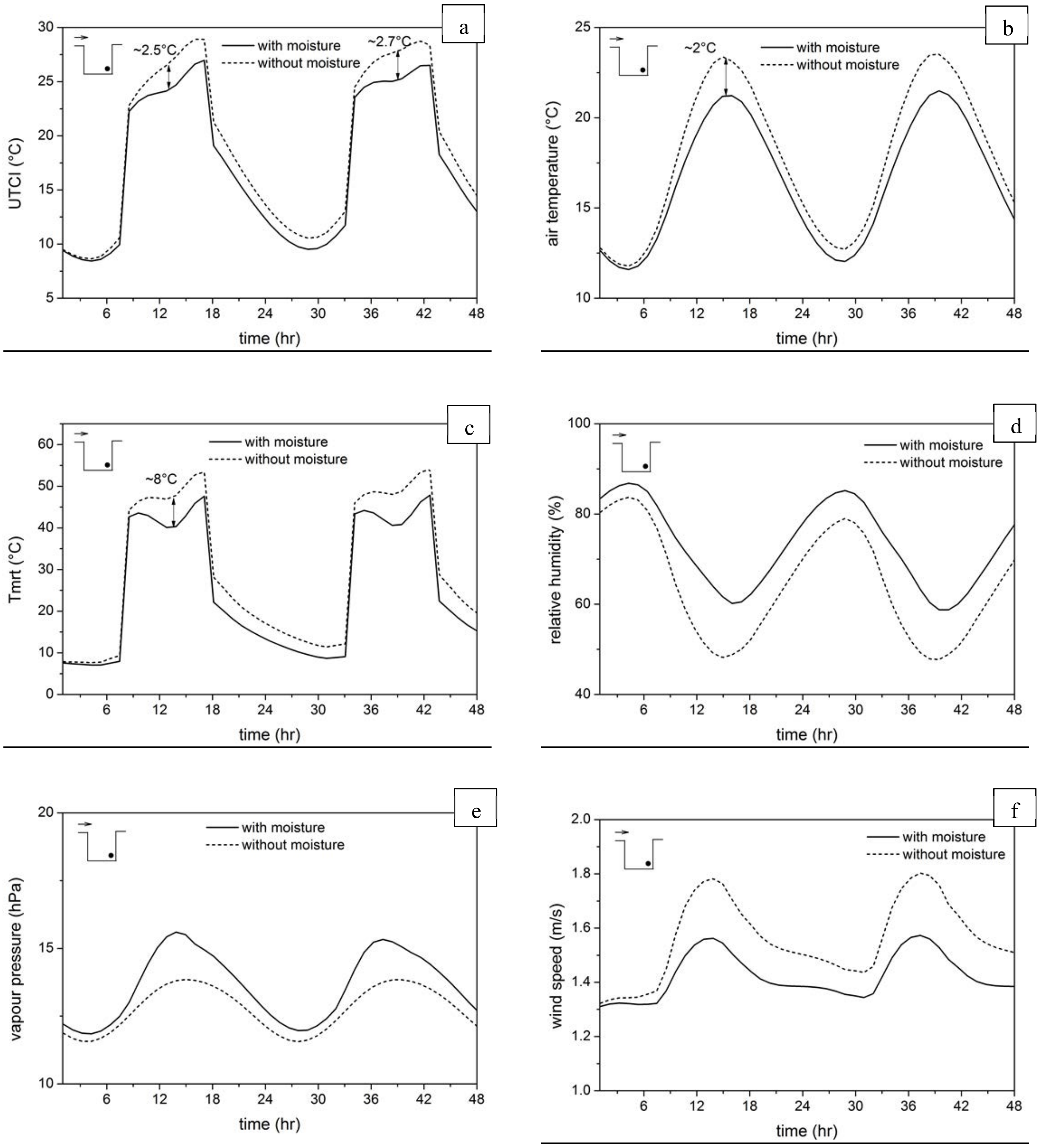


*Fig.12. Comparison of cases with and without moisture for a) UTCI b) air temperature c) mean radiant temperature d) vapour pressure e) relative humidity and f) wind speed, at the position of a person standing 1 m from the windward wall.*

Figure 12a shows the UTCI for a person standing 1 m away from the windward wall, for two cases, i.e. with and without evaporative cooling. It can be seen that the person can feel up to max. 2.5°C cooler during the warmest part of the day on the first day and 2.7°C on the second day due to evaporative cooling. To understand this phenomena better, we look at the four parameters which influence the UTCI at the studied location, being the air temperature, the mean radiant temperature ($T_{mrt}$), the vapour pressure (or RH), and the wind speed. The evolution of these parameters during the 48 hr drying, for cases with and without moisture, is shown in Figures 12b, c, d, e and f. It can be seen that for the case with moisture, the air temperature and $T_{mrt}$ at the studied location are approx. 2°C and 8°C lower in comparison to the case without moisture, respectively, while the vapor pressure is approx. 2 hPa (relative humidity approx. 15%) higher and the wind speed is approx. 0.3 m/s lower. Lower air temperature and radiant temperature due to evaporative cooling result in an improved thermal comfort, while a higher relative humidity and lower wind speed result in a lower thermal comfort. The more comfortable conditions during the second day is that some parts of the wall are already in the

second drying phase and dry slower, resulting in a lower vapor pressure in the street canyon.
Further a parametric study learns that the evaporative cooling is most effective when the wind speed is low, since in this case the removal of heat by wind is less efficient.

## CONCLUSIONS

An urban microclimate model is presented, which consists of an air flow model solved by CFD, a heat and moisture transport model taking into account evaporative cooling effects by porous urban surfaces, a radiation model taking into account solar and longwave radiation including multiple reflections and a building energy simulation model. For a detailed description of the this model and results describing the influence of the urban microclimate on the building energy we refer to our accompanying paper at this conference (Modelling the urban microclimate and its impact on the energy demand of buildings and building clusters). In this paper we first present wind tunnel results showing the effect of buoyancy on the air flow and temperature in a street canyon. These results are used to validate our CFD model. The results show that CFD can predict the general flow structures and the influence of buoyancy. The detailed flow field inside the street canyon is strongly dependent on the flow structure inside the shear layer at the top of the street canyon. Therefore to get accurate results for the flow profiles inside the street canyon, the flow inside the shear layer has to be predicted correctly. Then, the urban microclimate model is used to study the effect of evaporative cooling on thermal comfort in a street canyon. It is shown that evaporative cooling can enhance the thermal comfort at low wind speeds by cooling down the urban surfaces and the air in the street canyon. However, due to the evaporation the relative humidity of the air in the street canyon increases, which results in a lowering of the thermal comfort.

## ACKNOWLEDGEMENTS

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