The influence of evaporative cooling on the micro-climate and thermal comfort in a street canyon

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THE INFLUENCE OF EVAPORATIVE COOLING ON THE MICRO-CLIMATE AND THERMAL COMFORT IN A STREET CANYON

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To my parents, Homa and Davoud,
for their never ending love and support
Abstract

Due to global warming and the tendency towards urbanization, the Urban Heat Island Effect (UHI) is becoming more important in the recent years. The UHI refers to higher temperatures observed in the populated cities in comparison to their rural hinterland. The UHI will result in higher cooling demand by buildings in addition to more negative influence on human health and comfort. One of the proposed methods for mitigating the UHI is evaporative cooling. Evaporative cooling involves evaporation of moisture from a surface, a process which requires energy, and therefore results in lower air and surface temperatures. In an urban area, evaporation can occur from wet urban surfaces, urban ponds or lakes, vegetation, etc. In this thesis, the focus lies on evaporation from wet building surfaces, after a rain shower, and how evaporative cooling influences the conditions in the street canyon. To do this, a model is proposed which couples three individual sub-models: a Computational Fluid Dynamics model (CFD) which solves the convective heat, air and moisture transport in the air, a Building Envelope Heat and Moisture (BE-HAM) model which solves the heat and moisture transport within the porous material, and a radiation model (RAD) which solves the radiative balance for short-wave and long-wave radiative exchange between the building surfaces and the sky. The proposed coupled model is used to evaluate the effect of evaporative cooling in a street canyon. Influence of temperature and relative humidity of the environment, wind speed as well as the material, thickness, color and position of the wet surface, on the cooling potential of the street canyon are evaluated. The cooling potential is evaluated by studying the comfort of a human in a street canyon using the Universal Thermal Climate Index (UTCI). Our studies show that the thermal comfort in the street canyon is the lowest (UTCI is highest) when low wind speeds are experienced. Buoyancy near the windward wall results in entrapment of air in the canyon, less ventilation, hence more uncomfortable conditions. The evaporative cooling potential is found to be higher when wind speeds are low. Results also shows that during a heat wave, when uncomfortable conditions are experienced due to high temperature and relative humidity in the air, evaporative cooling is not as effective as during a hot summer day. This is due to the fact that evaporation results in a large increase of vapour pressure, which cancels out the evaporative cooling effect of lower air and mean radiant temperature.
Zusammenfassung

höher ist für tiefe Windgeschwindigkeiten. Die Resultate zeigen ausserdem, dass während einer Hitzewelle, bei der der Komfort wegen den hohen Temperaturen und hohen relativen Feuchtigkeit der Luft tief ist, die Verdunstungskühlung weniger effektiv ist als während eines heissen Sommertages. Der Grund dafür ist, dass die Verdunstung zu einer starken Zunahme der relativen Luftfeuchtigkeit führt, was zum Teil den Effekt der tieferen Luft- und mittleren Strahlungstemperaturen durch die Verdunstungskühlung aufhebt.
Résumé

Découlant du réchauffement climatique et de l’urbanisation croissante, le phénomène d’Îlot de Chaleur Urbain (ICU ou Urban Heat Island (UHI) effect en anglais) est devenu de plus en plus important au cours des dernières années. Le phénomène d’ICU se caractérise par des températures plus élevées en milieu urbain par rapport au milieu rural. L’ICU résultera en une demande accrue d’énergie de refroidissement et influencera négativement la santé et le confort des habitants. L’une des méthodes proposées pour en réduire ses effets est le refroidissement par évaporation, où l’énergie requise pour l’évaporation de l’humidité a pour effet d’abaisser la température de la surface humide. Dans un environnement urbain, l’évaporation peut avoir lieu à la surface des matériaux poreux, des étendues d’eau, en zone de végétation, etc. Cette thèse se concentre sur l’évaporation de l’humidité contenue dans les façades d’immeuble après un épisode de pluie et comment l’abaissement de la température influence les conditions environnementales dans les canyons urbains, i.e. dans les rues. Pour ce faire, un modèle couplant trois sous-modèles est proposé : un modèle CFD (Computational Fluid Dynamics) qui calcule le transport d’air et d’humidité ainsi que la conduction et la convection de chaleur dans l’air, un modèle BE-HAM (Building Envelope Heat and Moisture) qui calcule le transport d’humidité et de chaleur dans les matériaux poreux, et un modèle RAD (RADIation) qui calcule les échanges de chaleur par radiation, à ondes courtes ou longues entre les éléments urbains et le ciel. Le modèle proposé est utilisé pour évaluer les effets du refroidissement par évaporation dans un canyon urbain. L’influence de la température et de l’humidité relative de l’air ambiant, de la vitesse du vent ainsi que de l’épaisseur et de la couleur des matériaux, ainsi que la position des surfaces humides, est prise en compte dans l’évaluation du potentiel de refroidissement d’un canyon urbain. Le potentiel de refroidissement est évalué en utilisant l’indice UTCI (Universal Thermal Climate Index) pour quantifier le confort ressenti par un humain placé dans le canyon. Nos études montrent que le confort thermique dans le canyon urbain est au plus bas (i.e. UTCI est le plus élevé) lorsque les vitesses de vent sont faibles. La poussée d’Archimède près du mur qui fait face au vent tend à emprisonner l’air dans le canyon et donc à diminuer de ventilation, rendant les conditions inconfortables. Le potentiel de refroidissement par évaporation est jugé élevé lorsque la vitesse du vent est faible. Les résultats montrent également que, durant une vague de chaleur, lorsque les conditions inconfortables...
sont ressenties en raison de températures et d’humidité relative de l’air élevées, le refroidissement par évaporation n’est pas aussi efficace que lors d’une chaude journée d’été normale. Cela est dû au fait que l’évaporation augmente la pression de vapeur, et donc l’humidité relative, ce qui annule la réduction de température de l’air et de la température radiante moyenne qui résultent de l’évaporation.
Acknowledgments

Looking back at this dissertation, I remember many moments, some happy and exciting, some sad and discouraging. I remember many people, many new encounters, many new experiences, many emotions, some cries and many laughs. At the end, it leaves me with a smile on my face, and a feeling of satisfaction and happiness. I'm happy that I managed to successfully finish this work, I'm grateful for the things I learned during this time, about myself, others and life, and I'm lucky to have met many nice people during this time each of whom were a part of this experience. I would like to thank all of these people.

First and foremost, I would like to thank my promoter, professor Jan Carmeliet, for sharing his knowledge with me, providing me with the opportunity to do this research project and for always inspiring me to take new steps.

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I would like to thank the members of my examination committee, Bert Blocken, Peter Moonen and René Rossi, for critically reading my thesis and providing me with valuable comments.

This dissertation is a combination of modeling and experimental work, and I was fortunate enough to have helpful and knowledgeable people around me whose support I could always count on.

I would like to show my appreciation to everyone who helped and supported me with the Neutron measurements at PSI. Thanks to Eberhard Lehman, and Peter Vontobel of the neutron imaging group at PSI, for their support during the measurements. Thanks to Dominique Derome, Marjan Sedighi Gilani, Thijs Defraeye and Peter Moonen for their support and also helping me with the image processing.

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Many thanks goes to the helpful and kind technicians at EMPA, Roger Vonbank, Stephan Carl, Beat Margelisch, Rudi Blessing and Walter Trindler who kindly and
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I cannot be thankful enough to Switzerland, its people, its mountains, its lakes and rivers and its cows and sheeps. I'm so happy that I had a chance to live in this wonderful country and spend some of the most amazing times of my life in different spots of this land. During the hard time working on this thesis, even thinking about spending some time in this beautiful nature was encouraging for me.

Finally I would like to thank some special people, my parents, Homa and Davoud who always believed in me and provided me with love and support to follow my dreams, my sister, Sheyda who although from a long distance, was always there for me, and my boyfriend, Cristoffel who was always patient and understanding. Without their supports, this book would not have been written.
Nomenclature

Roman Symbols

$A$  
surface area (m$^2$)

$B$  
radiosity (J/m$^2$s)

$C$  
heat gained or lost by convection (W)

$C_\mu$  
empirical constant or variable

$c_b$  
blood specific heat capacity (J/Kkg)

$c_{p,a}$  
specific heat capacity of dry air (K/kgK)

$c_{p,g}$  
specific heat capacity of gaseous phase (K/kgK)

$c_{p,l}$  
specific heat capacity of liquid water (K/kgK)

$c_{p,s}$  
specific heat capacity of solid matrix (K/kgK)

$c_{p,v}$  
specific heat capacity of water vapour (K/kgK)

$c_p$  
specific heat capacity (J/kgK)

$D$  
number of days of the year since January 1

$d$  
characteristic length (m)

$D_T$  
thermal diffusion coefficient (kg/ms)

$D_{va,eff}$  
effective diffusion coefficient (m$^2$/s)

$D_{va,mat}$  
binary apparent diffusion coefficient between the dry air and water vapour in porous material (m$^2$/s)

$D_{va,t}$  
turbulent diffusion coefficient (m$^2$/s)

$D_{va}$  
binary diffusion coefficient (m$^2$/s)
$E$ energy of incident neutrons (meV)

$E_{diff}$ evaporative heat loss due to skin diffusion (W)

$E_{res}$ evaporative heat loss due to respiration (W)

$E_{sw}$ evaporative heat loss due to evaporation of sweat (W)

$ET$ equation of time (min)

$F$ view factor (-)

$F_{cs}$ heat flux from core to skin (W/m$^2$)

$f_p$ projected area factor (-)

$F_{sc}$ heat flux from skin through clothing to outer surface of the clothing (W/m$^2$)

$F_{ss}$ angle factor between surface and sky (-)

$G$ gebhart factor (-)

$g$ total mass flux (kg/m$^2$s)

$g_a$ mass flux of dry air (kg/m$^2$s)

$g_{c,s}$ convective mass flux at the surface (kg/m$^2$s)

$g_d$ diffusive mass flux (kg/m$^2$s)

$g_g$ mass flux of gaseous phase (kg/m$^2$s)

$g_l$ mass flux of liquid water (kg/m$^2$s)

$g_r$ gravitational acceleration (9.8 m/s$^2$)

$g_v$ mass flux of water vapour (kg/m$^2$s)

$H$ hour angle (°)

$H$ street canyon height

$h_a$ enthalpy of dry air (J/kg$\_a$)

$h_{ref}$ reference height (m)

$h_v$ enthalpy of water vapour (J/kg$\_v$)

$I$ intensity of neutron beam (1/m$^2$s)

$I$ identity matrix
\( I_{\text{dif}} \)  solar radiation intensity flux coming from the other surfaces (W/m\(^2\))
\( I_{\text{dir}} \)  solar radiation intensity flux coming from the sun (W/m\(^2\))
\( I_{DN} \)  direct normal short-wave radiation intensity flux (W/m\(^2\))
\( I_t \)  total short-wave radiative flux (W/m\(^2\))
\( I_t \)  turbulence intensity (%)
\( k \)  turbulent kinetic energy (m\(^2\)/s\(^2\))
\( K_l \)  liquid permeability (s)
\( K_t \)  total permeability (s)
\( K_v \)  water vapour permeability (s)
\( L \)  latitude (°)
\( L \)  street canyon length
\( L \)  thermal load on the human body (kcal/m\(^2\)hr)
\( l_{cl} \)  heat resistance of clothing (Km\(^2\)/W)
\( L_L \)  local longitude (°)
\( L_S \)  standard meridian (°)
\( L_v \)  latent heat of evaporation (2.5x10\(^6\) J/kg)
\( M \)  metabolic rate (W)
\( n \)  total number of specimen
\( P(E) \)  Maxwell-Boltzmann probability density function for the energy of particles in a classical gas
\( P_{\text{atm}} \)  atmospheric pressure (101325 Pa)
\( p_a \)  partial pressure of dry air (Pa)
\( p_c \)  capillary pressure (Pa)
\( p_g \)  pressure of gaseous phase (Pa)
\( p_l \)  pressure of liquid water (Pa)
\( p_{v,\text{sat}} \)  saturation vapour pressure (Pa)
\( p_v \)  partial pressure of water vapour (Pa)
$Pr_t$  
- turbulent Prandtl number (-)

$q$  
- conductive heat flux (J/m$^2$s)

$Q_A$  
- net advected heat flux in urban street canyon (W)

$Q_{dif,s}$  
- short-wave radiative flux, coming from the other surfaces (W)

$Q_{dir,s}$  
- short-wave radiative flux, coming from the sun (W)

$Q_d$  
- diffused mass flux between the street canyon and the air above (kg/m.s)

$Q_E$  
- net sensible heat flux in urban street canyon (W)

$Q_e$  
- exchange flux between the street canyon and the air above (m$^3$/s)

$Q_H$  
- net latent heat flux in urban street canyon (W)

$Q_l$  
- long-wave radiative flux (W)

$ql$  
- long-wave radiation intensity (J/m$^2$s)

$Q_r$  
- net radiative heat flux in urban street canyon (W)

$q_{rad}$  
- total radiative heat flux (J/m$^2$s)

$Q_s$  
- net stored energy in urban materials (W)

$q_s$  
- combined convective and conductive heat at the surface (J/m$^2$s)

$Q_T$  
- anthropogenic heat flux in urban street canyon (W)

$q_{tot}$  
- total heat flux (J/m$^2$s)

$R$  
- universal gas constant (8.31451 J/molK)

$Ra$  
- specific gas constant of dry air (287.044 J/KgK)

$R_g$  
- specific gas constant of the mixture (287.044 J/KgK)

$R_{s,l}$  
- heat gained or lost by radiation (W)

$R_v$  
- specific gas constant of water vapour (461.524 J/KgK)

$Ri$  
- Richardson number (-)

$S$  
- rate of heating or cooling (W)

$S_l$  
- liquid saturation (%) 

$Sc_t$  
- turbulent Schmidt number (-)

$ST$  
- noon-based local solar time (min)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW</td>
<td>sweat rate (kg/m²s)</td>
</tr>
<tr>
<td>T</td>
<td>absolute temperature (K)</td>
</tr>
<tr>
<td>t</td>
<td>time (s)</td>
</tr>
<tr>
<td>Ta</td>
<td>air temperature (°C)</td>
</tr>
<tr>
<td>Tcl</td>
<td>clothing surface temperature (°C)</td>
</tr>
<tr>
<td>Tc</td>
<td>core temperature (°C)</td>
</tr>
<tr>
<td>Tin</td>
<td>internal time scale (s)</td>
</tr>
<tr>
<td>Tmrt</td>
<td>mean radiant temperature (°C)</td>
</tr>
<tr>
<td>Tref,0</td>
<td>reference temperature for the definition of enthalpy (273.15 K)</td>
</tr>
<tr>
<td>Tref</td>
<td>reference temperature (K)</td>
</tr>
<tr>
<td>Tsk</td>
<td>mean skin temperature (°C)</td>
</tr>
<tr>
<td>Ts</td>
<td>temperature at the surface (K)</td>
</tr>
<tr>
<td>Tumrt</td>
<td>mean radiant temperature resulting from long-wave radiative exchanges (°C)</td>
</tr>
<tr>
<td>U</td>
<td>mean horizontal wind speed (m/s)</td>
</tr>
<tr>
<td>u</td>
<td>streamwise (x) component of velocity vector (m/s)</td>
</tr>
<tr>
<td>u⁺</td>
<td>dimensionless mean air speed (-)</td>
</tr>
<tr>
<td>ur,ABL</td>
<td>ABL friction velocity (m/s)</td>
</tr>
<tr>
<td>uc</td>
<td>uncertainty on the mean wind speed (%)</td>
</tr>
<tr>
<td>uref</td>
<td>horizontal wind speed at the reference height (m/s)</td>
</tr>
<tr>
<td>V</td>
<td>total volume of the porous material (m³)</td>
</tr>
<tr>
<td>va</td>
<td>velocity of dry air (m/s)</td>
</tr>
<tr>
<td>Vave</td>
<td>average velocity magnitude in all samples (m/s)</td>
</tr>
<tr>
<td>vb</td>
<td>blood flow from the body core to the skin (l/sm²)</td>
</tr>
<tr>
<td>vg</td>
<td>velocity of gaseous phase (m/s)</td>
</tr>
<tr>
<td>Vi</td>
<td>velocity magnitude of iᵗʰ sample (m/s)</td>
</tr>
<tr>
<td>vl</td>
<td>velocity of liquid water (m/s)</td>
</tr>
</tbody>
</table>
\( V_{pore} \) volume of the open pores \((m^3)\)

\( V_{RMS} \) standard deviation of the velocity magnitude (-)

\( v_v \) velocity of water vapour \((m/s)\)

\( W \) physical work output \((W)\)

\( W \) street canyon width

\( w \) moisture content of the porous material \((kg/m^3)\)

\( w_0 \) initial moisture content \((kg/m^3)\)

\( w_a \) dry air content \((kg/m^3)\)

\( w_{cap} \) capillary moisture content \((kg/m^3)\)

\( w_{crit} \) critical moisture content \((kg/m^3)\)

\( w_g \) moist air content \((kg/m^3)\)

\( w_{ini} \) initial moisture content \((kg/m^3)\)

\( w_l \) liquid water content \((kg/m^3)\)

\( w_v \) water vapour content \((kg/m^3)\)

\( x_a \) mass fraction of dry air \((Kg_{a}/Kg_g)\)

\( x_v \) mass fraction of water vapour \((Kg_v/Kg_g)\)

\( y \) coordinate in lateral \((y)\) direction \((m)\)

\( y^+ \) dimensionless wall distance (-)

\( z_0 \) aerodynamic roughness length \((m)\)

\( z_B \) thickness of brick specimen \((m)\)

\( z_W \) thickness of water layer \((m)\)

**Greek Symbols**

\( \alpha \) absorptance (-)

\( \alpha_p \) clothed human body absorptance (-)

\( \beta \) \( R_v T \)

\( \beta \) solar altitude \((^\circ)\)

\( \beta_t \) volumetric thermal expansion coefficient \((1/K)\)
\( \gamma \) normalized derivative of the surface tension to the temperature
\( \delta \) declination angle (\(^\circ\))
\( \delta_a \) water vapour diffusion coefficient (s)
\( \delta_v \) water vapour diffusion coefficient in porous material (s)
\( \varepsilon \) emissivity for long-wave radiation (-)
\( \varepsilon \) turbulence dissipation rate (-)
\( \varepsilon(E) \) an energy sensitivity parameter for each pixel of the scintillator
\( \varepsilon_p \) human body emissivity (-)
\( \varepsilon_s \) emissivity for short-wave radiation (albedo) (-)
\( \theta \) incidence angle (\(^\circ\))
\( \kappa \) von Karman constant (0.4187(-))
\( \lambda \) air conductivity (0.0242 W/mK)
\( \lambda \) thermal conductivity of the porous material (W/mK)
\( \lambda_{eff} \) effective thermal conductivity (W/mK)
\( \lambda_g \) thermal conductivity of the gasous phase (W/mK)
\( \lambda_t \) turbulent thermal conductivity (W/mK)
\( \mu \) attenuation coefficient (1/m)
\( \mu \) dynamic viscosity (kg/ms)
\( \mu_{dry} \) vapour resistance factor of dry material (-)
\( \mu_p \) vapour resistance factor of the porous material (-)
\( \mu_t \) turbulent viscosity (kg/ms)
\( \rho \) density (kg/m\(^3\))
\( \rho \) reflectivity (-)
\( \rho_a \) dry air density (kg/m\(^3\))
\( \rho_{bl} \) blood density (kg/l)
\( \rho_b \) bulk density (kg/m\(^3\))
\( \rho_g \) gas density (kg/m\(^3\))
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_l$</td>
<td>liquid water density (kg/m$^3$)</td>
</tr>
<tr>
<td>$\rho_v$</td>
<td>water vapour density (kg/m$^3$)</td>
</tr>
<tr>
<td>$\Sigma$</td>
<td>tilt angle (°)</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Stefan-Boltzmann constant ($5.67 \times 10^{-8}$ W/m$^2$K$^4$)</td>
</tr>
<tr>
<td>$\tau$</td>
<td>transmittance (-)</td>
</tr>
<tr>
<td>$\tau$</td>
<td>tortuosity (-)</td>
</tr>
<tr>
<td>$\tau_w$</td>
<td>wall shear stress (Pa)</td>
</tr>
<tr>
<td>$\nu$</td>
<td>kinematic viscosity (m$^2$/s)</td>
</tr>
<tr>
<td>$\phi$</td>
<td>relative humidity (%)</td>
</tr>
<tr>
<td>$\phi$</td>
<td>solar azimuth (°)</td>
</tr>
<tr>
<td>$\phi_{0,l}$</td>
<td>open porosity occupied by liquid water (%)</td>
</tr>
<tr>
<td>$\phi_0$</td>
<td>open porosity (%)</td>
</tr>
<tr>
<td>$\psi$</td>
<td>azimuth (°)</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>perimeter of the porous surface (2H+W)</td>
</tr>
<tr>
<td>$\omega$</td>
<td>specific dissipation rate (1/s)</td>
</tr>
</tbody>
</table>

**Subscripts**

<table>
<thead>
<tr>
<th>Subscript</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>initial state</td>
</tr>
<tr>
<td>a</td>
<td>dry air</td>
</tr>
<tr>
<td>B</td>
<td>brick specimen</td>
</tr>
<tr>
<td>c</td>
<td>convective</td>
</tr>
<tr>
<td>cl</td>
<td>centre line</td>
</tr>
<tr>
<td>d</td>
<td>diffusive</td>
</tr>
<tr>
<td>dif</td>
<td>diffused</td>
</tr>
<tr>
<td>dir</td>
<td>direct</td>
</tr>
<tr>
<td>e</td>
<td>above the street canyon</td>
</tr>
<tr>
<td>eff</td>
<td>effective</td>
</tr>
<tr>
<td>g</td>
<td>gas</td>
</tr>
</tbody>
</table>
gr  ground
i  inside the street canyon
l  liquid water
lw  leeward wall
ref  reference location
s  short-wave
s  solid
s  surface
TS  test setup
W  water
w  water vapour
ww  windward wall

**Acronyms**

ABL  atmospheric boundary layer
ACH  air change rate (1/h)
BE-HAM  building envelope heat and moisture
CB  ceramic brick
CFD  computational fluid dynamics
CHTC  convective heat transfer coefficient
CMTC  convective mass transfer coefficient
CMTC*  equivalent CMTC
CS  calcium silicate
DEHS  Di-Ethyl-Hexyl-Sebacat
DNS  direct numerical simulation
ET*  effective temperature
FFT  fast fourier transformation
FP  flat plate
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>HW</td>
<td>heat wave</td>
</tr>
<tr>
<td>IA</td>
<td>interrogation area</td>
</tr>
<tr>
<td>LES</td>
<td>large-eddy simulation</td>
</tr>
<tr>
<td>LRNM</td>
<td>low Reynolds number modeling</td>
</tr>
<tr>
<td>MEMI</td>
<td>Munich energy-balance model for individuals</td>
</tr>
<tr>
<td>MET</td>
<td>metabolic rate</td>
</tr>
<tr>
<td>MP</td>
<td>mineral plaster</td>
</tr>
<tr>
<td>NEUTRA</td>
<td>neutron transmission radiography</td>
</tr>
<tr>
<td>OUT-SET*</td>
<td>standard effective temperature for outdoor environment</td>
</tr>
<tr>
<td>PET</td>
<td>physiological equivalent temperature</td>
</tr>
<tr>
<td>PIV</td>
<td>particle imaging velocimetry</td>
</tr>
<tr>
<td>PMMA</td>
<td>polymethyl methacrylate</td>
</tr>
<tr>
<td>PMV</td>
<td>predicted mean vote</td>
</tr>
<tr>
<td>PPD</td>
<td>predicted percentage of dissatisfied</td>
</tr>
<tr>
<td>PSI</td>
<td>Paul Scherrer institute</td>
</tr>
<tr>
<td>PT</td>
<td>perceived temperature</td>
</tr>
<tr>
<td>QNI</td>
<td>quantitative neutron imaging</td>
</tr>
<tr>
<td>RAD</td>
<td>radiation model</td>
</tr>
<tr>
<td>RANS</td>
<td>Reynolds-averaged Navier-Stokes</td>
</tr>
<tr>
<td>RH</td>
<td>relative humidity</td>
</tr>
<tr>
<td>RMS</td>
<td>root mean square</td>
</tr>
<tr>
<td>SC</td>
<td>street canyon</td>
</tr>
<tr>
<td>SET*</td>
<td>standard effective temperature</td>
</tr>
<tr>
<td>SIMPLE</td>
<td>semi-implicit method for pressure linked equations</td>
</tr>
<tr>
<td>SINQ</td>
<td>swiss neutron spallation source</td>
</tr>
<tr>
<td>TMY</td>
<td>typical meteorological year</td>
</tr>
<tr>
<td>UHI</td>
<td>urban heat island</td>
</tr>
<tr>
<td>UTCI</td>
<td>universal thermal climate index</td>
</tr>
<tr>
<td>XPS</td>
<td>extruded polystyrene</td>
</tr>
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Chapter 1

Introduction

1.1 Background

Climate change and the increasing trend towards urbanization, result in an increase in temperature of the urbanized areas. According to United Nations (2010), as of 2010, more than half of the world's population is living in towns or cities (Moonen et al., 2012). This increasing trend towards urbanization results in growth and densification of the cities. This phenomenon leads to an increase in the air temperature in the densely built urban areas in comparison to the surrounding rural hinterland. This phenomenon is called “urban heat island”. Other causes for the urban heat island are (Oke et al., 1991):

- lower long-wave radiation losses from the street canyon to the sky due to the specific geometry of the street canyons and blockage of infrared radiation emitted from surfaces,

- increased use of materials such as brick, concrete or asphalt with high thermal capacity, which store more sensible heat during the day and release it back to the environment at night,

- increased use of dark colored materials with low albedo, which absorb more radiation and reflect less,

- decreased use of natural soil, bodies of water or vegetation, to take advantage of their evaporation and transpiration abilities,

- increase of anthropogenic heat production due to increase in the number of automobiles and combustion systems,

- decrease of convective transfer of heat, specially during night from the surfaces of the street canyon due to lower wind speeds,
• increase of pollutants produced in urban areas (due to transportation, industry, etc.). High concentration of pollutants leads to an increase in the trapped long-wave radiation.

In warm and moderate-climate regions, the urban heat island and global warming, can affect the energy demand for cooling in urban areas, as well as health and comfort of its inhabitants. Measurements taken at approx. 30 urban and suburban areas as well as in 10 urban street canyons in Athens, showed a doubling of the cooling load and tripling of the peak electricity load for cooling (Santamouris, 2001). In addition to affecting energy demand, increased air temperatures in urban areas lead to heat stress, which in addition to causing discomfort, results in reduced mental and physical performance, as well as physiological and behavioral change (Evans, 1982).

In addition to the resulting urban heat island effect, a lot of research has been directed towards its mitigation. Some of the suggested methods are: use of materials with higher albedo (bright colored materials), reduction of anthropogenic heat release, control of urban pollution, taking advantage of evaporative cooling, modification of thermal capacity of surface materials, modification of urban geometry, and introduction of shading canopies. In this thesis, we focus on the methods which make use of evaporative cooling, for which examples such as ground-level water surfaces (Krueger and Pearson, 2008) and roof ponds (Runsheng et al., 2003; Tiwari et al., 1982), surfaces wetted by wind-driven rain (Blocken, Roels, and Carmeliet, 2007), and vegetated surfaces (Alexandri and Jones, 2008), can be mentioned. Studies by Dimoudi and Nikolopoulou (2003) show that an increase of 10% of the ratio of green to building area for specific studied urban configurations, can result in a reduction of 0.8 K in the ambient air temperature. Huang et al. (1987) show that an additional 25% increase in tree cover of an urban area can save up to 40% of the annual cooling energy demand of an average residential house in Sacramento, US.

In the past, a number of researchers have developed models in order to analyze
the urban environment and to evaluate its energy budget. Most of these models capture the main phenomena, but they introduce several assumptions to simplify the problem and to reduce the computational cost. These assumptions may neglect some phenomena, which can have an important influence on the effects of evaporative cooling. Some of these models do not accurately model the convective heat exchange between the urban surfaces and the air, by either using a global convective transfer coefficient for an entire wall surface or by simply relating the convective transfer coefficient to a reference wind speed (Arnfield and Grimmond, 1998; Arnfield, 2000; Mills, 1993; Terjung and O’rourke, 1980; Terjung and Louie, 1974). While some models do not include moisture and the influence of latent heat of evaporation on the heat flux (Arnfield and Grimmond, 1998; Arnfield, 2000; Mills, 1997), some others do not clearly specify the amount of moisture exchange between the air and the porous surfaces (Chen et al., 2004). A computationally expensive part of urban canopy modelling is modelling the air flow around the buildings and in the urban space. Therefore some models avoid CFD (computational fluid dynamics) simulations and use either simplified models (Arnfield, 2000; Mills, 1993) or “attenuation factors” for the above canyon wind speed, to obtain the air conditions in the canyon (Arnfield and Grimmond, 1998). Also most of the models do not consider radiation.

1.2 Scope and methodology

Knowing the limitations of existing models, in this thesis we develop a coupled model capable to investigate how the local wind flow pattern induces non-uniform drying of the urban surfaces, and how this drying results in a modification of the local microclimate and the thermal comfort in the street canyon. The model takes into account the influence of direct short-wave radiation, long-wave radiative exchange between the urban surfaces and the sky (including multiple reflections and buoyancy), the effect of latent heat of evaporation, and material properties.

The proposed model consists of three sub-models. A computational fluid dynamics model (CFD) which solves the convective heat, air and moisture transport in the air, a Building Envelope Heat and Moisture (BE-HAM) model which solves the heat and moisture transport within the porous materials, and a radiation model (RAD) which solves the radiative balance for short-wave and long-wave radiative exchange between the building surfaces and the sky. The model is supplemented by a comfort model to evaluate the comfort of a pedestrian in the street canyon.

The way and frequency by which these three sub-models interact and exchange information is critical. The information has to be exchanged between the models frequently enough to produce accurate results, although very frequent exchange of data increases the cost of computation. For this purpose, the exchange time step size which provides a good trade-off between accuracy and computation cost needs to be determined by means of a sensitivity study.
1.3 Outline

This thesis consists of 7 chapters. Chapter 2 reviews the state of the art regarding urban street canyons, convective heat and mass transfer coefficients, convective drying of porous materials, and human comfort. In Chapter 3, the coupled model including the individual sub-models and constitutive equations are introduced, and the coupling strategy is discussed. In Chapter 4, the proposed coupled model is used to analyse the drying behavior of two ceramic brick specimens, and the simulation results are compared with experimental results. Similarities and differences between the two cases are discussed. In Chapter 5, the proposed coupled model is applied to case studies and the effectiveness of various factors on the evaporative cooling potential of a street canyon is quantified. Chapter 6 includes a general discussion about the findings of this thesis, and recommendations for future research, as well as a summary of the conclusions of this thesis.
Chapter 2

State of the art

2.1 Introduction

In this chapter, the state of the art about different topics covered in this thesis is given. It starts with an introduction to urban street canyons, their energy budget, and the air flow in and above them. Next, definitions of the convective heat and mass transfer coefficients are given, the methods used for calculating them are explained and their shortcomings are discussed. We then look at the phenomenon of convective drying of a wet porous material. Finally the human comfort topic is covered, providing details about human physiological modelling and the existing indices for studying human comfort.

2.2 Urban Street Canyon

2.2.1 Urban boundary layer and urban canopy layer

The boundary layer above an urban setting can be divided into two main regions: an urban canopy layer (UCL) and an urban boundary layer (UBL) (Oke, 1988) (Fig. 2.1). The UCL is the air space between the individual urban roughness elements, i.e. the buildings, up to the roof height. In this thesis a single urban street canyon of the urban canopy is modelled in detail. The UCL is modelled at microscale and its climate is mainly affected by the immediate surroundings, materials, geometries and exchange of air between street canyon and UBL. The UBL is situated directly above the UCL. Its climate is affected by the conditions of the urban area below it. In this thesis, we focus on the UCL, although we are also interested to understand the interactions and exchanges between the two layers.
2.2.2 Energy budget

In an urban environment, there is a balance between energy gains and energy losses (Fig. 2.2). This energy balance can be written as:

$$Q_r + Q_T = Q_E + Q_H + Q_s + Q_A$$

(2.1)

where $Q_r$ is the net radiative flux, $Q_T$ is the anthropogenic heat flux, $Q_E$ is the net sensible heat flux, $Q_H$ is the net latent heat flux, $Q_s$ is the stored energy in urban materials and $Q_A$ is the net energy transferred to or from the street canyon through advection in the form of sensible or latent heat (Santamouris, 2001).

Figure 2.1: Schematic representation of the urban atmosphere illustrating a two-layer classification of thermal modification (Oke, 1988)

Figure 2.2: Schematic representation of the energy budget of an urban canopy (Oke, 1988)
Studies show that the radiative flux, being an important term, is higher in rural areas in comparison to suburban areas. Also night losses are much higher in rural areas, and compensate for daytime gains (Santamouris, 2001; Cleugh and Oke, 1986).

### 2.2.3 Air flow in an urban street canyon

Air flow in an urban street canyon can be different from the air flow around an isolated building. It is very important to know about the specific flow pattern in an urban street canyon for the purpose of ventilation, pollutant dispersion or comfort studies in an urban environment.

A rectangular street canyon can be characterized by its height (H), width (W) and length (L). Combinations of these three parameters can create various street canyon configurations, each of which can have their specific flow pattern. Oke (1988) has defined three categories of flow regimes over arrays of buildings, when the wind direction is perpendicular to the long axis of the street canyon (Fig. 2.3). When the buildings are far apart (H/W>0.5), the flow fields around the buildings do not interact (Fig. 2.3a). As the spacing gets less, 'isolated roughness flow' occurs which is when the wakes become disturbed. 'Wake interference flow' is when the combination of height and spacing of the building arrays disturbs the cavity eddies. A secondary flow forms in the canyon, when the downward flow of the eddy is reinforced by the reflection down the windward face of the next building downstream (Fig. 2.3b). 'Skimming flow' occurs at large H/W, when a stable circular vortex is established in the canyon (Fig. 2.3c). In this regime, the bulk of the flow does not enter the canyon.

![Flow regimes](image-url)
2.3 Convective heat and mass transfer at air-material interface

2.3.1 Convective heat transfer coefficient

The combined convective and conductive heat exchange \( q_\text{s} \) \((J/m^2s)\)) between the air and a surface can be expressed as:

\[
q_\text{s} = CHTC(T_s - T_{\text{ref}})
\]  

(2.2)

where \( T_s \) (K) is the temperature at the surface, \( T_{\text{ref}} \) (K) is the temperature at the reference location, and \( CHTC \) (W/m\(^2\)K) is the convective heat transfer coefficient.

The value of the \( CHTC \) strongly depends on the flow regime. Based on the Richardson number \( (Ri) \), thermal convection can be subdivided into regimes of natural \((Ri<1)\) and forced convection \((Ri>1)\). The Richardson number is defined as:

\[
Ri = \frac{g_r \beta_t (T_s - T_{\text{ref}}) d}{U^2}
\]  

(2.3)

where \( g_r \) is the gravitational acceleration \((9.8 \text{ m/s}^2)\), \( \beta_t \) is the volumetric thermal expansion coefficient \((0.00343 \text{ 1/K})\), \( U \) \((\text{m/s})\) is the reference velocity, and \( d \) \((\text{m})\) is the characteristic length.

For forced convective flow regimes \((Ri>1)\), the \( CHTC \) is usually correlated to the wind speed at a reference location by means of a power-law correlation. These correlations have been derived from wind-tunnel experiments on flat plates or wall-mounted bluff bodies, or from full-scale experiments on specific building surfaces. An overview is given in Palyvos (2008) and Defraeye et al. (2011). Many of the existing correlations only consider a single \( CHTC \) value for each surface and do not take into account the spatial distribution over the surface.

Another method for obtaining the \( CHTC \) is by means of Computational Fluid Dynamics (CFD) modelling, which allows to obtain high spatial resolution data, as well as to consider high Reynolds number flow \((Re = 10^5-10^7)\) occurring in the atmospheric boundary layer. CFD studies in the field of building aerodynamics have been conducted using steady Reynolds-averaged Navier-Stokes (RANS) simulations, and usually employ wall functions to model the boundary layer at the wall surface (Emmel et al., 2007), where the flow quantities close to the wall are modelled by means of semi-empirical functions rather than being resolved explicitly. Other approaches, such as Unsteady RANS (URANS), Detached-Eddy Simulations (DES) and Large-Eddy Simulations (LES) (which will be explained in more detail in Sec. 3.2.2.4), have been applied as well, but are computationally more demanding (Liu and Barth, 2002).
For boundary layer modelling, it has been shown that for a stand alone building, the wall function approach is less accurate for determining the \( CHTC \) than Low-Reynolds Number Modelling (LRNM), where the boundary layer is resolved entirely all the way to the wall and the influence of the wall on turbulence is modelled. Wall functions can lead to errors of more than 40% (Blocken et al., 2009; Defraeye et al., 2010). Therefore, for determining \( CHTCs \), LRNM is preferred over wall functions.

Basically the \( CHTC \) concept is a simplified way to represent a complex heat transfer problem at the boundary layer. The \( CHTC \) is affected not only by the magnitude of the wind speed close to the surface, but also by the roughness of the surface and the turbulence level. Since these factors can change in space and time, the \( CHTC \) is not constant in space and time either. As an example, Fig 2.4 shows the variation of the \( CHTCs \) along the windward and leeward walls of a street canyon, for different reference wind speeds, where the reference location is chosen at the inlet of the domain. These results are obtained by means of CFD simulations. The walls are at 21°C while the incoming air is at 20°C. Due to the specific flow pattern in the street canyon, the local air speed varies along the wall, causing a variation in the \( CHTC \). As can be seen, the top of the windward wall has higher values of the \( CHTC \) than the bottom part. Also the middle section of the leeward wall has higher \( CHTC \) values. This is related to the specific flow field as well as the distribution of turbulent kinetic energy in the street canyon (Fig. 2.5), which influences the amount of heat exchanged between the wall surface and the street canyon (heat flux) and therefore the \( CHTC \).

The choice of the reference location is a critical factor in the calculation of the \( CHTC \). As an illustration, Figs. 2.6 and 2.7 show the \( CHTCs \) along the walls of a street canyon for mixed convective conditions, including forced and buoyant cases \((Ri = 0.03 \text{ to } 1.6)\), calculated using CFD. The windward wall of the street canyon is heated to different higher surface temperatures, \( \Delta T \), while the ground and leeward wall have a temperature of 21°C. Eight temperature differences between incoming air

![Figure 2.4: CHTC along the height of the a) windward wall and b) leeward wall, for various wind speeds](image-url)
CHAPTER 2. STATE OF THE ART

![Velocity and turbulent kinetic energy field in the street canyon](image)

**Figure 2.5:** Velocity and turbulent kinetic energy field in the street canyon

and the windward wall are considered, ranging from 1 to 60°C. For the calculation of the Richardson number, the domain inlet is chosen as the reference location for air temperature, the inlet velocity at 10 m height is the reference velocity, and the characteristic length is chosen as the height (H) of the street canyon (10 m).

![Variation of the CHTC along the surfaces of a street canyon for cases with the temperature at the inlet taken as reference](image)

**Figure 2.6:** Variation of the CHTC along the surfaces of a street canyon for cases with the temperature at the inlet taken as reference
2.3. CONVECTIVE HEAT AND MASS TRANSFER AT AIR-MATERIAL INTERFACE

The incoming air has a velocity of 3.5 m/s at 10 m height and a uniform temperature of 20°C. For calculating \( CHTC \), Eq. 2.2 is used where the heat flux at the wall is obtained from the CFD simulation. To study the effect of choice of reference location on the \( CHTC \), two different reference temperatures are chosen: i) the temperature of the incoming air, at the inlet of the domain (Fig. 2.6) and ii) the average temperature in the street canyon (Fig. 2.7). The dashed curve in Figs. 2.6 and 2.7 shows the limit case for purely forced convection (i.e. buoyancy is not considered). It is seen that forced convection is dominant for temperature differences below 10°C \( (Ri < 0.3) \) when the reference is the inlet and for temperature differences below 8.5°C \( (Ri < 4.56) \) when the reference is the average conditions in the street canyon. For larger temperature differences, buoyant effects become important. A number of observations can be made:

i) For the forced convective regime, the \( CHTC \) curves for the heated wall have a similar distribution and a single correlation for the \( CHTC \) can be established.

ii) For the non-heated surfaces (here being the ground and the leeward wall), the \( CHTC \) profiles do not coalesce in a single curve and no single correlation for the \( CHTC \) can be determined.

iii) When choosing a more local reference location, e.g. the average temperature in the street canyon, the spread in the \( CHTC \) profiles does not become smaller.

4) For all surfaces, the \( CHTC \)'s vary significantly depending on the location and adopting a single \( CHTC \) value for each surface is therefore less appropriate.

As a consequence, we may expect that the local \( CHTC \) will change continuously in time when the surface temperature and the local air flow conditions change, for
example when a wall is heated by the sun. Given the unsteady nature of the wind flow especially in the street canyon (e.g., diurnal variation), and knowing that, depending on the boundary conditions, the heat and moisture distribution in a street canyon can vary over time, choosing one surface-averaged CHTC, or one single CHTC profile, applicable to all cases and all moments in time is unrealistic. In Defraeye (2011) the same conclusion was drawn for a stand-alone building.

2.3.2 Convective mass transfer coefficient

Convective moisture transfer results from moist air movement. In analogy with heat transfer, the convective mass (moisture) flux at a surface \( g_{c,s} (kg/m^2s) \) can be written as:

\[
g_{c,s} = CMTC (p_{v,s} - p_{v,ref})
\]

where \( p_{v,s} \) is the vapour pressure at the surface, \( p_{v,ref} \) is the reference vapour pressure, and \( CMTC \) (s/m) is the convective mass transfer coefficient.

The discussion made about the CHTC in the previous section is also applicable to the CMTC. Similar to the CHTC, the CMTC is also affected by the wind speed and the turbulence level close to the surface. Therefore the CMTC is not necessarily constant in space and time either.

The CMTC is often calculated from the CHTC using the Chilton-Colburn analogy (Chilton and Colburn, 1934):

\[
CMTC = CHTC \left[ \frac{\delta_a}{\lambda} \right]^{(2/3)} \left[ \frac{1}{R_v T c_{p,a} \rho_a} \right]^{(1/3)}
\]

where \( \delta_a \) is the water vapour diffusion coefficient \((1.87 \times 10^{-10} \text{ s})\), \( \lambda \) is the air conductivity \((0.0242 \text{ W/mK})\), \( R_v \) is the specific gas constant of water vapour \((461.524 \text{ J/kgK})\), \( T \) is the reference temperature \((293.15 \text{ K})\), \( c_{p,a} \) is the heat capacity of air \((1006 \text{ J/kgK})\), and \( \rho_a \) is the density of air \((1.225 \text{ kg/m}^3)\).

2.3.3 Convective drying at the surface of a wet porous material

In this section, we describe the convective drying process at the surface of a wet porous material. Fig. 2.8 shows the typical drying process of a point on the surface of a wet porous material as a function of time.

At the beginning of the drying process, the material initially experiences a large surface temperature drop followed by a period of constant surface temperature. This regime, also characterized by a constant relative humidity of approximately 100% at the surface and a constant drying rate, is called the first drying phase. In the first drying phase, the liquid transport from inside the material to the surface is sufficiently
fast so that a relative humidity of approx. 100% is maintained at the surface. As evaporation occurs at the air-porous material interface, the drying rate is governed by the boundary conditions and not by the material properties. Nevertheless, the material properties do affect the length of the first drying phase, since this duration is dependent on the liquid transport to the surface. When the material starts to dry out at the surface reaching lower relative humidity values, the drying rate decreases since the "dry" outer porous-material layer forms an additional resistance for vapour transport and therefore hinders the removal of moisture from the inside of the material towards the surface, in addition to the boundary-layer resistance, expressed by the CMTC. This phase is called the second drying phase, which is also marked by sudden drop of the relative humidity below 100% and an increase of the local temperature, since less heat is required for the evaporation of water.

Materials with a coarse porosity and a high liquid permeability mostly show a long first drying phase. Fine porous materials, showing hygroscopic behavior and a lower liquid permeability, more often show a limited first drying phase and longer second drying phase. It is therefore clear that coarse porous materials with high permeability are the favorable materials to use for promoting evaporative cooling. Drying behavior of various materials in a street canyon are shown in the case study section (Chapter 5).

### 2.3.4 Convective drying in a street canyon

In this section we describe the convective drying of a wet porous surface in a street canyon. For this case, the moisture conditions (vapour pressure, $p_v$) in the street
canyon can have a large influence on the drying behavior of the canyon surfaces. The moisture conditions in the street canyon are affected by the amount of moisture evaporating from the wet porous surfaces, as well as the exchange flux between the air in the canyon and the air above. Understanding the drying behavior of porous surfaces in a street canyon is important if we are interested in understanding the influence of evaporative cooling on the climatic conditions in the street canyon. Conditions which lead to a longer first drying phase of the porous surfaces of a street canyon are favorable since at this stage, the surface attains its lowest temperature due to evaporative cooling. To investigate the influence of the various factors affecting the drying behavior of the porous material, we developed a simplified analytical model, which is described below. Although this section describes the work performed by the author, we believe the results describes a phenomenon which is appropriate for the 'state of the art' section.

The proposed nodal model considers a 2D street canyon (Fig. 2.9), under isothermal conditions, where the air in the canyon is assumed well mixed and the exchange flux between the canyon and the air above is known and stays constant with time. For the air inside the street canyon we assume a domain, where the air conditions at this region is represented by a node situated at its center. Also a node situated at the center of the shear layer represents the conditions of the air above the street canyon which we assume to be the same as the inlet conditions, and we assume that the conditions of the air at this node are not changed by the mixing with the air coming out of the street canyon. The canyon has a unit length in the third dimension. Initially all the surfaces of the street canyon are assumed wet. The drying in the material is assumed to be 1D and the same for all surfaces of the street canyon. The

![Figure 2.9: Schematic representation of the simplified model for studying drying of the porous material in a street canyon](image-url)
non-exposed surfaces are assumed impermeable and adiabatic (marked by dashed line in Fig. 2.9). For drying of the porous material, the model considers two stages of drying: i) when the moisture content of the material \( w \) is larger than the critical moisture content \( w_{\text{crit}} \) (first drying phase), and ii) when \( w \) is smaller than \( w_{\text{crit}} \) (second drying phase) (See Fig. 2.10). The material initially has a moisture content of \( w_0 \). When the convective drying starts, as long as \( w > w_{\text{crit}} \), moisture content in the material decreases uniformly. As soon as \( w \) drops below \( w_{\text{crit}} \), a dry layer forms at the surface of the material (\( \Delta x \)) and the size of this dry layer increases as the drying continues. The two stages of drying are shown in Fig. 2.10. In this figure, \( w_{\text{crit}} \) is shown by a thick black line, \( d \) is the thickness of the material and \( x \) is the thickness of the dry zone at the surface of the material.

![Figure 2.10: Schematic representation of change of moisture content along the depth of the material during drying](image)

The mass balance in the street canyon can be written as:

\[
A \frac{d\rho_{v,i}}{dt} = \frac{Q_e}{1} (\rho_{v,e} - \rho_{v,i}) + \Omega \frac{C_{MTC}^*}{\alpha} (p_{v,sat} - p_{v,i}) + \delta \frac{2}{\alpha} (p_{v,e} - p_{v,i})
\]

(2.6)

The term on the left side of the equation is change of the water vapour density per unit time in the total area \( A = H.W \) of the (2D) street canyon. The first term at the right hand side of the equation is related to the air exchange between the canyon and the air above \( (Q_e) \), the second term describes the convective mass flux from the porous surfaces to the street canyon \( (g_{c,s}) \) multiplied by the perimeter of the surface, and the third term is related to the diffusive mass flux between the air above and the air in the street canyon \( (Q_d) \).

In Eq. 2.6, \( p_v \) (Pa) is the vapour pressure, \( \rho_v \) (kg/m\(^3\)) is the vapour density, subscripts
i and e refer to the middle of the street canyon and the shear layer above the street canyon, respectively. \( Q_e \) (m\(^3\)/s) is the air exchange flux between the street canyon and the air above, \( \delta_a \) (s) is the water vapour diffusion coefficient, \( A \) is the area of the street canyon=H.W (H=height of the canyon and W=width of the canyon), \( \Omega \) is the perimeter of the porous surface=2H+W, \( \alpha \) is the aspect ratio=H/W, and \( p_{v,\text{sat}} \) (Pa) is the saturated vapour pressure. The \( CMTC^* \) is an equivalent \( CMTC \) which is determined as a series of resistances, combining the \( CMTC \) at the surface due to convection and the vapour resistance factor of the dry material formed at the surface after the second drying phase (Fig. 2.11).

\[
CMTC^*(t) = \frac{1}{\frac{1}{CMTC} + \mu_{dry}x(t)/\delta_a} \tag{2.7}
\]

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig2_11.png}
\caption{The equivalent \( CMTC \) \( (CMTC^*) \)}
\end{figure}

where \( \mu_{dry} \) is the vapour resistance factor of dry material, and \( x \) is the dimension of the dry zone at the surface of the material (Fig. 2.10), which during the first drying phase is zero, and during the second drying phase, is calculated as:

\[
x(t) = x(t - \Delta t) + \Delta x(t) \tag{2.8}
\]

where \( \Delta x \) is the increase of dry thickness during a time step \( \Delta t \), calculated as:

\[
\Delta x(t) = \frac{g_{c,s}\Delta t}{w_{crit}} \tag{2.9}
\]

where \( g_{c,s} \) (kg/m\(^2\)/s) is the mass flux from the porous surfaces to the street canyon calculated as:

\[
g_{c,wt}(t) = CMTC^*(t)(p_{v,\text{sat}} - p_{v,i}(t)) \tag{2.10}
\]
2.3. CONVECTIVE HEAT AND MASS TRANSFER AT AIR-MATERIAL INTERFACE

We assume a step by step approach (explicit time stepping), where at every step, \( t \), the \( p_{v,i}(t) \) can be calculated starting from the \( p_{v,i}(t - \Delta t) \) (\( p_{v,i} \) of the previous step). The \( CMTC^* \) is also calculated using the same method. Between the steps, we solve the mass balance equation (Eq. 2.6) obtaining an exponential behavior (Fig. 2.12).

\[
\begin{align*}
\text{Figure 2.12:} & \quad \text{Change of vapour pressure inside the street canyon during the drying process}
\end{align*}
\]

Assuming the ideal gas law \( (p = \rho RT) \) and solving Eq. 2.6, \( p_{v,i}(t) \) is calculated as:

\[
p_{v,i}(t) = (p_{v,i}(t - \Delta t) - p_{v,i}(\infty)) e^{-a.\Delta t} + p_{v,i}(\infty)
\]

(2.11)

where \( p_{v,i}(t - \Delta t) \) and \( p_{v,i}(\infty) \) are the vapour pressure at the center of the street canyon for the previous time step, and the equilibrium value \((t=\infty)\), respectively. For every step, \( p_{v,i,\infty}(t) \) is calculated using an updated value of \( CMTC^* \) as:

\[
p_{v,i,\infty}(t) = \frac{\left(\frac{Q_e}{A} + \frac{2\delta_{a}\beta}{\alpha A}\right) \rho_l + \left(\frac{\Omega}{A} CMTC^*(t) \cdot \beta\right) p_{v,sat}}{\frac{Q_e}{A} + \frac{2\delta_{a}\beta}{\alpha A} + \frac{\Omega}{A} CMTC^*(t) \cdot \beta}
\]

(2.12)

\( a \) in Eq. 2.11 is calculated as:

\[
a(t) = \frac{Q_e}{A} + \frac{2\delta_{a}\beta}{\alpha A} + \frac{\Omega}{A} CMTC^*(t) \cdot \beta
\]

(2.13)

where \( \beta = R_v T \).

The proposed model also predicts the change of the average moisture content, \( w \), in the porous material. For the first drying phase, where \( w > w_{\text{crit}} \), \( w \) is calculated by:

\[
w(t) = w(t - \Delta t) - \frac{g_{c,wt} \cdot \Delta t}{d}
\]

(2.14)
For the second drying phase, where \( w < w_{\text{crit}} \), \( w \) is calculated by:

\[
    w(t) = w_{\text{crit}} (1 - \frac{x}{d})
\]

where \( d \) (m) is the material thickness.

The proposed model is applied for a 2D 10 x 10 m street canyon \((H=W=10 \text{ m})\) (Fig. 2.9). The thickness of the porous surfaces \((d)\) is chosen as 5 cm. The initial moisture content of the porous surfaces is 95 kg/m\(^3\) and the initial vapour pressures in and above the street canyon \((p_{v,e})\) are the same and equal to 935 Pa (temperature of 20\(^\circ\)C and RH of 40\%). The vapour pressure of the air above the street canyon is assumed to remain constant in time and equal to 935 Pa. Realistic values chosen for \( Q_e, CMTC, w_{\text{crit}} \) and \( \mu \) are based on preliminary simulations and experiments. The purpose of this study is to evaluate the influence of these parameters on the drying behavior of the material and the vapour pressure in the street canyon.

An initial simulation was performed with the \( CMTC \) and \( w_{\text{crit}} \) equal to \( 5 \times 10^{-8} \text{ 1/s} \) and 78 kg/m\(^3\), respectively. The air exchange between the canyon and the air above the canyon is referred to in air changes per hour (ACH), calculated as \( Q_e/V \) where \( V \) is the volume of the street canyon \((100 \text{ m}^3 \text{ in this case})\). ACH is chosen as 22 \(1/\text{h} \) \((Q_e=0.6 \text{ m}^3/\text{s})\). Figs. 2.13a and b show the vapour pressure in the centre of the canyon \((p_{v,i})\) and the moisture content of the specimen as a function of time, respectively. It can be seen that initially, as moisture is evaporating from the wet porous surfaces, the vapour pressure at the centre of the street canyon increases very fast and then attains a constant value for approx. 5 hours. This is an equilibrium condition when at the surfaces, \( w > w_{\text{crit}} \) (first drying phase) and the mass flux from the wet wall to the canyon is constant. The duration of this period is influenced by the \( CMTC \) at the surface of the material, the magnitude of the exchange flux \((Q_e)\) and the \( w_{\text{crit}} \) of the material. This period coincides with the the first drying phase.

**Figure 2.13:** a) vapour pressure in the centre of the street canyon and b) moisture content of the porous material as a function of time
of the porous material. At a certain point, a dry layer is formed at the surface of
the porous material, and the material enters the second drying phase (as described
in Sec. 2.3.3). This phase can be identified by a change in the slope of the moisture
content curve of the porous material (slower drying)(Fig. 2.13b). At this stage, the
drying rate at the porous walls decreases and therefore also the vapour pressure in
the street canyon drops. It should be noted that the drop in the vapour pressure at
the centre of the street canyon results in a partial increase of the drying rate of the
porous material, which is a rebound effect. In order to capture this effect an iterative
calculation should be done. We eliminate the iterative calculation by selecting a small
time step (60 sec) for the explicit time stepping algorithm.

The initial increase of the vapour pressure in the street canyon, is influenced by the
CMTC at the surfaces of the porous sections as well as by the magnitude of the
exchange flux between the air in the street canyon and the air above. The duration
of the first drying phase is additionally influenced by the value of critical moisture
content of the porous material \( w_{\text{crit}} \). To show the influence of these factors on the
drying rate of the material and the vapour pressure in the street canyon, additional
simulations are performed by means of the simplified model.

Figs. 2.14a and b show the vapour pressure in the centre of the street canyon and
the moisture content of the porous surfaces as a function of time, when the value of
the CMTC is modified, and compare the conditions with the base case. The CMTC
was once increased from 5x10^{-8} 1/s to 8x10^{-8} 1/s and once decreased to 2x10^{-8} 1/s.
Increasing the CMTC results in an increase of the mass flux from the wet porous
material to the street canyon. Therefore it can be seen that for the case with higher
CMTC, the vapour pressure at the centre of the canyon reaches higher values during
the first drying phase, in comparison to the base case, but the duration of the period
with high vapour pressure is shorter. Due to the higher CMTC and higher mass
flux, the porous material dries faster, reaches the critical moisture content faster
and enters the second drying phase earlier than the base case. The opposite can be
observed when the CMTC is decreased, i.e. an increase of \( p_{v,i} \) to a lower value, a
longer duration of the first drying phase, and a slower drying of the porous material,
in comparison to the base case.

Figs. 2.14c and d show the vapour pressure in the centre of the street canyon and
the moisture content of the porous surfaces, as a function of time, when the value of
the exchange flux \( Q_e \) is modified in terms of the ACH. ACH is once increased from
22 l/hr to 72 l/h and once decreased to 4 l/h, which are both realistic values for
higher or lower wind speeds, respectively. For higher exchange flux values between
the air in the SC and the air above, more of the moisture evaporated from the porous
surfaces leaves the street canyon, which results in a lower \( p_{v,i} \) value in comparison to
the base case, and therefore a higher drying rate of the porous material. Therefore the
moisture content at the porous surface reaches the critical value faster, in comparison
to the base case. On the other hand, a lower exchange flux results in a higher \( p_{v,i} \), a
slower drying of the porous material and a longer duration of the first drying phase.
Figure 2.14: Comparison of vapour pressure in the centre of the street canyon for changes in a) CMTC c) exchange flux and e) $w_{crit}$, comparison of moisture content of the porous surfaces as a function of time for changes in b) CMTC d) exchange flux and f) $w_{crit}$.

Figs. 2.14e and f show the vapour pressure in the centre of the street canyon and the moisture content of the porous surfaces as a function of time, when the value of the critical moisture content of the porous material ($w_{crit}$) is changed. The $w_{crit}$ is once increased from 78 to 85 kg/m$^3$ and once decreased to 60 kg/m$^3$. It can be seen
that variation of the $w_{\text{crit}}$ does not affect the initial increase of the $p_{v,i}$, and all cases reach the same values, although it affects the duration of the first drying phase and the duration of constant $p_{v,i}$. When the material has a lower $w_{\text{crit}}$, it takes longer for the material to reach this critical moisture content, therefore the duration of the first drying phase is longer. On the other hand, material with higher $w_{\text{crit}}$ can reach this values faster.

This study shows that due to the specific shape of the street canyon, the drying of a porous material is more complex than for a flat plate. It was shown that CMTC, $w_{\text{crit}}$, and $Q_e$ have a large influence on the drying behavior of the porous surfaces. It was observed that each of these parameters can influence the vapour pressure in the street canyon, the drying speed of the porous material, and the duration of the first drying phase and the period of constant vapour pressure in the street canyon. The CMTC can influence the drying by modifying the moisture flux at the surface of the material. The $w_{\text{crit}}$ value can influence the drying by determining the duration of the first drying phase, and $Q_e$ can influence the drying by changing the moisture conditions in the street canyon which will influence the drying rate at the surface. It should be noted that variations in the initial $p_{v,e}$ also influences the drying behavior of the porous material and the conditions in the street canyon, although this influence was not shown here.

2.4 Human comfort

2.4.1 Human physiological modelling

The understanding of human's physiological behavior is gaining importance, due to increased exposure to more extreme environments. This leads to the development of more accurate tools to model the physiological behavior. These models normally consist of a controlled part (passive system) being the model of the physical body, and a controller part (active system) being the simulation of the human thermoregulatory system. The classic heat balance of a human body is written as:

$$S = M + W + R_{s,l} + C + E_{\text{res}} + E_{\text{diff}} + E_{\text{sw}}$$

(2.16)

where $S$ is the rate of heating or cooling, $M$ is the metabolic rate (internal energy production by oxidation of food) (W), $W$ is the physical work output (W), $R_{s,l}$ is the heat gained or lost by radiation (W), $C$ is the heat gained or lost by convection (W), and $E_{\text{res}}$, $E_{\text{diff}}$ and $E_{\text{sw}}$ are the evaporative heat losses due to respiration, skin diffusion and evaporation of sweat (W), respectively.

Although all human comfort models solve the above mentioned balance equation, they differ in their parameterization. As an example, a few models are described and compared below:
The model of Fanger (1970), being one of the most well known applications of the human energy balance, defines three conditions for a person to be in thermal comfort: i) the body to be in heat balance, ii) the sweat rate (SW) is at comfort level, and iii) the mean skin temperature ($T_{sk}$) is at comfort level. The comfort level for SW and $T_{sk}$ can be achieved from (Rohles and Nevins, 1971):

$$T_{sk} = 35.7 - 0.0275(M - W)$$ (2.17)

$$SW = 0.42(M - W - 58.15)$$ (2.18)

In a two-node model proposed by Gagge et al. (1986), the mean skin temperature ($T_{sk}$) and sweat rate (SW) are not related to the internal heat production, but calculated using human thermoregulatory processes. In this model, the core and skin of the human body are treated analytically as two concentric shells.

Another model is the Munich Energy-balance Model for Individuals (MEMI) by Hoepppe (1999; 1993). MEMI is also a two-node model, which takes into account the thermoregulation of human body. Since in this model, the clothing surface temperature ($T_{cl}$), the skin temperature ($T_{sk}$) and the core temperature ($T_{c}$), are each calculated separately, two additional terms are added to the basic energy balance equations of the human body. These two are the heat flux from core to skin ($F_{cs}$ in W/m$^2$) and heat flux from skin through clothing to the outer surface of the clothing ($F_{sc}$ in W/m$^2$).

$$F_{cs} = v_b\rho_{bl}c_b(T_c - T_{sk})$$ (2.19)

$$F_{sc} = \frac{1}{l_{cl}}(T_{sk} - T_{cl})$$ (2.20)

where $v_b$ is the blood flow from the body core to the skin (l/sm$^2$), $\rho_{bl}$ is the blood density (kg/l), $c_b$ is the blood specific heat capacity (Ws/kgK) and $l_{cl}$ is the heat resistance of clothing (Km$^2$/W)

A more complex multi-node human thermoregulation model is the Fiala model (Fiala et al., 2001) which simulates the human body in more detail. This model consists of two parts, a controlled passive part and a controlling active part. The passive part models the physical human body and heat transfer occurring inside the body and at its surface. It consists of 12 body elements, comprising a total of 187 tissue nodes. The active part models the thermoregulatory responses of the central nervous system. Each body element is subdivided in three sectors: anterior, posterior and inferior. The active part predicts four essential thermoregulatory responses of the central nervous system being the suppression (vasoconstriction), elevation (dilatation) of the cutaneous blood flow, shivering, and sweat moisture excretion.
2.4.2 Current comfort indices

2.4.2.1 Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD)

Fanger (1970) uses two indices: the PMV (Predicted Mean Vote) and the PPD (Predicated Percentage of Dissatisfied) to evaluate thermal comfort. The PMV index predicts the mean response of a large group of people according to the psycho-physical ASHRAE scale shown in Table 2.1 (ASHRAE, 2009).

<table>
<thead>
<tr>
<th>Scale</th>
<th>PMV</th>
</tr>
</thead>
<tbody>
<tr>
<td>hot</td>
<td>+3</td>
</tr>
<tr>
<td>warm</td>
<td>+2</td>
</tr>
<tr>
<td>slightly warm</td>
<td>+1</td>
</tr>
<tr>
<td>neutral</td>
<td>0</td>
</tr>
<tr>
<td>slightly cool</td>
<td>-1</td>
</tr>
<tr>
<td>cool</td>
<td>-2</td>
</tr>
<tr>
<td>cold</td>
<td>-3</td>
</tr>
</tbody>
</table>

The PMV is calculated by:

\[
PMV = \left[ 0.303e^{-0.036M} + 0.025 \right]L
\] (2.21)

where \( L \) (kcal/m\(^2\)hr) is the thermal load on the body, which is the difference between the internal heat production and the heat loss to the actual environment, and \( M \) is the metabolic rate (W).

The PPD predicts the percentage of thermally dissatisfied people using the thermal scale shown above. PPD is related to PMV by:

\[
PPD = 100 - 95e^{(0.03353PMV^4 + 0.2179PMV^2)}
\] (2.22)

2.4.2.2 Perceived Temperature (PT)

The Perceived Temperature (PT) is defined as the “air temperature of a standard environment (calm wind, air temperature (\(T_a\)) equal to mean radiant temperature (\(T_{mrt}\)), relative humidity (RH) of 50 %, metabolic rate of 2.3 MET equal to 135 W/m\(^2\), which corresponds to walking at 4 km/h) that would produce the same thermal stress as the actual environment” (Jendritzky and Tinz, 2009). MET is a unit often used to measure the metabolic rate of a human, and 1 MET = 58 W/m\(^2\). The mean radiant temperature (\(T_{mrt}\)) for a person at a certain position with certain surroundings is the uniform temperature of an imaginary black enclosure which gives the same radiant heat loss from the person as the actual environment.
The PT is calculated using the Klima-Michel-model (KMM) of the German national weather service (Deutscher Wetterdienst, DWD). This model uses Fanger’s (Fanger, 1970) PMV equations as the base and adds the latent heat flux (Gagge et al., 1986). This model then is adapted to outdoor conditions by incorporating the parameterization of the radiant fluxes (Jendritzky and Nuebler, 1981).

In this model the insulation value of clothing \( I_{cl} \) is a variable ranging from summer clothing (0.5 clo) to winter clothing (1.75 clo) (1 clo = 0.155 Km\(^2\)/W) and it is assumed that people adapt their behavior in order to gain comfortable conditions.

### 2.4.2.3 OUT-SET*

OUT-SET* (Pickup and de Dear, 2000), is an adaption of the Standard Effective Temperature (SET*) (Gagge et al., 1986), a well establish indoor index, to outdoors, by including radiation (Spagnolo and De Dear, 2003).

SET*, is an improved version of Effective Temperature (ET*) (Gagge and Gonzalez, 1974), by representing a standard set of conditions typical to an indoor application. SET* is an equivalent air temperature of an isothermal environment, \( T_a \) equals to \( T_{mrt} \), at 50% RH and air speed <0.15 m/s, in which a person, wearing clothing standardized for the activity concerned, has the same heat stress and thermoregulatory strain as in the actual environment.

### 2.4.2.4 Physiological Equivalent Temperature (PET)

The Physiological Equivalent Temperature (PET) is "the very air temperature at which the energy balance for the assumed indoor conditions is balanced with the same mean skin temperature and sweat rate as calculated for the actual outdoor conditions" (Hoeppe, 1999; 1993). The reference indoor condition are: \( T_a = T_{mrt} \), \( P_v = 12\, hPa \) (approx. equivalent to RH = 50% at \( T_a = 20^\circ C \)), \( v = 0.1 \, m/s \), light activity (work metabolism of 80W) and heat resistance of clothing of 0.9 clo. The PET is calculated by MEMI model.

### 2.4.2.5 Universal Thermal Climate Index (UTCI)

The Universal Thermal Climate Index (UTCI) is calculated using the Fiala model (Fiala et al., 2001) in combination with a clothing model. It is expressed as an equivalent ambient temperature of a reference environment providing the same physiological response of a reference person as the actual environment (Fiala et al., 2012). In the clothing model, the clothing insulation is adjusted to the ambient temperature taking into account the seasonal clothing adaptation habits of Europeans. The insulation, vapour resistance and surface air layer insulation of the clothing are influenced by the change in wind speed and body movement. For the reference
condition, a metabolic rate of 135 W/m² and a walking speed of 1.1 m/s are considered, while the mean radiant temperature is equal to the ambient temperature, the relative humidity is set at 50% for an ambient reference temperature below 29°C and water vapor pressure of 20 hPa for higher reference temperatures. The wind speed at 10 m height is 0.5 m/s.

2.4.2.6 Comparison of the indices

The PMV and the PPD are indices applied for indoor studies. The four other indices studied above (PT, PET, OUT-SET* and UTCI) have all been applied to study the comfort conditions in outdoor spaces.

The PT, OUT-SET* and UTCI all consider a fixed RH of 50% for the reference indoor condition while considering $T_a = T_{mrt}$. The PET on the other hand considers a fixed vapour pressure of 12 hPa independent from $T_a$. Knowing that the RH changes with temperature, applying a constant vapour pressure for the PET is found to be a more accurate method.

The PET, UTCI and OUT-SET* are calculated based on a human body thermoregulatory system, which is not the case for the PT. This makes the PT to be less accurate for extreme outdoor conditions.

PT, UTCI and OUT-SET* all have variable clothing insulation values and activity levels (human adaptive behavior), while the PET considers a fixed $I_{cl}$ of 0.9 clo and activity level of 80 W, which are typical for an indoor office environment.

In this thesis, the UTCI is chosen as the index for human comfort evaluation.

2.5 Conclusions

This chapter included the state of the art regarding the topics covered in this thesis. Initially the flow in and above an urban street canyon as well as its energy budget was described.

Further the phenomenon convective drying and the terms convective heat and mass transfer coefficients, $CHTC$ and $CMTC$, were introduced and their sensitivity various factors such as location on the surface, wind speed and reference location was shown.

It is known that in order to take advantage of the cooling effect due to evaporation of moisture from wet surface in an urban environment, understanding the flow as well as the drying behavior of porous material is crucial. Hence the convective drying of a flat porous surface was described. It was shown that, when the porous material forms the walls of a street canyon, its drying behavior is altered. This behavior is closely related to the flow conditions in the street canyon, namely the $CMTC$ at the surfaces, and the exchange flux at the top of the canyon.
Further the human thermal comfort subject was covered, describing some existing human physiological models and indices used for analyzing human thermal comfort.

In the next chapter, a coupled model is introduced for accurately modelling the convective drying of a porous material in an urban setting, taking into account variations of the convective transfer coefficients as a function of time. The individual sub-models of the coupled model are described, the modelling equations are given and the coupling strategy is discussed.
Chapter 3

Coupled model for an elongated street canyon

3.1 Introduction

In this chapter, the coupled model is introduced. It consists of three sub-models: a CFD model which solves the convective heat, air and moisture transport in the air, a Building Envelope Heat and Moisture (BE-HAM) model which solves the heat and moisture transport within the porous material, and which exchanges information with the CFD model, and a radiation model (RAD) which solves the radiative balance for short-wave and long-wave radiative exchange between the building surfaces and the sky. It is known that three dimensionality of the flow field is important, specially under buoyant conditions, and a 2D model may not capture all the flow details accurately. In this thesis, due to the high computational cost of 3D simulations, a 2D model is developed. Studies have shown that for elongated street canyons exposed to perpendicular wind conditions, the vortex in the street canyon is well predicted by 2D simulations (Sini et al., 1996).

A schematic representation of the entire domain, including the CFD, BE-HAM and RAD sub-models, is shown in Figs. 3.1a and 3.1b. The sub-models exchange information at the “exchange interfaces”.

In the following sections, each of the sub-models will be explained. Afterwards, the model for evaluating the comfort of a pedestrian in the street canyon, is discussed. Finally, the coupling strategy is explained in detail.
3.2 Computational Fluid Dynamics model (CFD)

3.2.1 Model description

The fluid domain consists of a 2D geometry and the CFD simulations are conducted using Ansys-Fluent 12.0 which uses the control volume method (Ansys, Inc., 2009). Steady RANS (Reynolds-averaged Navier-Stokes) is used in combination with the realizable $k-\varepsilon$ turbulent model (Shih et al., 1995). Low Reynolds Number Modelling (LRNM) is used for near wall treatment. Second-order discretization schemes as well as the SIMPLE algorithm for pressure-velocity coupling are employed (Kundu and Cohen, 2002). Pressure interpolation is second order.

The domain (Fig. 5.1) consists of a velocity inlet, a pressure outlet, and various surfaces, some of which exchange information with the other models. At the inlet of the domain, profiles of mean horizontal wind speed ($U$), turbulent kinetic energy ($k$), and turbulence dissipation rate ($\varepsilon$), as well as a constant with height temperature ($T$) and relative humidity ($RH$), are imposed. Details about the inlet conditions for specific simulations are given in Chapter 5. At the domain outlet, zero static pressure is imposed. The top of the domain is modelled as symmetry. All the other surfaces are modelled as no-slip boundaries with zero roughness due to limitations of LRNM.
3.2. COMPUTATIONAL FLUID DYNAMICS MODEL (CFD)

Figure 3.2: CFD domain with boundary conditions

3.2.2 Constitutive equations

3.2.2.1 Numerical modelling of fluid flow

CFD is a method to solve the Navier-Stokes equations representing fluid flow. To do this, a spatial discretization method is used, namely the Finite Volume Method. In this method, the domain is split into several separate volumes, called cells, and the flow parameters are numerically solved in each of these cells. Where transient phenomena are studied, a time domain discretization is also used. More detailed information on the numerical method used in CFD can be found in Ferziger and Peric (2002).

3.2.2.2 Conservation equations

The Navier-Stokes equations are the conservation equations for mass, momentum and energy in fluid flow. The conservation equations for incompressible flow are:

Conservation of mass:
\[ \nabla \mathbf{u} = 0 \quad (3.1) \]

Conservation of momentum:
\[ \frac{\partial}{\partial t} (\rho \mathbf{u}) + \nabla (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \mu \nabla^2 \mathbf{u} + \rho \mathbf{g} \quad (3.2) \]

Conservation of energy:
\[ \frac{\partial}{\partial t} (\rho h) + \nabla (\rho h \mathbf{u}) = -\nabla q \quad (3.3) \]
CHAPTER 3. COUPLED MODEL FOR AN ELONGATED STREET CANYON

Conservation of species:

\[ \frac{\partial}{\partial t}(\rho x) + \nabla (\rho x u) = -\nabla g_d \quad (3.4) \]

where \( h \) is the enthalpy, \( p \) is the pressure, \( \rho \) is the density, \( x \) is the mass fraction, \( q \) is the conductive heat flux, \( g_d \) is the diffusive mass flux, \( u \) is the instantaneous velocity vector, \( g_r \) is the gravitational acceleration, and \( \mu \) is the dynamic viscosity.

The fluid, moist air, consists of a mixture of two ideal gases, dry air and water vapour. The mass fraction of each component \( x_a \) and \( x_v \), respectively, is calculated as:

\[ x_a = \frac{\rho_a}{\rho_g} \quad (3.5) \]
\[ x_v = \frac{\rho_v}{\rho_g} \quad (3.6) \]

where \( \rho_g \), \( \rho_a \) and \( \rho_v \) (kg/m\(^3\)) are the densities for the mixture, dry air and water vapour, respectively. The mass fractions, \( x_a \) and \( x_v \) are related by:

\[ x_a + x_v = 1 \quad (3.7) \]

Another way of defining the amount of moisture in the air, apart from mass fraction, is relative humidity (\( \phi(\%) \)) which is defined as:

\[ \phi = \frac{p_v}{p_{v,sat}} \quad (3.8) \]

where \( p_v \) (Pa) is the vapour pressure, and \( p_{v,sat} \) (Pa), is the saturation vapour pressure, which can be calculated from the temperature \( T \) using:

\[ p_{v,sat} = e^{65.8094 - \frac{2066.27}{T} - 5.946lnT} \quad (3.9) \]

Enthalpies of dry air and water vapour in the mixture \( (h_a \text{ and } h_v \text{ (K/kg)}) \) can be written as:

\[ h_a = c_{p,a}(T - T_{ref,0}) \quad (3.10) \]
\[ h_v = c_{p,v}(T - T_{ref,0}) + L_v \quad (3.11) \]

where \( T_{ref,0} \) is the reference temperature \( (273.15 \text{ K}) \), \( L_v \) \( (2.5\times10^6 \text{ J/kg}) \) is the latent heat of evaporation, and \( c_{p,a} \) and \( c_{p,v} \) \( (\text{J/kgK}) \) are the specific heat capacities of dry air and water vapour, respectively.
3.2. COMPUTATIONAL FLUID DYNAMICS MODEL (CFD)

3.2.2.3 Transport equations

Heat conduction

Heat conduction in the air is defined by Fourier’s law as:

\[ q = -\lambda_g \nabla T \]  

(3.12)

where \( \lambda_g \) is the thermal conductivity of the gaseous phase (moist air). To account for the additional contribution of the different mixture components by diffusion (Bird et al., 2007), the total heat flux of the mixture can be written as:

\[ q_{\text{tot}} = q + \sum_i h_i g_{d,i} \]  

(3.13)

where \( h_i \) is the enthalpy of the component \( i \), and \( g_{d,i} \) is the diffusive mass flux of component \( i \).

In turbulent flows, \( \lambda_g \) is replaced by \( \lambda_{\text{eff}} \) (effective thermal conductivity) to take into account the influence of turbulence:

\[ q = -\lambda_{\text{eff}} \nabla T \]  

(3.14)

where

\[ \lambda_{\text{eff}} = \lambda_g + \lambda_t = \lambda_g + \frac{c_{p,g} \mu_t}{Pr_t} \]  

(3.15)

where \( Pr_t \) is the turbulent Prandtl number (here taken as 0.85), \( c_{p,g} \) is the specific heat capacity of the gaseous phase, and \( \mu_t \) is the turbulent viscosity.

Gaseous diffusion

Fick’s law describes the diffusive mass flux, originating from a concentration gradient, by:

\[ g_{d,i} = -\rho_g D_{va} \nabla \frac{\rho_i}{\rho_g} = -\rho_g D_{va} \nabla x_i \]  

(3.16)

where \( D_{va} \) is the binary diffusion coefficient between dry air and water vapour. To account for the effect of the temperature gradient on the mass transfer (thermo-diffusion or Soret effect), when large temperature gradients are found, the diffusive mass flux can be written as:
\[ g_{d,i} = -\rho g D_{va} \nabla x_i - D_{T,i} \nabla \ln T = -\rho g D_{va} \nabla x_i - D_{T,i} \frac{\nabla T}{T} \] (3.17)

where \( D_{T,i} \) is the thermal diffusion coefficient of component \( i \) of the mixture.

In turbulent flows, an effective diffusion coefficient is used to take into account the influence of turbulence:

\[ g_{d,i} = -\rho g D_{va,eff} \nabla \frac{\rho_i}{\rho} \] (3.18)

where

\[ D_{va,eff} = D_{va} + D_{va,t} = D_{va} + \mu_t \frac{\mu_t}{\rho g S_{St}} \] (3.19)

where \( D_{va,t} \) is the turbulent diffusion coefficient and \( S_{St} \) is the turbulent Schmidt number, here taken as 0.7, although it is known to vary to some extent in the flow field (Tominaga and Stathopoulos, 2007; Blocken et al., 2008).

### 3.2.2.4 Turbulence modelling

For solving turbulent flow, several modelling approaches exist. The most commonly known approaches are: Reynolds-Averaged Navier-Stokes (RANS), Large-Eddy Simulation (LES) and Direct Numerical Simulation (DNS).

In DNS, the exact Navier-Stokes equations are solved completely. All vortices and eddies are resolved and nothing is modelled. This model is very exact but very time-consuming and requires huge computational resources, therefore it is only used for small and simple cases. For the urban environment (Re \( \geq 10^5 \)), it is not currently possible to apply DNS.

In LES, the large eddies are resolved and the effect of small eddies on large eddies are modelled. The distinction between small and large scales is made using a filter, where eddies having a scale smaller than the filter size are not explicitly resolved but modelled. The computational cost of LES for most cases of practical interest in the urban environment is smaller than for DNS, but still too large.

With RANS, only the mean flow is explicitly resolved and all scales of turbulence are modelled. RANS is not as exact as DNS or LES but is computationally much less expensive, making it suitable for many cases in urban physics. In this method, the instantaneous scalar and vector flow variables in the Navier-Stokes equations are decomposed into mean and fluctuating components:

\[ u = \bar{u} + u' \] (3.20)
where $\bar{u}$ is the time averaged wind speed and $u'$ is the fluctuating component. Substituting these variables into Navier-Stokes equations (3.2), and taking its time-average, yields the RANS equations:

$$
\frac{\partial}{\partial t} (\rho \bar{u}_i) + \frac{\partial}{\partial x_j} (\rho \bar{u}_i \bar{u}_j) = -\frac{\partial \bar{p}}{\partial x_i} + \mu \frac{\partial^2 \bar{u}_i}{\partial x_j^2} + \rho g_i + \frac{\partial}{\partial x_j} (-\rho u'_i u'_j) \quad (3.21)
$$

An additional term which appears in the RANS equations is the Reynolds stress $(-\rho u'_i u'_j)$ which accounts for turbulence. In RANS, these Reynolds stresses are modelled with turbulence models, by solving additional transport equations in order to close the set of RANS equations.

Several RANS turbulence models exist. The three main types are the linear and non-linear eddy-viscosity models and the Reynolds stress model (RSM). In eddy-viscosity models, the turbulent Reynolds stresses are related to the mean flow field by means of an eddy viscosity or turbulent viscosity ($\mu_t$). The Reynolds stresses are modelled by the Boussinesq eddy-viscosity approximation:

$$
-\rho u'_i u'_j = \mu_t \left[ \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right] - \frac{2}{3} \rho k \delta_{ij} \quad (3.22)
$$

where $k$ is the turbulent kinetic energy and $\delta_{ij}$ is the Kronecker delta.

The complexity of eddy-viscosity models depends on the number of transport equations solved for turbulence. There exist one-equation models, such as the Spalart-Allmaras model (Spalart and Allmaras, 1992), and two-equation models, such as the $k - \varepsilon$ (Jones and Launder, 1972; Launder and Spalding, 1974) or $k - \omega$ (Wilcox, 1988; 1998) models. In standard $k - \varepsilon$ model which is used for a wide range of applications, the turbulent viscosity is calculated from $k$ and $\varepsilon$ as:

$$
\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (3.23)
$$

where $\varepsilon$ is the turbulence dissipation rate and $C_\mu$ is an empirical constant usually taken 0.09. Due to some deficiencies of the $k - \varepsilon$ models, modified models have been introduced such as realizable $k - \varepsilon$ model (Shih et al., 1995), with a new formulation for the turbulent viscosity where $C_\mu$ is no longer constant and a new transport equation for $\varepsilon$.

The RSM is a more advanced turbulence model, where the isotropic eddy-viscosity assumption is avoided and the transport equations for the Reynolds stresses, together with an equation for the dissipation rate, are solved, resulting in total of seven transport equations for three-dimensional flow problems. In the RMS, the turbulent viscosity is calculated is the same way as in the standard $k - \varepsilon$ model by Eq. 3.23.
3.2.2.5 Atmospheric boundary layer flow

The airflow close to the surface changes due to the roughness of the earth’s surface, showing a gradual increase of the wind speed with height. The resulting boundary layer near the earth’s surface is called the Atmospheric Boundary Layer (ABL). For a neutral ABL, the turbulence in the lowest 10-20% of the ABL originates mainly from surface friction (instead of from thermal stratification), and the ABL thickness mainly depends on the roughness of the terrain. For such neutral ABL, the vertical profile of mean horizontal wind speed $(U)$ over a terrain with constant surface roughness can be related to the height $(z)$ using the relationship below (Richards and Hoxey, 1993):

$$U(z) = \frac{u_{\tau,ABL}}{\kappa} \ln \left( \frac{z + z_0}{z_0} \right)$$

(3.24)

where

$$u_{\tau,ABL} = \kappa U_{ref} \ln^{-1} \left( \frac{h_{ref} + z_0}{z_0} \right)$$

(3.25)

with $z_0$ the aerodynamic roughness length of the terrain, $\kappa$ the von Karman constant (0.4187), $z$ the vertical coordinate, $u_{\tau,ABL}$ the friction velocity, $h_{ref}$ the reference height and $U_{ref}$ the horizontal wind speed at the reference height.

The earth’s roughness is represented by $z_0$. $z_0$ is not the physical length of the roughness elements but reflects the roughness that is felt by the flow, taking into account the size of the roughness elements, their spacing and shape. $z_0$ can be estimated using the roughness classification by Davenport, updated by Wieringa (1992).

Using the $k - \varepsilon$ model, the turbulent kinetic energy and the turbulence dissipation rate in a horizontally homogeneous ABL, with constant shear stress with height, can be calculated by (Richards and Hoxey, 1993):

$$k = \frac{u_{\tau,ABL}^2}{\sqrt{C_{\mu}}}$$

(3.26)

$$\varepsilon = \frac{u_{\tau,ABL}^3}{\kappa(z + z_0)}$$

(3.27)

3.2.2.6 Near-wall treatment

In the region close to a surface, where the viscous effects become important, the velocity is represented in a dimensionless form $(u^+)$:

$$u^+ = \frac{u}{u_{\tau}}$$

(3.28)
where \( u \) is the velocity, and \( u_\tau \) is the friction velocity at the wall:

\[
    u_\tau = \frac{\sqrt{\tau_w}}{\rho}
\]

where \( \tau_w \) is the wall shear stress. The dimensionless wall distance \( (y^+) \) is calculated by:

\[
    y^+ = \frac{u_\tau y}{v}
\]

where \( y \) is the distance (normal) to the wall and \( v \) (m\(^2\)/s) is the kinematic viscosity.

The near wall region is composed of three separate regions:

- the linear sub-layer (or viscous sub-layer), very close to the wall \((y^+ < 5)\), where the viscous effects are dominant,
- the buffer layer, or intermediate layer, where viscous and turbulent effects are about equally important, and
- the log-law layer \((\pm 30 < y^+ < 10^2-10^3)\), where the inertial effects dominate over the viscous effects, and the turbulence mainly governs the transport of momentum and heat.

In the near-wall region, Low-Reynolds Number Modelling (LRNM) or Wall Functions are needed to account for the influence of the wall on the boundary-layer flow. In LRNM, the boundary layer is resolved all the way to the wall and the influence of the wall on the turbulence i.e. the damping of turbulence in the near-wall region is accounted for. To do this, a high cell density in the wall-normal direction and a small \( y^+ \) value for the wall-adjacent cell is required so that the centre of the wall-adjacent cell is located within the viscous sublayer \((y^+<5)\). For flows with high Reynolds number, a very low cell wall distance of the wall-adjacent cell is required since \( \tau_w \), the wall shear stress, increases with increasing wind speed, and since \( y^+ \sim u_\tau \) and \( u_\tau \sim \sqrt{\tau_w} \). This significantly increases the computational cost using LRNM and for this reason, another approach, namely the wall-function approach, is often used for high-Reynolds-number flows. Wall-functions model the flow quantities close to the wall by means of semi-empirical functions instead of resolving them explicitly. In this approach, the centre of the wall-adjacent cell is located outside the region that is affected by viscous effects (viscous sublayer and buffer layer), but it is still in the logarithmic layer, therefore \( 30 < y^+ < 500 \) which results in much lower grid resolution in the near-wall region, and a lower computational cost compared to LRNM. Because of the higher accuracy, LRNM is used in this thesis.
3.3 Building Envelope Heat and Moisture model (BE-HAM)

3.3.1 Model description

Drying of the porous material is simulated using a Building Envelope Heat and Moisture (BE-HAM) transport model. This model solves the coupled heat and moisture (i.e., vapor and liquid) transport in porous media by means of the finite element method. A detailed description of the underlying assumptions, the governing equations and the model validation can be found in Janssen et al. (2007). Important to note is that latent heat due to phase change is explicitly taken into account in this model.

The surfaces which exchange information with the CFD and radiation model are exposed to the following boundary conditions:

\[
q_{\text{tot}} = q_{c,s} + \left( L_v + c_{p,v} T \right) g_{c,s} + q_{\text{rad}} \tag{3.31}
\]

\[
q_{c,s} = CHTC \left( T_s - T_{\text{ref}} \right) \tag{3.32}
\]

\[
g = g_{c,s} = CMTC \left( p_{v,s} - p_{v,\text{ref}} \right) \tag{3.33}
\]

where \( q_{\text{tot}} \) (J/m\(^2\)s) is the total heat flux, \( g \) (kg/m\(^2\)s) is the total mass flux, \( q_{\text{rad}} \) (J/m\(^2\)s) is the combined short and long-wave radiative flux at the wall surface, \( c_{p,v} \) (1800 J/kgK) is the specific heat capacity of water vapor, and \( L_v \) (2.5x10\(^6\) J/kg) is the latent heat of evaporation. The remaining symbols have been defined earlier.

3.3.2 Constitutive equations

3.3.2.1 Description of a porous medium

A porous material consists of a solid material matrix and a pore space (porosity), which can be filled with gas (water vapor or dry air) or liquid. In this thesis, the continuum approach is applied to model the heat and moisture transport in porous material where the different phases are not treated separately at a certain point in the material.

3.3.2.2 Definitions and constitutive equations

Liquid, water vapour and dry air content

A porous material consists of a solid material matrix and a pore space, which is a combination of open porosity (pores connected to the surface) and closed pores. The
open porosity \((\phi_0 \text{ m}^3/\text{m}^3)\) and the solid material content \((w_s \text{ kg/m}^3)\) are defined as:

\[
\phi_0 = \frac{V_{\text{pore}}}{V} \tag{3.34}
\]

\[
w_s = (1 - \phi_0)\rho_s \tag{3.35}
\]

where \(V\) is the total volume of the porous material (including the pores) \((\text{m}^3)\), \(V_{\text{pore}}\) is the volume of the open pores \((\text{m}^3)\), and \(\rho_s \text{ (kg/m}^3\) is the solid material matrix density.

The liquid saturation, \(S_l \text{ (%)}\), can be defined as:

\[
S_l = \frac{\phi_{0,l}}{\phi_0} \tag{3.36}
\]

where \(\phi_{0,l}\) is the open porosity occupied by liquid water.

The open pores in the porous material can be filled with gas (water vapour or dry air) or liquid. The dry air \((w_a)\), water vapour \((w_v)\), liquid water \((w_l)\), and moist air \((w_g)\) contents \((\text{kg/m}^3)\) are calculated by:

\[
w_l = \phi_0 S_l \rho_l \tag{3.37}
\]

\[
w_a = \phi_0 (1 - S_l) \rho_a \tag{3.38}
\]

\[
w_v = \phi_0 (1 - S_l) \rho_v \tag{3.39}
\]

\[
w_g = w_a + w_v \tag{3.40}
\]

\[
\rho_g = \rho_v + \rho_a \tag{3.41}
\]

where \(\rho\) is density \((\text{kg/m}^3)\), subscripts \(l, a, v\) and \(g\) refer to liquid, air, water vapour, solid and gas, respectively.

The moisture content of a porous material \((w)\) is defined as:

\[
w = w_l + w_v \tag{3.42}
\]

**Behavior of dry air, water vapour and moist air**

Dry air and water vapour can, in good approximation, be considered as ideal gases. Therefore we can write:

\[
p_v = \rho_v R_v T \tag{3.43}
\]
where \( p_a \) (Pa) is the dry air partial pressure, \( p_v \) (Pa) is the water vapour partial pressure, \( T \) (K) is the absolute temperature, and \( R_v \) (461.524 J/kgK) and \( R_a \) (287.044 J/kgK) are the water vapour and dry air specific gas constants which are determined by:

\[
R_v = \frac{R}{m_v}
\]

(3.45)

\[
R_a = \frac{R}{m_a}
\]

(3.46)

where \( R \) (8.31451 J/molK) is the universal gas constant and \( m_a \) (28.966 g/mol) and \( m_v \) (18.01534 g/mol) are the molar masses for dry air and water vapour, respectively.

Moist air can be considered as binary mixture of dry air and water vapour and behaves as:

\[
p_g = \rho_g R_g T
\]

(3.47)

with \( R_g \approx R_a = 287.044 \text{ J/KgK} \). Dalton’s law defines the total gas pressure, \( p_g \) (Pa), to be:

\[
p_g = p_v + p_a
\]

(3.48)

Sorption equilibrium

When a dry porous material is exposed to moist air, the pore surface absorbs water molecules resulting in an increase of its moisture content. At this stage, first monolayer molecular adsorption and then multilayer molecular adsorption occurs. At higher relative humidity, surface tension forces the water molecules to change to a more stable arrangement forming a meniscus between the liquid and the gaseous phase, resulting in capillary condensation (Fig. 3.3). At this stage an equilibrium exists between the relative humidity, the liquid water saturation and the capillary pressure. The capillary pressure \( (p_c) \) is defined as:

\[
p_c = p_l - p_g
\]

(3.49)

where \( p_l \) is the liquid pressure and \( p_g \) is the gas pressure. The capillary pressure is related to relative humidity \( (\phi) \) by Kelvin’s law:

\[
p_c = \rho_l R_v T \ln \phi
\]

(3.50)
3.3. BUILDING ENVELOPE HEAT AND MOISTURE MODEL (BE-HAM)

Hygroscopic curves, which are determined experimentally by means of sorption isotherm measurements, present the equilibrium moisture content of each material as a function of relative humidity. Materials, such as calcium silicate brick, which show a moisture content in the hygroscopic range, are referred to as hygroscopic materials, while materials such as ceramic brick, which hardly show any hygroscopic behavior except at very high relative humidity, are referred to as non-hygroscopic materials (Fig. 3.4).

3.3.2.3 Transport equations

Mass flux

The mass flux (kg/m²s) is defined as the mass flow per unit surface and per unit time and is calculated for every component as:

\[ g_l = w_l v_l = \rho_l \phi_0 S_l v_l \]  \hspace{2cm} (3.51)

\[ g_a = w_a v_a = \rho_a \phi_0 (1 - S_l) v_a \]  \hspace{2cm} (3.52)

\[ g_v = w_v v_v = \rho_v \phi_0 (1 - S_l) v_v \]  \hspace{2cm} (3.53)
Figure 3.4: Hygroscopic curve for a hygroscopic (calcium silicate brick (Poupeeleer, 2007)) and a non-hygroscopic (ceramic brick (Derluyn et al., 2008)) material

\[
g_g = w_g v_g = \rho_g \phi_0 (1 - S_l) v_g
\]

(3.54)

where \( \mathbf{v}_\alpha \) is the velocity vector (m/s) of the fluid phase \( \alpha \). The gas velocity and mass flux of the gas mixture are defined as:

\[
\mathbf{v}_g = \frac{\rho_\alpha}{\rho_g} \mathbf{v}_\alpha + \frac{\rho_v}{\rho_g} \mathbf{v}_v
\]

(3.55)

\[
g_g = g_\alpha + g_v
\]

(3.56)

**Heat conduction**

The conductive heat flux is described by Fourier’s law as:

\[
\mathbf{q} = -\lambda \nabla T
\]

(3.57)

where \( \lambda \) (W/mK) is the effective thermal conductivity of the porous material.

**Fluid flow**

Darcy’s law describes the advective flux of the liquid and gaseous phase as:

\[
g_g = -K_g \nabla p_g
\]

(3.58)

\[
g_l = -K_l \nabla p_l
\]

(3.59)
where \( K_g \) and \( K_l \) (s) are the gas and liquid permeability of the porous material, respectively. The gas pressure, \( p_g \), is commonly assumed constant and equal to the atmospheric pressure, \( P_{atm} \).

\[
p_g = P_{atm} = 101325 \text{ Pa} \tag{3.60}
\]

Combining Eq. 3.49, Eq. 3.58, Eq. 3.59, and Eq. 3.60, we get:

\[
g_g = 0 \tag{3.61}
\]

\[
g_l = -K_l \nabla p_l = -K_l \nabla p_c \tag{3.62}
\]

Water vapour and dry air diffusion

The diffusion of water vapour and dry air through the gaseous mixture is proportional to the concentration gradient which is described by Fick’s law as:

\[
g_{d,a} = -\rho_g D_{va,mat} \frac{\rho_a}{\rho_g} \nabla \rho_a \tag{3.63}
\]

\[
g_{d,v} = -\rho_g D_{va,mat} \frac{\rho_v}{\rho_g} \nabla \rho_v \tag{3.64}
\]

where \( g_{d,a} = -g_{d,v} \) under assumption of Eq. 3.60, \( D_{va,mat} \) is the binary apparent diffusion coefficient between the dry air and water vapour in the porous material (m\(^2\)/s) calculated as:

\[
D_{va,mat} = \frac{D_{va}}{\tau} \phi_0 (1 - S_l) \tag{3.65}
\]

where \( \tau \) is the tortuosity of the pore space and \( D_{va} \) is the binary diffusion coefficient (m\(^2\)/s) given by Schirmer (1938):

\[
D_{va} = 2.31.10^{-5} \frac{P_{atm}}{p_g} \left( \frac{T}{273.16} \right)^{1.81} \tag{3.66}
\]

Assuming that \( \rho_g \) is quasi constant under atmospheric pressure and at temperatures below 50° C, Eq. 3.64 can be written as:

\[
g_{d,v} = -\rho_g D_{va,mat} \frac{\rho_v}{\rho_g} = -\frac{D_{va,mat}}{R_v T} \nabla p_v = -\delta_v \nabla p_v = -\frac{\delta_a}{\mu_p} \nabla p_v \tag{3.67}
\]

where \( \delta_v \) (s) is the water vapour diffusion coefficient in the porous material equal to \( D_{va,mat}/R_v T \), \( \delta_a \) (s) is the water vapour diffusion coefficient of dry air (\( \approx 1.87.10^{-10} \) at 20° C) and \( \mu_p \) is the vapour resistance factor of the porous material (-).
3.3.2.4 Conservation equations

The conservation equations of heat and mass transport in porous material are given below. The assumptions used to obtain these equations are (Defraeye, 2011):

- Three difference phases exist, namely solid, liquid and gas, where the solid phase only consists of solid material matrix (no ice).
- Moist air is a perfect mixture of two ideal gases: dry air and water vapour.
- Moist air, liquid water and solid matrix are assumed incompressible.
- No chemical reactions are taken into account.
- Gravitational and air-pressure effects are neglected compared to capillary forces.
- Liquid transport due to thermal gradients is neglected.
- The liquid permeability is independent of temperature.
- The pressure of the gaseous phase is constant and equal to atmospheric pressure.
- Moisture storage is independent of temperature.
- Material properties are assumed isotropic.
- Temperature remains below boiling temperature of water.

Conservation of mass

\[
c_{mm} \frac{\partial p_c}{\partial t} + c_{mh} \frac{\partial T}{\partial t} - \nabla T \left( k_{mm} \nabla p_c + k_{mh} \nabla T \right) = 0
\]  

(3.68)

with \( c_{mm} \) and \( c_{mh} \) being the capacity terms, and \( k_{mm} \) and \( k_{mh} \) the permeability terms, and subscripts \( m \) and \( h \) refer to moisture and heat, respectively.

\[
c_{mm} = \frac{\partial w}{\partial p_c}
\]  

(3.69)

\[
c_{mh} = 0
\]  

(3.70)

\[
k_{mm} = K_l + \frac{\delta v p_v}{\rho_l R_v T}
\]  

(3.71)

\[
k_{mh} = \frac{\delta v p_v}{\rho_l R_v T^2} (\rho_l L_v + p_c (T \gamma - 1))
\]  

(3.72)
Conservation of heat

\[ c_{hh} \frac{\partial T}{\partial t} + c_{hm} \frac{\partial p_c}{\partial t} - \nabla \cdot (k_{hh} \nabla T + k_{hm} \nabla p_c) = 0 \] (3.73)

with \( c_{hh} \) and \( c_{hm} \) being the capacity terms, and \( k_{hh} \) and \( k_{hm} \) the permeability terms, and subscripts \( m \) and \( h \) refer to moisture and heat, respectively.

\[
\begin{align*}
    c_{hh} &= c_{p,s} \rho_s + c_{p,l} w \\
    c_{hm} &= c_{p,l} T \frac{\partial w}{\partial p_c} \\
    k_{hh} &= \lambda + (c_{p,v} T + L_v) \frac{\delta_v p_v}{\rho_l R_v T^2} \left( \rho_l L_v + p_c (T \gamma - 1) \right) \\
    k_{hm} &= c_{p,l} T K_l + (c_{p,v} T + L_v) \frac{\delta_v p_v}{\rho_l R_v T} 
\end{align*}
\]

where \( c_{p,s}, c_{p,l} \) and \( c_{p,v} \) are the specific heat capacities of the solid matrix, liquid water and water vapour, respectively, \( K_l \) is the liquid water permeability, \( \rho_l \) is the liquid water density, \( L_v \) is the latent heat of evaporation, \( \lambda \) is the thermal conductivity of the porous material, \( w \) is the moisture content of the porous material, \( \delta_v \) is the water vapour diffusion coefficient in the porous material, \( p_c \) is the capillary pressure, \( R_v \) is the specific gas constant of water vapour, \( T \) is the temperature, \( t \) is the time and \( \gamma \) is the normalized derivative of the surface tension to the temperature.

### 3.4 Radiation model (RAD)

#### 3.4.1 Model description

In order to understand and model the surface energy budget of an urban area, it is important to understand the radiation budget at urban surfaces, including incoming short-wave radiation, emitted long-wave radiation and reflected short-wave and long-wave radiation.

The radiation model solves the radiative balance, considering the long-wave radiative exchange between windward wall, leeward wall, ground and sky, as well as the incoming short-wave solar radiation. The total radiation flux, \( q_{rad} \) for surface \( k \) is calculated as:

\[
q_{rad} = \frac{Q_{l,k} + Q_{dir,s,k} + Q_{dif,s,k}}{A_k} \quad (3.78)
\]
where $Q_{l,k} \text{ (W)}$ is the long-wave radiative flux for surface $k$, $Q_{\text{dir},s,k} \text{ (W)}$ is the short-wave radiative flux for surface $k$ coming from the sun, $Q_{\text{dif},s,k} \text{ (W)}$ is the short-wave radiative flux for surface $k$ coming from the other surfaces, and $A_k$ is the area of surface $k$. Multiple reflections are considered for all radiative fluxes by using Gebhart factors, $G$ (Gebhart, 1961; 1971) described later (Sec. 3.4.2).

The radiation model was verified by comparison with the building energy simulation model TRNSYS 17.0 (Transys, 2010) for a benchmark problem.

### 3.4.2 General equations

The long-wave radiative flux for a surface $k \,(Q_{l,k} \text{ (W)})$, is calculated as:

$$Q_{l,k} = A_k \varepsilon_k \sigma T_k^4 - \sum_{i=1}^{n} A_i \varepsilon_i \sigma F_{i,k} T_i^4$$

(3.79)

where $i$ is a surface that exchanges long-wave radiation with surface $k$ (Fig. 3.5), $T$ is the absolute temperature (K), $\sigma$ is the Stefan-Boltzmann constant (5.67x10$^{-8}$ W/m$^2$/K$^4$), $\varepsilon$ is the emissivity of the surface, $A$ is the surface area (m$^2$) and $F_{i,k}$ is the view factor between surfaces $i$ and $k$, calculated using equations provided by Siegel and Howell (2002).

![Figure 3.5: Schematic representation of the long-wave radiation exchange between surfaces $i$ and $k$](image)

In reality, a surface can receive long-wave radiation not only directly from a source, but also indirectly by reflection from other surfaces. In order to account for multiple reflections to surface $k$ from other surfaces $i$ (where $i=1...n$ and $n$ is the total number of surfaces), the view factor $F$ is replaced by the Gebhart factor, $G$ (Gebhart, 1961; 1971):

$$Q_{l,k} = A_k \varepsilon_k T_k^4 - \sum_{i=1}^{n} A_i \varepsilon_i T_i^4 G_{i,k}$$

(3.80)

where the Gebhart factor is calculated by:
3.4. Radiation Model (RAD)

\[ G = (I - F\rho)^{-1}F(1 - \rho) \]  

where \( \rho \) is the reflectivity matrix and \( I \) the identity matrix. The Gebhart factor is based on the assumption that a part of the radiation received by opaque surfaces is absorbed and the remaining part is reflected in a diffuse way, therefore specular reflection of direct solar irradiation is not considered.

The short-wave radiative flux, coming from the sun, for surface \( k \) (\( Q_{\text{dir},s,k} \) (W)) including multiple reflections is calculated as:

\[ Q_{\text{dir},s,k} = A_k(1 - \varepsilon_{s,k})I_{\text{dir},k} + \sum_{i=1}^{n} A_i G_{i,k} \varepsilon_{s,i} I_{\text{dir},i} \]  

where \( G \) is the Gebhart factor as described above, \( \varepsilon_{s,k} \) is the albedo of surface \( k \), and \( I_{\text{dir}} \) is the solar radiation intensity flux (W/m\(^2\)) coming from the sun.

The short-wave radiative flux, coming from the other surfaces, for surface \( k \), (\( Q_{\text{dif},s,k} \) (W)), including multiple reflections is calculated as:

\[ Q_{\text{dif},s,k} = \sum_{i=1}^{n} A_i I_{\text{dif},i} G_{i,k} \]  

3.4.3 Calculation of the short-wave radiation intensity flux

The total short-wave radiation, \( I_t \), reaching a surface on the earth is given by:

\[ I_t = I_{\text{dir}} + I_{\text{dif}} \]  

The direct short-wave radiation intensity flux on a surface, \( I_{\text{dir}} \), is calculated by:

\[ I_{\text{dir}} = I_{DN} \cos \theta \]  

where \( \theta \) is the incidence angle, shown in Fig. 3.6, which is the angle between the incoming solar rays and a line normal to the receiving surface, and \( I_{DN} \) (W/m\(^2\)) is the direct normal short-wave radiation intensity flux:

\[ I_{DN} = Ae^{\frac{B}{\sin \beta}} \]  

Values for constants \( A \) and \( B \) are provided in the ASHRAE Handbook (ASHRAE, 2009), tabulated for the 21st day of each month of the year (Table 3.1). These values are for average cloudless days, and can vary throughout the year owning to changing dust and water-vapour content of the air. \( \beta \) (Fig. 3.6) is the solar altitude.
The incidence angle, $\theta$, is calculated by:

$$\cos \theta = \cos \beta \cos \gamma \sin \Sigma + \sin \beta \cos \Sigma$$  \hspace{1cm} (3.87)

where $\gamma$ is the difference between the solar azimuth $\phi$ and the azimuth $\psi$ of a normal to the surface, and $\Sigma$ is the tilt angle (Fig. 3.6).

The value $\sin \beta$ is calculated as:

$$\sin \beta = \cos L \cos \delta \cos H + \sin L \sin \delta$$  \hspace{1cm} (3.88)

where $L$ is the altitude, $H$ is the hour angle, and $\delta$ is the declination angle calculated as (Howell et al., 1982; Duffie and Beckman, 1991):

$$\delta = 23.45 \sin \frac{360(D + 284)}{365}$$  \hspace{1cm} (3.89)

where $D$ is the number of days elapsed since January 1st.

The hour angle ($H$) in Eq. 3.88 is an angular measure of time, equal to $15^\circ$ per hour with morning as positive and afternoon as negative values. $H$ is measured as:

$$H = 15(12 - ST)$$  \hspace{1cm} (3.90)

where $ST$ is the noon-based local solar time, calculated by:

$$ST = LT + ET/60 - 4/60 + (L_S - L_L)$$  \hspace{1cm} (3.91)

where $LT$ is the local standard time, $L_S$ is the standard meridian, $L_L$ is the local longitude, and $ET$ is the equation of time calculated as:

$$ET = 9.8 \sin 2b - 7.53 \cos b - 1.5 \sin b$$  \hspace{1cm} (3.92)

where $b$ is calculated as $360(D - 81)/365$.

The diffuse short-wave radiation intensity flux ($I_d$ (W/m$^2$)) is calculated as:

$$I_{dif} = CI_{DN}F_{ss}$$  \hspace{1cm} (3.93)

where $C$ is the diffuse radiation factor (ASHRAE, 2009) which is tabulated in Table 3.1, and $F_{ss}$ is the angle factor between surface and sky, giving the fraction of short-wave radiation emitted by the sky that reaches the surface. $F_{ss}$ is 0.5 for vertical surfaces and 1.0 for horizontal surfaces.
Table 3.1: Constants A, B and C from ASHRAE (2009) for the 21st day of each month

<table>
<thead>
<tr>
<th>Months</th>
<th>A, W/m²</th>
<th>B, dimensionless</th>
<th>C, dimensionless</th>
</tr>
</thead>
<tbody>
<tr>
<td>January 21</td>
<td>1,229.475</td>
<td>0.142</td>
<td>0.058</td>
</tr>
<tr>
<td>February 21</td>
<td>1,213.713</td>
<td>0.144</td>
<td>0.060</td>
</tr>
<tr>
<td>March 21</td>
<td>1,185.340</td>
<td>0.156</td>
<td>0.071</td>
</tr>
<tr>
<td>April 21</td>
<td>1,134.900</td>
<td>0.180</td>
<td>0.097</td>
</tr>
<tr>
<td>May 21</td>
<td>1,103.375</td>
<td>0.196</td>
<td>0.121</td>
</tr>
<tr>
<td>June 21</td>
<td>1,087.613</td>
<td>0.205</td>
<td>0.134</td>
</tr>
<tr>
<td>July 21</td>
<td>1,084.460</td>
<td>0.207</td>
<td>0.136</td>
</tr>
<tr>
<td>August 21</td>
<td>1,106.528</td>
<td>0.201</td>
<td>0.122</td>
</tr>
<tr>
<td>September 21</td>
<td>1,150.663</td>
<td>0.177</td>
<td>0.092</td>
</tr>
<tr>
<td>October 21</td>
<td>1,191.645</td>
<td>0.160</td>
<td>0.073</td>
</tr>
<tr>
<td>November 21</td>
<td>1,220.018</td>
<td>0.149</td>
<td>0.063</td>
</tr>
<tr>
<td>December 21</td>
<td>1,232.628</td>
<td>0.142</td>
<td>0.057</td>
</tr>
</tbody>
</table>

Figure 3.6: The solar angles (ASHRAE, 2009)

3.4.4 Surface properties

When a surface is irradiated, the radiation may be absorbed, reflected or transmitted through the material, and:

$$\alpha + \tau + \rho = 1$$

where \(\alpha\) is the absorptance, \(\tau\) is the transmittance and \(\rho\) is the reflectance. For an opaque surface \(\alpha + \rho = 1\) and for a black surface, \(\alpha = 1\).

Absorptance of a non-black body is related to its emissivity (\(\varepsilon\)). According to
Kirchhoff’s law, for a grey body, emissivity and absorptance are equal, therefore, from here on, we only talk about emissivity $\varepsilon$. We have to distinguish between the emissivity of a grey body for short-wave (solar) and long-wave (infrared) radiation. The values of emissivity for short-wave (albedo) and long-wave radiation ($\varepsilon_s$ and $\varepsilon$, respectively) for different building materials are given in Table 3.2:

**Table 3.2:** Emissivity ($\varepsilon$) and albedo ($\varepsilon_s$) for different building materials (ASHRAE, 2009)

<table>
<thead>
<tr>
<th>Materials</th>
<th>$\varepsilon$</th>
<th>$\varepsilon_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>polished metal</td>
<td>0.05-0.10</td>
<td>0.10-0.40</td>
</tr>
<tr>
<td>brick</td>
<td>0.75-0.90</td>
<td>0.65-0.80</td>
</tr>
<tr>
<td>glass</td>
<td>0.90-0.95</td>
<td>&lt;0.15</td>
</tr>
<tr>
<td>white finishes</td>
<td>0.60-0.75</td>
<td>0.30-0.50</td>
</tr>
<tr>
<td>black finishes</td>
<td>0.90-0.98</td>
<td>0.85-0.98</td>
</tr>
</tbody>
</table>

### 3.5 Coupling strategy

An efficient coupling strategy has been developed to minimize computational run-time without sacrificing accuracy. Since the time-scales for air transport in the air domain are much smaller than in the porous domain(s), we can assume that the air flow quasi immediately adjusts to changes in boundary conditions at the interface. The heat and moisture transport in the porous material is characterized by larger time-scales and hence transient behavior has to be considered. Furthermore, common porous materials exhibit severe non-linearity in their properties, especially those governing moisture transport. Therefore, steady-state CFD simulations are conducted for the air domain at every coupling time step ($\Delta t_{ex}$), while the BE-HAM simulations are performed transient within this coupling time step: they employ adaptive time-stepping. The size of the exchange time step ($\Delta t_{ex}$), governing data exchange between the two models, is determined based on a sensitivity study which will be discussed in Sec. 5.2.3. The diagram below (Fig. 3.7) shows the schematics of the coupling strategy. The steps included in the coupling can be described as follows and can be seen in Fig. 3.8:

1. For every exchange time step ($\Delta t_{ex}$), the BE-HAM model conducts a transient simulation, with variable internal time steps, and passes the final surface temperatures to the RAD model. The RAD model calculates the long and short-wave radiative balance at the surfaces and sends back the new radiative heat fluxes to the BE-HAM model. Here again, for the same exchange time step ($\Delta t_{ex}$), a new BE-HAM simulation is conducted and the final surface temperatures are passed again to the RAD model. For every exchange time step, the BE-HAM and the RAD models exchange data (temperature and radiative heat flux) until the solution is converged between both models.
2. The final surface temperatures as well as the moisture contents, calculated using the BE-HAM model, at the interfaces between the air and porous domains are passed on to the CFD model and a steady-state CFD simulation is performed until a converged solution is attained.

3. The CFD model calculates the \( CHTC \) and the \( CMTC \) values at the air and porous domain interfaces and passes them to the BE-HAM model. These convective transfer coefficients are calculated from the heat or mass fluxes provided by CFD and reference temperature and vapour pressure \( (T_{ref} \text{ and } p_{v,ref}) \) which are taken at the centre of the street canyon.

Steps 1 to 3 are repeated again until the end of the simulation.
3.6 Comfort model

In this thesis the Universal Thermal Climate Index (UTCI) (Fiala et al., 2012) is used for the evaluation of human comfort. For calculation of the UTCI, the BioKlima 2.6 software package is used. Parameters used for calculation of the UTCI are the air temperature (°C), vapor pressure (Pa), wind speed (m/s) and mean radiant temperature (°C). The air temperature, vapor pressure and wind speed at a certain location in the street canyon are outputs of the CFD model. The mean radiant temperature ($T_{mrt}$) is calculated as:

$$T_{mrt} = \left(\frac{T^4_{umrt} + A_p\alpha_p I_{dir}}{A_{eff}\varepsilon_p\sigma}\right)^{0.25}$$  \hspace{1cm} (3.95)

where $I_{dir}$ (W/m$^2$) is the direct solar radiation intensity flux, $\alpha_p$ is the clothed human body absorptance (0.9 for color temperature of 1200 K) (Fanger, 1970), $\varepsilon_p$ is the human body emissivity (0.97), $\sigma$ is the Stefan-Boltmann constant, $A_p$ is the area of the person projected onto the plane perpendicular to the direction of the radiant source and $A_{eff}$ is the effective radiation area of human body. In order to make the calculation of $T_{mrt}$ independent of the size of the actual person, the projected area factor, $f_p$, is introduced, relating $A_p$ and $A_{eff}$ by (Fanger, 1970):

$$f_p = \frac{A_p}{A_{eff}}$$  \hspace{1cm} (3.96)

$f_p$ is a function of solar altitude and solar azimuth. Averaged over 360° solar azimuth, $f_p$ can be calculated by:

$$f_p = 0.308\cos(\beta(1 - \frac{\beta^2}{48402}))$$  \hspace{1cm} (3.97)

where $\beta$ is the solar altitude.

$T^4_{umrt}$ is calculated as:

$$T^4_{umrt} = \frac{1}{\sigma}(B_1F_{p-1} + B_2F_{p-2} + ... + B_iF_{p-i})$$  \hspace{1cm} (3.98)

where $F_{p-i}$ is the view factor between a standing person and surface $i$ (Fanger, 1970) and $B_i$ is the radiosity of surface $i$, calculated as:

$$B_i = \varepsilon_i\sigma T^4_i + \rho_i q_l, i$$  \hspace{1cm} (3.99)

where $q_l, i$ (J/m$^2$s) is the long-wave radiation arriving at surface $i$. 

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3.6. COMFORT MODEL

UTCI threshold values have been identified based on the occurrence of thermal stress, shown in Table 3.3 (Broede et al., 2011).

Table 3.3: UTCI equivalent temperatures categorized in terms of thermal stress (Broede et al., 2011)

<table>
<thead>
<tr>
<th>UTCI range (°C)</th>
<th>stress category</th>
</tr>
</thead>
<tbody>
<tr>
<td>above +46</td>
<td>extreme heat stress</td>
</tr>
<tr>
<td>+38 to +46</td>
<td>very strong heat stress</td>
</tr>
<tr>
<td>+32 to +38</td>
<td>strong heat stress</td>
</tr>
<tr>
<td>+26 to +32</td>
<td>moderate heat stress</td>
</tr>
<tr>
<td>+9 to +26</td>
<td>no thermal stress</td>
</tr>
<tr>
<td>0 to +9</td>
<td>slight cold stress</td>
</tr>
<tr>
<td>-13 to 0</td>
<td>moderate cold stress</td>
</tr>
<tr>
<td>-27 to -13</td>
<td>strong cold stress</td>
</tr>
<tr>
<td>-40 to -27</td>
<td>very strong cold stress</td>
</tr>
<tr>
<td>below -40</td>
<td>extreme cold stress</td>
</tr>
</tbody>
</table>

Broede et al. (2011) have done studies for investigating the sensitivity of the UTCI regarding variations in humidity, wind speed and radiation intensity. Fig. 3.9a shows the effect of relative humidity on the offset of the UTCI from air temperature (UTCI-$T_a$). This is calculated for $T_{mrt} = T_a$ and for a wind speed of 0.5 m/s in air temperature below 20°C (reference conditions). It can be seen that at low air

![Figure 3.9](image-url)

**Figure 3.9:** a) Influence of relative humidity on the offset of the UTCI from the air temperature and b) Psychrometric chart with UTCI calculated with reference conditions and different vapour pressure (Broede et al., 2011)
temperatures, the UTCI is not much affected by humidity. At moderate temperatures, relative humidity values larger than the reference (50%) result in an increase in UTCI, while lower relative humidity values result in a decrease in the UTCI. For air temperatures above 20°C, Fig. 3.9b shows an increase of the UTCI with increase of humidity (leftwards bending of contour lines). The dark gray line in this figure shows the relative humidity for the reference condition. This effect is much stronger at higher air temperatures and higher vapour pressures.

Fig. 3.10 shows the influence of wind speed at 10 m above ground, on the UTCI offset from air temperature, for different air temperatures. The relative humidity and mean radiant temperature are the ones of the reference condition (Sec. 2.4.2.5). At air temperatures above 35°C, an increase in wind speed results in an increase in heat stress. For low temperatures, cold stress is greatly increased at higher wind speeds. Fig. 3.11 shows the variation of the UTCI with variation of radiant heat load, expressed as $T_{mrt}-T_a$ for various air temperatures. The wind speed and relative humidity are the ones of the reference condition (Sec. 2.4.2.5). It can be seen that the UTCI increases linearly with radiation intensity. The increase of the UTCI is approx. 3K per 10K increase in $T_{mrt}$.

![Figure 3.10: Effect of wind speed at 10 m above the ground on the offset of the UTCI from the air temperature (Broede et al., 2011)](image-url)
3.7 Conclusions

In this chapter, the proposed coupled model was introduced. The three main sub-models, i.e. the CFD, the BE-HAM and the RAD models, and the governing equations were described. The comfort model was discussed which evaluates the thermal comfort of a human in the street canyon. The way in which the three sub-models exchange information, is described in Sec. 3.5.

In the next chapters, the results of the coupled model are compared with experimental results and the similarities and differences are discussed (Chp. 4). Further, the coupled model is used for different case studies to evaluate the effectiveness of evaporative cooling in a street canyon (Chp. 5).
Chapter 4

Model validation

4.1 Introduction

In Chapter 3, the coupled micro-climate model was introduced, which consists of three sub-models: a CFD model which solves the convective heat, air and moisture transport in the air domain, a BE-HAM model which solves the heat and moisture transport within the porous material, and a radiation model which solves the radiative balance for short-wave and long-wave radiative exchange between the building surfaces.

The proposed model contains a number of assumptions and simplifications. For the air domain we consider a 2D, steady state flow field hence the air velocity, air temperature and vapour pressure in the air domain remain constant in time. For the porous material, we consider a 2D domain and we assume a constant pressure of the gaseous phase equal to the atmospheric pressure. Information is exchanged between the CFD and BE-HAM models at every time step without conducting iterations between the two. Considering these assumptions and simplifications, the proposed model needs to be validated. To that extent, experiments were conducted which looked at: i) drying of a ceramic brick specimen in a micro wind-tunnel using neutron radiography, and ii) wind flow studies above the ceramic brick specimen in a micro wind-tunnel using particle imaging velocimetry. Results of the conducted tests are compared with the numerical simulation results and the differences between the two are discussed. It should be noted that the experiments were performed on scaled specimen (approx. 4 x 9 x 1 cm). The reason for this choice is the limitation of the neutron radiography setup regarding the the maximum specimen size that can be tested. We are aware of the fact that this downscaling might cause differences in the flow pattern in comparison to a real size street canyon and differences in the drying behavior of the porous surfaces. The similarities between the two scales will be discussed later in this chapter. The current study is conducted to confirm the accuracy of the coupling procedures between
CHAPTER 4. MODEL VALIDATION

the sub-models.

In this chapter, first in Sec. 4.2, the experimental setup and methods used are described. These include the description of the micro wind-tunnel, the neutron radiography technique and the particle imaging velocimetry technique. The results achieved using these experimental methods are provided and discussed.

Next, in Sec. 4.3, the experimental results are compared with simulation results achieved using coupled and uncoupled simulations. Similarities between the two are discussed and possible reasons for observed differences are given.

4.2 Experiments

Two types of experiments are conducted: i) experiments using neutron radiography to observe the drying behavior of a ceramic brick specimen, and ii) experiments using Particle Imaging Velocimetry (PIV) in order to observe the flow conditions above the specimen. Both experiments are conducted in a micro wind-tunnel, which allows to perform controlled drying of the specimen in the neutron setup.

In this section, first the micro wind-tunnel is described, followed by the description of the tested specimens and their transport properties. Then each of the two experimental methods (neutron radiography and PIV) are explained and the achieved results are discussed.

4.2.1 Micro wind-tunnel

A small scale open-circuit wind-tunnel, suitable for studying the convective drying of specimens in a neutron setup, is employed (Fig. 4.1). The micro-tunnel is mainly made of transparent polymethyl methacrylate (PMMA). For the neutron radiography experiments, the test section is made of 99% pure aluminum, due to its transparency to neutrons. For the PIV experiments, the test section is in PMMA, like the rest of the micro-tunnel. A schematic representation of the micro wind-tunnel, including its dimensions, is shown in Fig. 4.2. A small axial fan of 50 mm diameter drives the air flow. By fan control, centerline air speeds \( \bar{u}_{cl} \) at the inlet of the channel from 0.28 m/s to 4.2 m/s can be obtained, corresponding to Reynolds numbers from 200 to 2900 (based on \( \bar{u}_{cl} \) and \( H = \) channel height of 10 mm). The location where the inlet profile (IP) is taken, is shown in Fig. 4.2. After going through a diffusing section, which reduces the air speed, the air passes through a honeycomb with 5 mm wide cells and a two-dimensional contraction (contraction ratio = 5). The honeycomb reduces the turbulence and non-uniformities which were created by the fan, while the contraction results in speed up of the flow to a required level for the test section. The channel section is 10 mm high and has a width to height ratio of 7, which is the minimum ratio to obtain a quasi two-dimensional channel flow (Dean, 1978). In the
test section, below the channel, specimens of maximum 90 mm in length and 50 mm in height, can be placed. More detailed information about the micro wind-tunnel can be found in Defraeye (2011).

Figure 4.1: The micro wind-tunnel

Figure 4.2: Schematic representation of the micro wind-tunnel, a) side view and b) top view
4.2.2 Test specimen

Two brick specimens were tested, one in the shape of a flat plate (FP) chosen as a simple geometry, and one with a cavity, which resembles the shape of a small-scale street canyon (SC) chosen as a more complex geometry (Fig. 4.3). For the FP specimen, the top surface is exposed to convective drying while the bottom surface and sides are made vapour tight. For the SC specimen, the upstream part of the cavity is 3 cm and the width and height of the cavity measure 2 x 2 cm. The surfaces that are exposed to convective drying are the windward, leeward and ground surfaces of the cavity, while the top, bottom and sides of the specimen are made vapour tight. Table 4.1 shows the volume and thickness of the two specimens, as well as their average moisture content just before the start of the experiment ($w_{ini}$). A schematic of the two specimens is shown in Fig. 4.3.

The material properties for the ceramic brick have been determined experimentally and can be found in Derluyn et al. (2008). Most important transport properties are given in the Table 4.2, where $\rho_b$ ($\text{kg/m}^3$) is the bulk density, $c_p$ ($\text{J/kgK}$) is the specific heat capacity, $\mu_{dry}$ (-) is the vapour resistance factor of the dry material, $\lambda$ ($\text{W/mK}$) is the thermal conductivity, and $w_{cap}$ ($\text{kg/m}^3$) is the capillary moisture content.

<table>
<thead>
<tr>
<th>specimen</th>
<th>volume ($\text{m}^3$)</th>
<th>thickness (m)</th>
<th>$w_{ini}$ ($\text{kg/m}^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat plate (FP)</td>
<td>$2.77\times10^{-5}$</td>
<td>0.01</td>
<td>121</td>
</tr>
<tr>
<td>Street canyon (SC)</td>
<td>$3.0305\times10^{-5}$</td>
<td>0.01</td>
<td>117</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\rho_b$ ($\text{kg/m}^3$)</th>
<th>$c_p$ ($\text{J/kgK}$)</th>
<th>$\lambda$ ($\text{W/mK}$)</th>
<th>$\mu_{dry}$ (-)</th>
<th>$w_{cap}$ ($\text{kg/m}^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2087</td>
<td>840</td>
<td>$1 + 0.0047w$</td>
<td>24.79</td>
<td>130</td>
</tr>
</tbody>
</table>

The vapour diffusion coefficient, as a function of moisture content $w$, is calculated by:

$$
\delta_v = \frac{2.61 \times 10^{-5}}{\mu_{dry} R_o T} \frac{1 - (w/w_{cap})}{0.503(1 - (w/w_{cap}))^2 + 0.497}
$$

(4.1)

The vapour diffusion coefficient is used to calculate the vapour permeability ($K_v$), given in Eq. 3.71:

$$
K_v = \frac{\delta_v \phi_{v,\text{sat}}}{R_o T \rho_l}
$$

(4.2)
where $\phi$ (-) is the relative humidity, $p_{v,sat}$ (Pa) is the saturated vapour pressure, $T$ (K) is the temperature, $R_v$ is the specific gas constant of water vapour (461.524 $\text{J/kgK}$) and $\rho_l$ is the density of water (1000 $\text{kg/m}^3$). The sum of vapour and liquid permeabilities is the moisture permeability of the material:

$$K_{mm} = K_v + K_l \quad (4.3)$$

Liquid and vapour permeabilities as a function of capillary pressure are shown in Fig. 4.4a. The moisture retention curve of the material is calculated by:

$$w(p_c) = w_{cap}[0.846\left(1 + (1.394 \times 10^{-5} p_c)^4\right)^{-0.75} + 0.154\left(1 + (0.9011 \times 10^{-5} p_c)^{1.69}\right)^{-0.408}] \quad (4.4)$$

The moisture retention curve is shown in Fig. 4.4b.

### 4.2.3 Neutron radiography

Previously, researchers have used neutron radiography for the determination of moisture diffusivity of various porous materials (Pel et al., 1993; Pleinert et al., 1998; El Abd et al., 2009), to investigate the drying process of quartz sand (Fijal-Kirejczyk et al., 2011) and concrete (de Beer et al., 2004). These studies show the applicability of neutron radiography for experimentally determining the water transport in porous materials.
CHAPTER 4. MODEL VALIDATION

Figure 4.4: a) Liquid and vapour permeabilities and b) moisture retention curves of ceramic brick

In neutron radiography, neutrons are emitted from a source, pass through a collimator, which shapes the emitted neutrons into a fairly unidirectional beam, and then pass through the test specimen. Depending on the neutron attenuation properties of the material, some of the neutrons are transmitted through the material which are then converted to visible light photons and led via a mirror onto a CCD camera. Using this method, 2D projections of an object can be recorded, which contain information on the attenuated radiation intensity. The attenuation of the beam is due to the interaction of neutrons with the nuclei of the atoms. The high attenuation of the neutron beam by hydrogen nuclei, which are the main components of water, makes neutron radiography a suitable method for visualization of water in a porous material (such as ceramic brick), and to investigate moisture transport and its distribution.

The open-circuit micro wind-tunnel is used to dry the specimen while the NEUtron Transmission RAdiography (NEUTRA) beamline at the Paul Scherrer Institute (PSI) is used for visualization of the water distribution in the specimen as a function of time. In the next section, the experimental setup is described in detail. Then, the experimental procedures are explained, followed by the achieved results.

4.2.3.1 Experimental setup

The imaging facilities of the NEUTRA beamline at the PSI in Villigen, Switzerland, are used for visualization of the water content distribution in the ceramic brick during its drying process. Being fed by the Swiss Neutron Spallation Source (SINQ), this beamline station relies on a neutron beam within the thermal spectrum, with a most probable energy level of about 25 meV (Lehmann et al., 2001).

Fig. 4.5 shows the schematic overview of the NEUTRA beamline and the test setup. The detector consists of a scintillator-CCD camera system, with a total field of view
of 108.5 x 108.5 mm$^2$. The scintillator, made of 100 µm thick zinc sulfide doped with $^6$Li as the neutron absorbing agent, converts the neutron signals into visible light photons. The photons are then led via a mirror onto a cooled 16-bit CCD camera (1024 x 1024 pixels). For the purpose of the present experiment, the exposure time is 8 seconds per radiography, and the attained spatial resolution is 106 µm per pixel. Based on the gray value range of dry and wet neutron images (Roels and Carmeliet, 2006), the attained moisture content resolution is 0.028 kg/m$^3$.

**Figure 4.5:** Schematic overview of the NEUTRA beamline and test setup

### 4.2.3.2 Experimental procedures

Initially the ceramic brick specimens are wet by immersion in water for a period of approx. 45 min, reaching a moisture content of 117 kg/m$^3$ for the SC (street canyon) and 121 kg/m$^3$ for the FP (flat plate) specimen. This initial moisture content, referred to as $w_{\text{ini}}$, is calculated by subtracting the specimen’s dry weight from the weight of the specimen after wetting, and dividing by the total volume of the specimen. After wetting, the specimens are wrapped with aluminum foil (to prevent evaporation) except for the top surface, hence creating a 2D drying behavior. The specimens are then mounted in the center of the micro wind-tunnel, along the centreline of the test section, while being thermally insulated on two sides with extruded polystyrene
After closing the top lid of the channel, the fan is switched on, producing a velocity at the center of the channel of approx. 2.3 m/s. The SC and FP specimens dry for a period of 24 hr and 12 hr, respectively.

During the drying process the weight change of the setup is continuously monitored and recorded (every 1 min) by placing the setup on a balance (accuracy of 0.01 g, corresponding to moisture content accuracy of 0.25% to 0.3%). Neutron radiography images of the specimens are taken approximately every 2 min.

Image Correction

In order to correct for some of the artifacts produced by the experimental configuration, prior to quantitative analysis explained in the next section, each raw neutron radiograph needs to be pre-processed which includes:

1. Dark current correction for the background noise of the CCD camera, performed by subtracting the radiograph acquired in absence of neutron beam from each radiograph of the specimen.

2. Intensity correction for temporal fluctuations of the incident beam, performed by averaging the beam variation in an area of the radiograph outside the specimen area, and applying this averaged correction factor to each pixel.

3. Flat field correction for eliminating spatial inhomogeneities in the beam (and detector) from the radiographs, performed by correcting (pixelwise) each radiograph with a radiograph with an open beam, i.e. without the test setup.

4. Black body correction for removing the neutron signal coming from scattering by the overall experimental configuration and environment, by subtracting a radiograph acquired when the test setup is shielded with boronated polyethylene, from each radiograph of the specimen.

5. Specimen scattering correction for neutrons that are scattered at small angles by the hydrogen atoms of the specimen itself.

To perform the above mentioned corrections, the Quantitative Neutron Imaging (QNI) software (Hassanein, 2006; Hassanein et al., 2005) is used.

Quantification of moisture content

Neutron radiography is based on intensity measurements of a neutron beam transmitted through an object. The intensity of the transmitted beam, $I$, can be described with the Beer-Lambert law:

$$I = I_0 e^{-\mu z}$$

(4.5)
where $I_0$ is the intensity of the incident neutron beam, $z$ is the thickness of the object along the beam direction and $\mu$ is the effective attenuation coefficient for neutrons (1/m), which describes the degree to which a material of one pure element interacts with and attenuates the neutron beam.

The effect of water, present in the specimen, on the neutron beam attenuation is considered equivalent to the effect of a water layer with thickness $z_W$ added to the dry specimen, of thickness $z_B$. Also the test setup (TS) attenuates the incident neutron beam. Implementing this description, Eq. 4.5 becomes:

$$I(t) = I_0 e^{-\{\mu_B z_B + \mu_{TS} z_{TS} + \mu_W z_W\}}$$  (4.6)

where the subscript $B$ refers to the dry brick specimen, the subscript $TS$ to the test setup and the subscript $W$ to the water (liquid and vapour). At a certain time, $t$, during the experiment, the change in the intensity of the transmitted beam with respect to the initial stage is due to the change of moisture content, i.e., due to the reduction of the "effective" water layer, $\Delta z_W(t)$, when drying. Therefore Eq. 4.6 can be written as:

$$I(t) = I_0 e^{-\{\mu_B z_B + \mu_{TS} z_{TS} + \mu_W(z_W(t_{ini}) + \Delta z_W(t))\}}$$  (4.7)

where $t_{ini}$ is the time of the first neutron image after the start of the drying experiment, $z_W(t_{ini})$ is the water thickness at the time $t_{ini}$, $\Delta z_W(t)$ is the reduction in water thickness at time $t$ due to the water removal from the specimen due to drying. $\Delta z_W(t)$ has a negative value, therefore the transmitted beam intensity ($I$) increases with time as the amount of water in the specimen decreases.

It was assumed that the change in neutron beam attenuation in this drying experiment is entirely due to the change of moisture content in the specimen (in analogy to Roels and Carmeliet (2006) for x-ray). The relative change in water thickness with time, $\Delta z_W(t)$, equivalent to the specimen water loss, can be determined by relating all images to the first image:

$$I(t) = I_0 e^{-\{\mu_B z_B + \mu_{TS} z_{TS} + \mu_W(z_W(t_{ini}) + \Delta z_W(t))\}} = I(t_{ini}) e^{\mu_W \Delta z_W(t)}$$  (4.8)

with

$$I(t_{ini}) = I_0 e^{-\{\mu_B z_B + \mu_{TS} z_{TS} + \mu_W z_W(t_{ini})\}}$$  (4.9)

where $I(t_{ini})$ is the intensity of the neutron beam for the initial image, at the start of the neutron experiment. Solving Eq. 4.8 for the change in water thickness ($\Delta z_W(t) < 0$) yields:

$$\Delta z_W(t) = -\frac{1}{\mu_W} \ln\left(\frac{I(t)}{I(t_{ini})}\right)$$  (4.10)
Multiplying $\Delta z_W$ with the water density, $\rho_W$, and dividing by the specimen thickness ($z_{B,ini}$) gives the change in water content of the specimen over time ($\Delta w(t)$, kg/m$^3$):

$$\Delta w(t) = \rho_W \frac{\Delta z_W(t)}{z_{B,ini}} = -\frac{\rho_W}{\mu_W z_{B,ini}} \ln \left( \frac{I(t)}{I(t_{ini})} \right)$$  \hspace{1cm} (4.11)

The water content at each point in time can then be determined by:

$$w(t) = w_{ini} + \Delta w(t)$$  \hspace{1cm} (4.12)

with $w_{ini}$ being the initial water content.

The preceding explanation of neutron radiography analysis as well as of the corrections are valid for a monochromatic neutron beam. Since the actual beam covers a spectrum of energy and since the attenuation parameters are dependent on energy, the exponential law described in Eq. 4.5 needs to be replaced by:

$$\frac{I(t)}{I_0(t)} = \frac{\int_0^\infty P(E)\varepsilon(E)e^{-\mu(E)z}dE}{\int_0^\infty P(E)\varepsilon(E)dE}$$  \hspace{1cm} (4.13)

where $E$ is the energy of the incident neutrons, $\varepsilon(E)$ is an energy sensitivity parameter for each pixel of the scintillator and $P(E)$ is the Maxwell-Boltzmann probability density function for the energy of particles in a classical gas.

### 4.2.3.3 Experimental results

In this section, the obtained moisture content distributions as a function of time, for the two ceramic brick specimens, are shown and the results are discussed.

**Flat plate specimen**

Fig. 4.6a depicts the change in moisture content vs. time for the FP specimen. The solid line is the result achieved using neutron radiography, the dashed line gives the moisture content data calculated from the gravimetric weight change of the specimen, and the large circle is the moisture content obtained from the dry weight and the weight of the specimen at the end of the test. It can be seen that although the neutron method slightly overestimates the moisture content in comparison to the balance and the manual weighing, the agreement is quite good. Therefore we can use the neutron data for further analysis of the drying process of the specimen. For this specimen, drying starts from a moisture content of approx. 121 kg/m$^3$ and reaches approx. 50 kg/m$^3$ after 12 hrs of drying.

Neutron radiography gives us the possibility to study the spatial distribution of moisture in our specimen. Fig. 4.7 shows the contours of moisture content in the
Figure 4.6: a) Average moisture content vs. time and, b) Profiles of moisture content along the height of the specimen (z-axis) for different times, for the FP specimen

Figure 4.7: Contours of moisture content in the FP specimen, achieved using neutron radiography, at different times during drying
FP brick specimen at various times during drying (after 0.6, 1.2, 2.4, 6 and 12 hrs). The air flow is coming from the left side (see dashed arrow). Two drying phases can be observed in these images: i) the first drying phase, which lasts for approx. 2 hours, where the moisture content is quite uniform, and ii) the second drying phase, where a drying front develops at the top of the specimen and slowly moves inwards as the drying continues.

From Fig. 4.7 we can see that drying of the FP brick specimen is rather 2D, therefore we can extract the average moisture content profiles across the height of the specimen (Fig. 4.6b). Here location '0 cm' refers to the top of the specimen (exposed to the air flow) and location '3.0 cm' is at the bottom of the specimen. Moisture content profiles after 0.6, 1.2, 2.4, 6 and 12 hr are shown. From this figure, the progression of the moisture content in the material can be clearly seen. The average moisture content in the specimen drops to approx. 110 kg/m$^3$ after 0.6 hr of drying. As the drying continues, the moisture content reduces over the entire height of the specimen; drying more significantly at the top and bottom. The drying at the top resembles the development of a drying front. The drying at the bottom is probably due to leakage via the joints of the aluminum tape. By the end of the experiment, the moisture content at the top of the specimen drops to approx. 10 kg/m$^3$.

Street canyon specimen

The second specimen is a ceramic brick specimen with a small cavity. First we look at the drying behavior of the entire specimen (Fig. 4.8), and analyse the change in moisture content as a function of time, obtained by neutron radiography (solid line), automatic balance (dashed line) and manual weighing (large circle). The gap observed between approx. 9 hr to 13 hr for the neutron radiography results is due to interruption of the neutron beam during the experiments. Similar to the observation for the FP specimen, it can be seen that neutron imaging slightly overestimates the moisture content in comparison to the balance and the manual weighing. The agreement is nevertheless quite satisfying and we continue using the neutron radiography data for further analysis. The specimen has an initial moisture content of 117 kg/m$^3$ and after 24 hrs of drying it reaches 35 kg/m$^3$.

Now we analyze the total moisture content distribution in the SC specimen at various times during the drying process achieved using neutron radiography (Fig. 4.9). Air flow is coming from the left side as indicated by the dashed arrow. It can be seen that drying starts at the windward, leeward and ground surface, followed by the gradual progress of the drying front deeper into the material. The images show that by the end of the drying period, the leeward section shows a larger dry section in comparison to the windward section. Similar to the FP specimen, some drying at the bottom side of the specimen is observed. Visual inspection after the test revealed that the aluminum tape was damaged and partially removed. To correct for this error, the bottom 0.5 cm of the specimen is not considered in the calculation of the moisture content.
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Figure 4.8: Average moisture content vs. time for SC specimen

For a more detailed analysis of the drying process, we focus on three 1 mm wide regions, one at the middle of the windward side, one at the middle of the leeward side, and one at 2 mm from the leeward side.

Figure 4.9: Contours of moisture content in the SC specimen, achieved using neutron radiography, at different times during drying
Figure 4.10: Location for three studied sections for SC specimen

side and one at the middle of the ground location. These sections are referred to as, windward, leeward and ground and are shown in Fig. 4.10. The average moisture content in the windward section decreases from approx. 117 kg/m$^3$ to approx. 50 kg/m$^3$ after 24 hrs of drying (Fig. 4.11a). The hourly moisture content profiles along the length of this section (0 cm is the side exposed to convective drying), show the change of moisture content after 0.5, 2, 6, 14 and 24 hrs (Fig. 4.11b). Until approx. 2 hrs after the start of the test, no clear drying front can be observed. This is the first drying phase when the liquid transport from inside the material to the surface is sufficiently fast, so that the relative humidity stays at approx. 100% and the moisture content stays above the critical value. After approx. 6 to 14 hrs, the start of the second drying phase can be observed. This can be noted by the appearance of a drying front at the surface exposed to convective drying (left side of the windward section), and its gradual progression deeper into the material. In the second drying phase, the "dry" outer porous-material layer forms an additional resistance for vapour transport and therefore the drying rate decreases. After 24 hrs, the moisture content at the surface reaches approx. 5 kg/m$^3$. For the leeward section (Fig. 4.11c and d), the average moisture content drops to approx. 30 kg/m$^3$ by the end of the test. It can be seen that the second drying phase happens between 6 to 14 hrs of drying and after 24 hrs, the moisture content becomes almost zero up to a depth of 0.25 cm. For the ground section (Fig. 4.11e and f), the average moisture content reaches approx. 25 kg/m$^3$ by the end of the test. The profiles of moisture content along the length of the section show that the section dries completely up to a depth of 0.5 cm from the surface exposed to convection after 24 hrs. Fig. 4.12 compares the average moisture content profiles along each of the 3 sections after 24 hrs of drying. As discussed, the ground section has the largest dry region by the end of the test, while the windward section has the smallest one.

From Fig. 4.12, it can also be seen that the leeward and ground sections dry faster and reach a lower moisture content value by the end of the 24 hr drying period, in comparison to the windward section. Knowing that the windward section had a larger length (4 cm) in comparison to the leeward (3 cm) and ground (2 cm), slower drying of this section is expected. More time is needed for all the water in the windward section to be transported to the windward surface and to evaporate. The same explanation can be given for the slower drying of the leeward section in comparison to the ground.
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Figure 4.11: Average moisture content vs. time for the a) windward, c) leeward and e) ground section. Profiles of moisture content along defined sections for different times for b) windward, d) leeward and f) ground.

Fig. 4.13 compares the amount of water loss from each of the sections, as a function of time. It can be seen that by the end of the drying period, mass loss for the windward section is approx. 3000 g/m², for the leeward section it is approx. 2700 g/m² and for the ground section it is approx. 2000 g/m². Higher mass loss for the windward
Figure 4.12: Average moisture content profiles along each of the sections (windward, leeward and ground) after 24 hrs of drying

section is expected due to the larger size of this area. It can be seen that the mass loss of the ground section occurs at a lower rate in comparison to the windward and leeward sections. We believe that the duration of the first drying phase for the ground section is very short (not visible from this figure), after which the rate of mass loss reduces significantly.

Figure 4.13: Mass loss (g/m$^2$) as a function of time for the windward, leeward and ground sections of street canyon specimen

4.2.4 Particle Imaging Velocimetry (PIV)

PIV measurements of the flow field in the micro wind-tunnel were conducted above the SC specimen and also inside the cavity of the SC specimen.

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4.2. EXPERIMENTS

4.2.4.1 Measurement principle

A PIV measurement is conducted by seeding the flow with small tracer particles and determining their displacement. For this purpose, the particles are illuminated twice within a very short time interval, with a thin laser sheet and each time an image of the particles is acquired. By dividing the image into small Interrogation Areas (IA), each containing a number of particles, and cross-correlating each image pair, the particle displacement can be determined. Best cross-correlation is achieved when one distinct correlation peak can be identified. Velocity vectors can then be obtained for each IA by dividing the particle displacement by the time interval between the two images. The flow field can be achieved by combining the velocity vectors from each IA (Fig. 4.14). For a detailed explanation about the PIV technique, please refer to Prasad (2000).

![Figure 4.14: PIV technique (LaVision GmbH)](image)

4.2.4.2 System

The employed PIV system consists of a laser beam, a guiding arm, a camera, and a seeding device. Fig. 4.15 shows a schematic overview of the PIV system and the test setup. The laser system is a Nd:YLF laser with a wavelength of 527 nm, a maximum energy per pulse of 30 mJ at 1 kHz repetition rate and a pulse duration of 150 ns. The laser beam passes through a flexible guiding arm equipped with a cylindrical lens of -50 mm at the exit end, producing a laser sheet with a thickness of 4 mm. The camera used for image acquisition is equipped with a 12 bit CMOS sensor having a maximum resolution of 2016 x 2016 pixels up to 639 Hz. For the purpose of these measurements, the camera was used with a 135 mm F2.0 Canon objective plus two teleconverters and two extension tubes providing a field of view of 32 x 32 mm². The software used for image acquisition and post-processing is DaVis 8.0 by LaVision GmbH (LaVision GmbH, 2011). To seed the flow, aerosol particles were produced from DEHS (Di-Ethyl-Hexyl-Sebacat) liquid using a particle generator.
4.2.4.3 Error estimation

During a PIV measurement, errors can arise from various sources (Prasad, 2000; Keane and Adrian, 1990; Huang et al., 1997; Raffel et al., 2007):

- Random errors: mismatch between the recorded and the effective particle size, results in an error on the location of the centroid of the particle. These errors usually scale with the particle diameter, so they can be minimized by having small pixels. Random errors can also occur during cross-correlation, if particles that are not image pairs, are matched.

- Tracking errors: caused by the fact that real particles will not follow exactly the streamline, due to their inertia.

- Gradient errors: loss in correlation due to deformation and rotation of the flow within an IA. By choosing an appropriate size of the field of view and of the IA, the gradient within an IA can be minimized.

- Curvature errors: loss of effects due to acceleration and curvature due to the fact
that PIV relies on only two illumination pulses. This error can be minimized by reducing the time between the two laser pulses.

- Bias errors: occur during the process of determining the particle displacement using a curve-fit method. For small particles (less than 1 pixel), the determined displacement can be biased to integer pixel values, resulting in clustering near these values.

- Systematic errors: such as calibration errors, and 2D approximation of flow field (disregarding the out-of-plane velocity component).

Due to the interaction between these errors minimizing one type often results in the amplification of another type. Providing a quantitative error estimation is therefore difficult. By following some best-practice-guidelines, mentioned in the next section, the overall errors can be minimized.

4.2.4.4 Image acquisition

In order to minimize the possible measurement errors, some best practice guidelines for PIV (Prasad, 2000; Keane and Adrian, 1990; Bolinder, 1999) were taken into account:

- It was ensured that the particle density exceeds 10-15 particles per IA;
- The time interval between the two laser pulses was chosen to ensure that the displacement of particles is about 25% of the size of the IA;
- If the ratio between the first and second tallest correlation peak in an IA was below 1.5, the vector was not considered.

For time-averaged measurements, it is important to acquire sufficient statistically-independent image pairs. Statistical independence can be achieved when the time between the two images is sufficiently long (larger than twice the internal time scale of the flow, being the lifetime of the large-scale energy-containing eddies). Therefore the sampling rate (SR) can be estimated by:

\[ SR \leq \frac{1}{2T_{int}} = \frac{U}{2l} \quad (4.14) \]

where \( T_{int} \) is the internal time scale (s), \( U \) is the characteristic wind speed (m/s) and \( l \) is the characteristic length (m). The values chosen for \( U \) and \( l \) for each specific case are given below.

For the current measurements, we distinguish two different scenarios, i) the approach flow, and ii) the flow in the cavity of the street canyon specimen. Due the the specific flow characteristics in each of these two scenarios, the minimum sampling rate is calculated separately for each.
For the approach flow, considering a characteristic velocity of 2.3 m/s (based on preliminary measurements) and a characteristic length of 0.01 m (height of the channel), the minimum sampling rate is calculated to be 115 Hz. For the flow in the cavity, considering a characteristic velocity of 0.2 m/s (based on preliminary measurements) and a characteristic length of 0.02 m (depth of the cavity), the minimum sampling rate is calculated to be 5 Hz.

The required number of images (NS) are estimated, using the central limit theorem (Ott, 1993; Rohsenow and Choi, 1961), from the tolerated uncertainty on the mean wind speed ($u_c$), the coefficient of confidence ($z_a/2$) and the turbulence intensity ($I_t$):

$$NS = \left( \frac{1}{u_c} \frac{z_a}{2} I_t \right)^2$$

(4.15)

where $z_a/2$ is 1.65, 1.95 and 2.33 for confidence levels of 90%, 95% and 98%, respectively, for Gaussian distributions. Based on 2% allowed uncertainty on the mean wind speed, confidence level of 95% and estimated maximum $I_t \approx 30\%$ for the flow above the FP specimen and $I_t \approx 10\%$ for the flow in the cavity, minimum 855 and 95 images need to be acquired, respectively.

### 4.2.4.5 Post-processing

For computation of the flow field, a standard cross-correlation function via FFT was employed using a multigrid analysis with two refinement steps with a refinement ratio of 2 and a final interrogation window size of 64 x 64 pixels with 75% overlap.

The average dimension of the seeded particles in the recorded images is around 2-3 pixels thus avoiding peak locking. The software used applies a Gaussian peak fit as a three-point estimator for the correlation peak with an order of accuracy of 0.1-0.05 pixels (Tropéa et al., 2007). The validation process included a median filter which compares the median of each vector with the median of the 8 neighboring vectors to replace bad vectors.

### 4.2.4.6 Results

**Street canyon specimen**

In this section we present the measured approach flow as well as the flow in the cavity, for the SC specimen, using the PIV method.
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Approach flow

The wind speed profile of the approach flow for the SC specimen is measured 6mm upstream of the cavity. The measurement location is governed by the size of the field of view (32 x 32 mm). Placing the cavity in the centre of the field of view leaves approximately 6mm of the upstream section in the field of view (Fig. 4.16).

![Diagram showing the position of field of view for the SC specimen and location of measured inlet profile for both SC and FP specimen.]

**Figure 4.16:** Position of field of view for the SC specimen and location of measured inlet profile for both SC and FP specimen

Figs. 4.17a, b, c and d show the profiles of x-velocity, y-velocity, turbulent kinetic energy, and turbulence dissipation rate at the inlet location. The x-velocity profile (stream wise component of the velocity vector) resembles the one of channel flow with a maximum x-velocity of approx. 2.3 m/s at 50% of the height of the channel. The Reynolds number, based on a reference velocity of 2.3 m/s and the height of the cavity (0.02 m), is 3000. The y-velocity shows the vertical component of the velocity vector, positive being upward and negative downward. It can be seen that except for a small section close to the surface, the y-velocity is positive, but having very small values compared to the horizontal component (x-velocity). The profile of turbulent kinetic energy ($k$) and turbulence dissipate rate ($\varepsilon$) show a small peak close the bottom
Figure 4.17: profiles of a) x-velocity, b) y-velocity, c) turbulent kinetic energy and d) turbulence dissipation rate, at the inlet (6 mm from the edge of the cavity) of the SC specimen

surface (at a height of 0.002 m) and a large peak near the top surface, reaching a maximum of 0.25 m²/s² and 17 m²/s³, respectively, which are due to boundary layer effects. The definition of $k$ employed by Davis differs from the commonly used one, and is calculated by (LaVision GmbH, 2011):

$$k = (3/4)V_{RMS}^2 \tag{4.16}$$

where $V_{RMS}$ is the standard deviation of the velocity magnitude calculated by:

$$V_{RMS} = \sqrt{1/(n-1) \sum_{i=1}^{n} (V_i - V_{ave})^2} \tag{4.17}$$

where $V_i$ is the velocity magnitude of the $i^{th}$ sample, $n$ is the total number of samples (vector fields), and $V_{ave}$ is the average velocity magnitude of all samples.
Flow field in the cavity

Fig. 4.18 shows the air speed in the cavity of the SC specimen. The calculated Reynolds number in the cavity is 3000 based on the inlet velocity and the height of the cavity. It can be seen that a vortex is formed in the cavity with the centre of the vortex located slightly above the centre of the cavity. High velocities are observed as the air enters the cavity, along the top edge of the windward section. Figs. 4.19a and b show the profiles of x and y-velocity component along vertical and horizontal lines through the centre of the cavity. From these figures, it can be seen that the peak of the y-velocity component is found at approx. 2 mm from the windward and leeward surfaces, and reaches approx. 0.37 m/s and 0.3 m/s, respectively. Also the peak of the x-velocity component lies approx. 3.5 mm from the ground surface and reaches approx. 0.27 m/s.

Figure 4.18: Air speed and turbulent kinetic energy in the cavity of the SC specimen measured using PIV

The plot of the turbulent kinetic energy in the cavity is also shown in Fig. 4.18. The turbulent kinetic energy reaches a maximum of approx. 0.02 m$^2$/s$^2$ near the top of the windward surface, as turbulent air enters the cavity with high velocity. As the air circulates in the cavity, the turbulent kinetic energy reduces to very low values.

Flat plate specimen

In this section we show the approach flow profiles for the FP specimen measured using PIV. These measurements have been performed by Defraeye (2011). The approach flow profiles are located at distance of 15 mm upstream of the edge of the specimen. The measured profiles of mean wind speed (individual x and y-velocity components
**Figure 4.19:** Profiles of a) y-velocity along the horizontal center line and, b) x-velocity along the vertical center line, measured using PIV.

**Figure 4.20:** Approach flow profiles of a) mean wind speed, b) turbulent kinetic energy and c) turbulence dissipation rate, for the FP specimen (Defraeye, 2011)
are not available), turbulent kinetic energy and turbulence dissipation rate are shown in Fig. 4.20. The centerline air speed $U_{cl}$ is 2.3 m/s ($Re = 1600$, based on $U_{cl}$ and $H$). The profile of mean velocity magnitude for the FP specimen compares well to the x-velocity for the SC specimen (Fig. 4.17), although the boundary layer is slightly thicker for the latter. This is due to the fact that the SC profile is measured further downstream (38 mm) (Fig. 4.16) and a boundary layer develops along this 38 mm.

4.3 Comparison of simulations and measurements

4.3.1 Influence of the moisture transport properties on the global drying behavior

In order to analyze the influence of the moisture transport properties of the ceramic brick specimen on its drying behavior, a 1D BE-HAM simulation was conducted, employing the measured change of mass flux averaged along the entire specimen, as the imposed boundary condition (Fig. 4.21). A 1D structured grid, consisting of 341 finite elements is constructed based on a grid sensitivity analysis, with gradual mesh refinement toward the air-porous material interface.

![Figure 4.21: Measured variation of the average mass flux over time at the top of the flat plate brick specimen](image)

Fig. 4.22a shows the average moisture content profiles along the height of the specimen for various times during drying, for the experiment and the simulation based on the moisture transport properties presented in Sec. 4.2.2. It can be seen that the measured profiles agree closely with the simulations for the major part of the material, although the experiments show a faster drop in the moisture content at the top surface exposed to air flow. The different behavior is attributed to the uncertainty in the material properties used for this simulation. These uncertainties can be due to
the fact that the ceramic brick specimen used for the determination of the material properties is not the same as the one used for the current experiment. In order to check the influence of the material properties on the drying behavior, the moisture retention curve as well as the liquid permeability are modified.

![Figure 4.22: Contours of average moisture content along the height of the specimen (top 2.5 cm) at different times during drying, comparing the experiment (solid lines) and simulation (dotted lines), for a) base material properties, b) modified moisture retention curve, c) modified liquid permeability and, d) modified moisture retention curve and liquid permeability](image)

For the moisture retention curve, the weight factors for the two pore systems in Eq. 4.4 are changed. The new moisture retention curve can be calculated from Eq. 4.18 where the factors 0.3 and 0.7, shown in bold, are the modified weight factors, instead of 0.846 and 0.154 in the original equation. This corresponds to a material with more fine pores compared to the original material. Fig. 4.23a shows the new moisture retention curve in comparison to the original one.

\[
\begin{align*}
w(p_c) &= w_{cap} \left[ 0.3 \left( 1 + (1.394 \times 10^{-5} p_c)^4 \right)^{-0.75} + 
0.7 \left( 1 + (0.9011 \times 10^{-5} p_c)^{1.69} \right)^{-0.408} \right] 
\end{align*}
\] (4.18)
4.3. COMPARISON OF SIMULATIONS AND MEASUREMENTS

Figure 4.23: a) Moisture retention curve (original and modified) and b) liquid permeability (original and modified)

In addition, changes are made to the liquid permeability ($K_l$) of the ceramic brick. The modified $K_l$ curve is shown in Fig. 4.23b, along with the original $K_l$ curve. The modified material has generally higher $K_l$ compared to the original one (except at very low capillary pressure) specially in the fine pore range.

Drying of the ceramic brick specimen is simulated again using i) the updated moisture retention curve, ii) the updated liquid permeability and iii) using both modified properties (Figs. 4.22b, c and d, respectively). From the results, it is clear that small changes to the material properties have a large effect on the resulting transport of moisture.

It can be seen that when only the moisture retention curve is modified, a drying front starts to appear, but the general drying speed is underestimated. When only the liquid permeability is modified, the drying speed is too high and no drying front appears. The simulation conducted when both these properties are modified results in the best overall agreement. This combination of material properties are used for the remaining simulations in this chapter.

4.3.2 Flat plate brick specimen

In this section, we compare the drying behavior of the flat plate brick specimen achieved using neutron radiography, with the simulation results. Two simulations are conducted, one coupled and one uncoupled. The uncoupled simulation is a BE-HAM simulation, where the location dependent profiles of the $CHTC$ and the $CMTC$ along the surface of the specimen are achieved from an initial CFD simulation and are kept constant with time. In the coupled simulation, they are updated during each time step.

The geometry, the imposed boundary conditions, as well as the mesh of the CFD
model are shown in Fig. 4.24. A 2D structured grid is constructed with 4216 control volumes, with gradual mesh refinement toward the top and bottom boundaries of the domain. For modeling the air flow, steady RANS is used in combination with the Reynolds stress model together with LRNM to take care of the viscosity-affected region. The Reynolds stress model is the most elaborate type of turbulence model, where the isotropic eddy-viscosity assumption is avoided and the transport equations for the Reynolds stresses, together with an equation for the dissipation rate, are solved (Ansys. Inc., 2009). The surface of the brick is modeled as no-slip boundary with zero roughness, since surface roughness cannot be accounted for when using LRNM. Values of $y^+$ at the surface of the brick are below 1.0.

![Diagram of computational model](image)

**Figure 4.24:** Computational model for numerical CFD analysis of the flat plate brick specimen

For the FP specimen case, the domain inlet is located at distance of 15 mm from the upstream edge of the specimen (as described in Sec. 4.2.4.6). The measured profiles of the mean wind speed, turbulent kinetic energy and turbulence dissipation rate are imposed at the inlet of the domain (Fig. 4.24). The measured temperature and relative humidity at the inlet correspond to the conditions in the NEUTRA beamline test room during the experiment (Fig. 4.25). The length of the downstream section is 30 mm, like in the experimental setup. The top surface as well as the downstream and upstream sections are modeled as no-slip walls with zero roughness.

The heat and moisture (liquid and vapour) transport in the material is modeled by means of the BE-HAM model. A 2D structured grid consisting of 9751 finite elements is used (Fig. 4.26), with gradual mesh refinement towards the air-porous material interface. At the top surface of the brick information is exchanged with the CFD model, while the other surfaces (sides and bottom of the brick) are assumed adiabatic and impermeable to moisture. The brick is at room temperature at the start of the experiment, being 22°C and has a moisture content of 121 kg/m³ ($w_{ini}$) (mass fraction of 0.01638). The transport properties presented in Sec. 4.3.1 (Fig. 4.23), are used. Based on a time stepping study, the exchange time step used for the coupling is chosen to be 100 sec.

Fig. 4.27b shows the average change in the moisture content along the height of the
4.3. COMPARISON OF SIMULATIONS AND MEASUREMENTS

**Figure 4.25:** Temperature and relative humidity in the test room of the NEUTRA beamline during the FP specimen experiment

**Figure 4.26:** Computational grid of the flat plate brick specimen for the BE-HAM model

FP specimen, comparing experiments, coupled simulation and uncoupled simulation. It can be seen that the coupled and uncoupled simulation show very similar behavior. This implies that the $CHTC$s and $CMTC$s along the surface of the flat plate specimen do not vary significantly with time. Figs. 4.28a and b, show the average $CHTC$ and $CMTC$ values along the surface of the FP specimen, during the drying period and confirms that they only show little variation.

The overall drying pattern, observed in the coupled simulation, is very similar to the experiment. The hourly profiles of moisture content along the height of the specimen resemble the experimental ones, but the drying front is underestimated during the first 4 hr of the experiment while it is overestimated afterwards.

Explanations for this behavior are:

i) In Sec. 4.3.1, we tried to find the transport properties that capture the drying behavior accurately. The agreement was not perfect. This could explain the observed difference between the simulation and the experiment.
ii) By assuming a 2D geometry, we implicitly assume that no drying occurs from the lateral surfaces of the specimen. Although we wrapped the specimen in aluminum foil to make it vapour tight and insulated it by means of XPS, the neutron images indicated that drying is occurring at the bottom of the specimen. Drying from the sides can hence also not be excluded.

iii) In the experimental setup, water evaporates from the 1 cm wide wet brick and mixes with the air inside the 7 cm wide test section, hereby lowering the vapour pressure of the air above the specimen. This diluting effect is not considered in our 2D simulation. Hence the vapour pressure above the specimen could be overestimated, which could explain the initial slower drying of the specimen in the simulation.
4.3.3 **Street canyon brick specimen**

In this section, we compare the measured flow field above the SC specimen to the simulated one, and we compare the resulting drying behavior.

4.3.3.1 **Comparison of the flow field**

In order to assess the accuracy of the CFD model, the measured flow field in the cavity of the SC specimen, is compared with the corresponding CFD calculations. The calculation domain as well as the imposed boundary conditions are shown in Fig. 4.29. A 2D structured grid is constructed consisting of 5990 control volumes, with gradual mesh refinement towards the air-porous material interfaces, and towards the shear layer. For modeling turbulent flow, the steady RANS approach is selected together with Reynolds stress model. For near wall modelling, LRNM is selected, and the $y^+$ values of the wall-adjacent cells for the three interfaces (windward, leeward and ground) are below 1.0, which is required for boundary layer modelling with LRNM. The three interfaces as well as the top surface of the specimen are modelled as no-slip walls with zero roughness, since surface roughness cannot be accounted for when using LRNM. Second-order discretization schemes as well as the SIMPLE algorithm for pressure-velocity coupling are employed. Pressure interpolation is second order.

![Figure 4.29: Calculation domain for the CFD simulation of the SC specimen](image-url)
The measured profiles of x and y-velocity are imposed at the inlet of the domain (in this case 6 mm upstream of the cavity) (Fig. 4.17).

Fig. 4.30 shows the flow field in the cavity using the Reynolds stress model (middle image), and compares it with the PIV measurements (left image).

![Figure 4.30](image)

**Figure 4.30:** Velocity field and turbulent kinetic energy in the cavity of the SC specimen for experiments (left image), CFD simulation using the Reynolds stress model (middle image), and CFD simulation using the modified Reynolds stress model (absence of turbulence in the shear layer) (right image).

Figs. 4.31a and b compare the profiles of x and y-velocity along horizontal and vertical lines in the centre of the cavity as obtained by means of PIV (black line with triangles) and using the Reynolds stress model (black solid line). Fig. 4.31c, shows the y-velocity along a horizontal line at the top of the cavity. From Figs. 4.30 and 4.31, it can be seen that the wind speeds in the cavity are generally overestimated using the Reynolds stress model.

For further comparison, we look at the turbulent kinetic energy field (TKE \(m^2/s^2\)) measured by means of PIV, and achieved from the CFD simulations using the Reynolds stress model (Figs. 4.30 and 4.32, show the cavity region and the entire field, respectively). It can be seen that the simulated turbulent kinetic energy distribution at the inlet region of the domain is close to the observations, although in the cavity, too high values are obtained. The highest observed turbulent kinetic energy in the cavity during the experiments is 0.02 \(m^2/s^2\), while it is 0.2 \(m^2/s^2\) in the simulation.
It appears that there is an over-production of turbulence in the shear layer above the cavity, where the transition occurs from high velocity flow above the cavity, to low velocity flow in the cavity. This can be due to the fact that the flow in the shear layer is not fully turbulent and is possibly in the transition regime, therefore the Reynolds stress model, which is mainly for fully turbulent flows, cannot accurately model this transition flow. For the purpose of more accurately modeling this transition flow, a transition region of 0.4 x 2 cm, centered around the shear layer, was identified, and the production of turbulence was disabled in this region. This region is shown by red rectangle in Fig. 4.32). In this method, suggested by Ansys. Inc. (2009) and applied by some researchers (Wolfe and Ochs, 1997), a laminar/turbulent transition boundary is created. The selected size chosen for the transition region is based on some preliminary simulations. The simulation was repeated with this modified Reynolds stress model. The resulting flow field is shown in Fig. 4.30. Figs. 4.31a, b and c compare the profiles of x and y-velocity along horizontal and vertical lines in the centre of the cavity as obtained by means of PIV (black line with triangles) and by the
Figure 4.32: Turbulent kinetic energy for the experiments, the CFD simulation with the Reynolds stress model and the CFD simulation with the modified Reynolds stress model (absence of turbulence in the shear layer, marked by the red rectangle)

Further we compare the turbulent kinetic energy fields in the cavity region and the entire region (Figs. 4.30 and 4.32, respectively). It can be seen that the modified Reynolds stress model predicts turbulent kinetic energy values which are much closer
4.3.3.2 Comparison of the drying behavior

In this section, we compare the drying behavior of the street canyon brick specimen achieved using neutron radiography, with the simulation results performed with: i) the coupled model and, ii) the uncoupled (only BE-HAM) model where the $CHTC_s$ and $CMTC_s$ along the exchange interfaces (windward, leeward, and ground), stay constant with time. The transport properties used for this study are the ones presented in Sec. 4.3.1.

The boundary conditions used for the CFD part of the coupled model are as described earlier. The turbulence model used is the modified Reynolds stress model, which as shown in Sec. 4.3.3.1, resulted in a better agreement with the experiments. The temperature and relative humidity at the inlet correspond to the conditions in the NEUTRA beamline test room during the experiment (Fig. 4.33). The brick is initially at 22.75°C, corresponding to the room temperature at the start of the experiment and at a moisture content of 117 kg/m$^3$ ($w_{ini}$) (mass fraction of 0.01638). The top surface of the specimen is assumed to have zero heat and mass exchange with the environment. The rest of the surfaces (sides and bottom of the specimen) are assumed to have zero heat and mass exchange with the environment. The heat and moisture (liquid and vapour) transport in the material is modelled by means of the BE-HAM model. A 2D structured grid consisting of 5361 finite elements is constructed (Fig. 4.34), with gradual mesh refinement towards the air-porous material interface, as well as towards

![Figure 4.33](image)

**Figure 4.33:** Temperature and relative humidity conditions in the test room at the NEUTRA beamline during the SC specimen experiment
the two sides of the ground section and the bottom side of the walls. The surfaces of the cavity (windward wall, leeward wall and ground) exchange information with CFD (Fig. 4.34). Based on a time stepping study, the exchange time step used for the coupling is chosen to be 100 sec.

![Computational grid of the SC brick specimen for the BE-HAM model](image)

**Figure 4.34:** Computational grid of the SC brick specimen for the BE-HAM model

Fig. 4.35 compares the average moisture content variation with time (for the experiment and the coupled simulation), as well as the change in moisture content along the length of each section (windward, leeward and ground) for various points in time (for the experiment, the coupled and the uncoupled simulation). In this figure, parts a and b refer to the windward section, c and d refer to the leeward section and, e and f refer to the ground section.

Comparing the experimental and coupled simulation results (Fig. 4.35), we can see that, although the overall drying rate is underestimated for all sections, the drying behavior of the windward section is captured quite well. The agreement is less for the leeward side and the ground. For these two sections, the simulated drying rate is much slower than in the experiment. There are some possible explanations for this mismatch: i) underestimation of the air velocity magnitude close to the wall and the exchange rate in the simulation, as well as other differences in the flow field, ii) uncertainties in the material properties, and iii) 3D effects. Each of these points are explained in more detail below.

**Underestimation of the velocity magnitude**

Although the flow field calculated using the modified Reynolds stress model, shows a better agreement with the experiments in comparison to the simulation with the standard Reynolds stress model, still the air velocity magnitudes close to the wall are underestimated in the simulation (Fig. 4.31). Also, as can be seen in Fig. 4.30, the shape of the vortex and the location of the centre of the vortex are slightly different.
in the measurements and simulations, which could be due to 3D effects.
Also the air exchange via the top of the cavity is underestimated in the simulations.

Figure 4.35: Average moisture content vs. time (comparison of experiment and coupled simulation with the modified Reynolds stress model) for the a) windward, c) leeward and e) ground sections. Change of moisture content along the length of each section for different times (comparison of experiment and coupled and uncoupled simulation with the modified Reynolds stress model) for b) windward, d) leeward and f) ground sections.
(Fig. 4.31c). The calculated air exchange rate per hour (ACH) at top of the cavity is approx. 1800 1/h for the experiments while it is 1500 1/h for the simulation with the modified Reynolds stress model. Lower air exchange rates result in an accumulation of moisture in the cavity, a higher vapour pressure and hence a lower drying rate. This phenomenon was demonstrated in Sec. 2.3.4 using a simplified model.

Uncertainties in the material transport properties

Although the modified material properties lead to a better agreement with the experimental observations (Sec. 4.3.1), still the simulation results showed differences with the experiments and specially the drying front was not captured accurately.

3D effects

The current simulations are performed in 2D. Assuming a 2D case can be a too simplified assumption for a few reasons:

i) By assuming a 2D case, we eliminate the possibility of material drying from the lateral sides. Although all the surfaces of the specimen were made impermeable by wrapping the specimen with aluminum foil, drying from other surfaces than the top surface might have occurred. We already noticed in the experiments that some drying is occurring at the bottom of the specimen. Drying from the front and back sides can not be detected in the neutron images since what we see is the total moisture amount over the thickness of the specimen.

ii) In the micro wind-tunnel, the cavity is not infinitely long and it is bounded between the side walls of the test section, therefore the flow pattern could be different than what we simulate in a 2D case. This could influence the drying behavior of the specimen.

iii) We did not use the brick specimen of the neutron radiography experiments for the PIV measurement since the surfaces of the ceramic brick reflected the laser light and resulted in erroneous information. For the PIV experiments, an object with the same geometry was constructed from XPS and covered with black mat tape. Small geometrical differences as well as differences in the roughness with the brick specimen can not be excluded and might result in a different flow pattern.

iv) Assuming a 2D flow field could result in overestimation of the vapour pressure in the channel above the specimen and in the cavity, since in the actual test, only the middle 1 cm section of the 7 cm wide channel is the wet ceramic brick. Therefore the moisture evaporating from the brick will mix with the air in the entire test section, which is not considered in the 2D model, therefore the simulated vapour pressure at the centre-line of the channel, could be higher than in the actual test condition, resulting in a slower drying rate.

This hypothesis was investigated by repeating the drying experiment in a climatic
chamber and monitoring the vapour pressure conditions at the inlet of the micro wind-tunnel and at the centre of the cavity. Fig. 4.36 shows the location of the sensors. The conditions in the climatic chamber represent the average conditions as during the test in the neutron facility (temperature of 23°C and relative humidity of 40%). Two series of experiments are conducted. Once with a setup similar to the actual test in NEUTRA (3D case) and once mimicking a 2D case. This was done by decreasing the width of the channel to the width of the brick specimen (Fig. 4.37). Fig. 4.38a shows the variation of the vapour pressure at the centre of the cavity ($p_v$ (centre)) with time and Fig. 4.38b shows the ratio between the vapour pressure at the inlet ($p_v$ (inlet)) and $p_v$ (centre), for the 2D and 3D experiments. In these figures, also the data achieved using the coupled simulation with the modified Reynolds stress model are given. It can be seen that the vapour pressure in the cavity measured for the 3D case drops faster and to a lower value, in comparison to the 2D case. This indicates that for the 3D case, there is more mixing of the air above the specimen with the air inside the cavity, which results in lower vapour pressure in the cavity and therefore faster drying of the specimen. Also the results of the coupled model using the modified Reynolds stress model shows better agreement with the 2D experiment, than with the 3D case.

Figure 4.36: Micro wind-tunnel a) side view and b) top view, showing the location of the sensor at the centre of the cavity and at the inlet for the test in the climatic chamber
4.4 Conclusions

In this chapter, the experimentally observed drying behavior of ceramic brick specimen was compared with simulations based on the coupled model introduced in Chapter 3. Two ceramic brick specimen were used for this comparison: a specimen in the shape of a flat plate (FP) and one with a cavity resembling the geometry of a...
street canyon (SC).

The influence of the material properties on the drying behavior was studied. For this purpose, the drying of the FP brick specimen was evaluated by conducting a 1D BE-HAM simulation. First the measured change of mass flux as obtained from neutron radiography as a function of time, averaged along the entire specimen length was used as boundary condition. The moisture retention curve as well as the liquid permeability were modified to obtain a better agreement with the experimental results.

Next the drying behavior was studied. For the FP specimen, the agreement between the coupled simulation and experimental results was satisfactory, although the drying front was overestimated, while the moisture content towards the bottom surface of the specimen was underestimated. The observed difference was attributed to a number of factors such as: i) uncertainties in the material properties, ii) not considering drying from lateral sides of the specimen in the simulations, and iii) the 2D assumption of the flow field, which overestimates the vapour pressure above the specimen. The results from the coupled and uncoupled simulations were very close, showing that variations of the \textit{CHTC}s and \textit{CMTC}s along the surface of the specimen during drying are small. This means uncoupled simulations can be used, using pre-calculated \textit{CHTC}s and \textit{CMTC}s for this simple geometry.

For the SC specimen, initial simulations with the Reynolds stress model showed overproduction of turbulence in the flow field. By disabling the production of turbulence in the shear layer above the cavity, the flow field and the turbulent kinetic energy values became much closer to the experimentally observed values. The coupled simulation using this modified turbulence model, predicts the drying behavior of the windward section quite well, although the drying rate of the leeward and ground sections is underestimated. The observed differences can be attributed to a number of factors such as: i) differences in the flow field (wind speed and turbulent kinetic energy values) in comparison to the experiments, due to deficiencies of the used turbulence model, ii) uncertainties in the material properties and iii) the 2D assumption which implies excluding the possibility of drying from lateral sides of the specimen, eliminating the 3D effect in the flow field, and overestimating the vapour pressure above the specimen. The coupled and uncoupled simulation provided different results, with the uncoupled model results being further away from the experimental results. This shows the importance of coupling when the variation of the \textit{CHTC}s and \textit{CMTC}s along the surfaces being dried is large during the drying process.

The coupled model will be used in the next chapter, to study the influence of evaporative cooling in a 10 x 10 m street canyon. Although the SC specimen had a similar geometry as a real street canyon, the flow characteristics are quite different. The Reynolds number for the 2 x 2 cm SC specimen is approx. 3000 based on the inlet velocity (2.3 m/s) and height of the cavity. The Reynolds number for the flow in the 10 x 10 m street canyon which will be studied in the next chapter is between 200000 to 800000, depending on the reference wind speed. In addition, the air change
rate per hour at the top of the cavity in the SC specimen is approx. 1800 l/h while
for the large scale street canyon, it is between 11 to 22 l/h depending on the reference
wind speed. It is clear that there is a difference in the flow characteristics of these
two cases. The 2 x 2 cm specimen studied in this chapter is thus not representative
of a real street canyon. Furthermore, we know that if the model is validated with
the small specimen, it is not validated for the large street canyon. However, since the
validation of the model for the full scale street canyon was not possible, we use the
coupled model for the studies of the next chapter.
Chapter 5

Case studies

5.1 Introduction

In this section, the coupled model described in chapter 3 is used to evaluate the effect of evaporative cooling on thermal comfort for different street canyon cases. First the configuration and the domain, common for all cases, is explained. Next, the boundary conditions are given, followed by a study to determine the appropriate time stepping. In the last part, different cases are studied in order to evaluate the influence of different parameters on the evaporative cooling potential and the thermal comfort.

5.2 Model

In this section, first the calculation domains for the CFD, the BE-HAM and the RAD models are presented. Next, a study to determine the appropriate time step size, $\Delta t_{ex}$, is shown and discussed.

5.2.1 Domains

5.2.1.1 CFD model

The fluid domain consists of a 2D 1:1 street canyon in an Atmospheric Boundary Layer (ABL) (Fig. 5.1). A square-shaped canyon is chosen as a generic element of the urban canopy. The canyon is 10 m wide and 10 m high. The calculation domain extends 4H in front of the canyon and 15H behind the canyon, where H is the canyon height. A domain height of 4H (above the canyon) was selected. These dimensions are equal to, or larger than, the dimensions recommended by Franke et al. (2007; 2011).
The CFD simulations are conducted using Ansys-Fluent 12.0 which uses the control volume method (Ansys, Inc., 2009). Based on the validation work of Blocken et al. (2009), Defraeye et al. (2010) and Xie et al. (2006), steady RANS in combination with the realizable \( k-\varepsilon \) turbulence model and Low Reynolds Number Modelling (LRNM) is selected. Second-order discretization schemes as well as the SIMPLE algorithm for pressure-velocity coupling are employed. Pressure interpolation is second order.

At the inlet of the domain, vertical profiles of the mean horizontal wind speed \( (U) \), turbulent kinetic energy \( (k) \) and turbulence dissipation rate \( (\varepsilon) \) are imposed (Richards and Hoxey, 1993), representing a homogeneous ABL:

\[
U(z) = \frac{u_{\tau,ABL}}{\kappa} \ln \left( \frac{z + z_0}{z_0} \right) \tag{5.1}
\]

\[
k = \frac{u_{\tau,ABL}^2}{\sqrt{C_\mu}} \tag{5.2}
\]

\[
\varepsilon = \frac{u_{\tau,ABL}^3}{\kappa(z + z_0)} \tag{5.3}
\]

where

\[u_{\tau,ABL} = \kappa U_{ref} \ln^{-1} \left( \frac{h_{ref} + z_0}{z_0} \right)\tag{5.4}\]

where \( z_0 \) is the aerodynamic roughness length of the terrain (assumed to be 0.03 m for grass-covered terrain according to Wieringa (1992)), \( \kappa \) is the von Karman constant (0.4187), \( z \) is the vertical coordinate, \( u_{\tau,ABL} \) is the friction velocity, \( h_{ref} \) is the reference height and \( U_{ref} \) is the horizontal wind speed at the reference height.

At the inlet of the domain, temperature \( (T_{inlet}) \) and relative humidity \( (RH_{inlet}) \) are imposed which follow a periodic function in time. The \( U_{10}, T_{inlet} \) and \( RH_{inlet} \) vary
from case to case. Symmetry is imposed at the top of the computational domain, which implies that the velocity component normal to the top surface is zero, as are the normal gradients of all other quantities. Zero static pressure is imposed at the domain outlet.

The remaining surfaces, i.e. the roofs, the street canyon walls and the ground surface, are modelled as no-slip boundaries with zero roughness. This is inconsistent with the assumed roughness for the approach flow profile, however a surface roughness cannot not be accounted for when using Low Reynolds Number Modeling (LRNM). This could hinder the horizontal homogeneity, although as shown by Blocken et al. (2007), this could be also the case when using wall functions and applying a surface roughness. Therefore, we analyse the streamwise change of the velocity and turbulence intensity profiles. Figs. 5.2a and b show the profiles of velocity and turbulence intensity, at the inlet and at the distance of 40 m (4H) from the inlet. The maximum difference between the inlet profile and the profile at 4H (i.e. the position of the canyon), is found at the distance of approx. 0.5 m from the roof, and is about 9% for the velocity and 20% for the turbulence intensity, compared to the inlet values at the reference height ($h_{ref}$).

The quantities at reference height (10 m above the roof level) are almost identical. Since all simulations are performed on the same grid, the mismatch in aerodynamic roughness length is not expected to bias the conclusions of the analysis.

![Figure 5.2: Comparison of the a) velocity magnitude and b) turbulence intensity as a function of height, at the inlet of the domain and at a distance of 40m from the inlet](image)

The surfaces at which information is exchanged between the BE-HAM, CFD and RAD models are the windward wall, the leeward wall and the ground, which initially have a temperature equal to the $T_{inlet}$ at the beginning of the simulation, and a relative humidity equivalent to a capillary pressure, $p_c$, of -13227 Pa when the surface is assumed wet (RH $\approx$ 100%). When the surface is dry, zero mass flux is imposed. The roofs on the left and right side of the canyon have a zero heat flux (adiabatic) and zero mass flux.
A 2D structured grid was constructed based on a grid sensitivity analysis consisting of 16706 control volumes (Fig. 5.3), with gradual mesh refinement towards the top and bottom of the vertical walls and towards the sides of the ground surface. The $y^+$ values of the wall-adjacent cells are below one, which is required for boundary-layer modelling with LRNM (Ansys. Inc., 2009).

![CFD grid](image)

**Figure 5.3: CFD grid**

### 5.2.1.2 BE-HAM model

Drying of the porous material is simulated using a Building Envelope Heat and Moisture (BE-HAM) transport model. In this study, the BE-HAM model consists of three separate domains, namely for the windward wall, the leeward wall, and the ground (Fig. 5.4). For each domain, a 2D structured grid is constructed based on a grid sensitivity analysis. The grid consists of 1060 finite elements (20 in x-direction and 53 in z-direction) for the windward wall, 530 finite elements (10 in x-direction and 53 in z-direction) for the leeward wall; and 462 finite elements (77 in x-direction and 6 in z-direction) for the ground (Fig. 5.4). For all surfaces, there is a gradual refinement toward the air-porous material interface, as well as refinement towards the two sides of the ground, and towards the bottom side of the walls, due to large expected moisture gradient in these regions.

The building walls are assumed to consist of a 9 cm outer leaf, being either ceramic brick, calcium silicate or mineral plaster, a water and vapor tight insulation layer, and a load-bearing inner wall. We assume that the inner part of the wall does not participate in the moisture transport (or buffering), and can be modelled as a thermal resistance (2.467 m²K/W). An indoor temperature of 20°C is selected. The top and bottom surfaces of the brick walls are assumed to be adiabatic and impermeable to moisture (Fig. 5.5).
The ground is assumed to consist of a 10 cm thick concrete or ceramic brick over a soil layer. The soil layer underneath the cover is modelled as a thermal resistance while its thermal capacity is not considered. For calculation purposes, we consider a 90 cm thick soil layer with a thermal resistance of 1.11 m²K/W. The soil temperature at 1 m depth is assumed to remain constant in time and equal to 10°C. We assume that the bottom surface of the top layer is impermeable to moisture.

**Figure 5.4:** BE-HAM grid

**Figure 5.5:** BE-HAM computational model with boundary conditions
The hygrothermal properties for the ceramic brick, calcium silicate, mineral plaster and concrete are provided in the appendix.

During the coupled simulations, each of these porous sections, i.e. windward wall, leeward wall, or ground, can be assumed wet or dry. For the simulation of the dry case, the porous material is assumed initially with no moisture inside (very small capillary vapour pressure) and to remain impermeable to moisture during the considered period of time.

### 5.2.2 Radiation

For the radiation sub-model, each of the three surfaces (windward, leeward and ground) are divided into 20 equal segments (Fig. 5.6). The view factor ($F$) between each two sets of these segments, and between a segment and the sky, is pre-calculated using equations provided by Siegel and Howell (2002). Short and long-wave radiation fluxes are calculated for each of these sections and then interpolated for all the points on the surface in the BE-HAM and CFD model.

In this model, the emissivity for the walls and ground is chosen to be 0.9, and for the sky 1. Values of surface albedo for the walls and ground for the different studied cases are given in Sec. 5.4. The temperature of the sky ($T_{sky}$) is set to 15°C.

![Computational grid for the RAD model](image)

**Figure 5.6:** Computational grid for the RAD model

### 5.2.3 Time stepping study

As described in Sec. 3.5, it is important to use an appropriate size for the exchange time step ($\Delta t_{ex}$) to achieve accurate results. Smaller $\Delta t_{ex}$, hence more frequent exchange between the sub-models, provides more accurate coupling results, however it increases the cost of simulation. Therefore a study is conducted to evaluate the influence of the exchange time step, $\Delta t_{ex}$, on the results.
The geometry and boundary conditions used are as explained above. For this study, the temperature and relative humidity at the inlet are set to constant values of 20°C and 20%, respectively. The windward wall is assumed wet and its temperature is set to 20°C. 24 hrs of drying are considered.

Seven exchange time steps of 30 sec, 60 sec, 120 sec, 240 sec, 480 sec, 960 sec and 1920 sec are considered. Since it is noted that the solution of the exchange times steps of 30 sec, 60 sec are very close to one another, and conducting a simulation with exchange time steps smaller than 30 sec is computationally very expensive, the exchange time step of 30 sec is chosen as the reference solution. The relative difference between the heat flux at the height of 9.5 m of the windward wall (0.5 m from the top of the wall), calculated using each of the time steps, and the heat flux calculated using the reference coupling time step, is evaluated. The relative error is calculated by:

\[
E_{\text{rel}}(\Delta t_{ex}=n) (t) = \frac{\int_0^t (q_{\Delta t_{ex}=n} - q_{\Delta t_{ex}=30}) dt}{\int_0^t q_{\Delta t_{ex}=30} dt} \quad (5.5)
\]

\[
\approx \frac{\sum_{i=1}^{t/\Delta t_{out}} (q_{\Delta t_{ex}=n} - q_{\Delta t_{ex}=30}) \Delta t_{out}}{\sum_{i=1}^{t/\Delta t_{out}} q_{\Delta t_{ex}=30} \Delta t_{out}} \quad (5.6)
\]

where \(E_{\text{rel}}(\Delta t=n)\) (%) is the relative error of the simulation with time step \((\Delta t)\) of \(n\) seconds, \(q\) is the total heat flux \((\text{J/m}^2\text{s})\) from the canyon to the wall, and \(\Delta t_{out}\) is the output time step used for calculation of the error.

The numerator in this equation represents the difference between the reference and considered exchange time step, \(\Delta t_{ex}\), of energy per square meter of wall \((\text{J/m}^2)\) transferred from the canyon to the wall at time \(t\). The denominator of this equation, is the total amount of energy per square meter transferred from the canyon to the wall at time \(t\) in the reference calculation. This method of calculating the error gives a good estimation of the fraction of energy per square meter of the wall transferred from the canyon to the wall for each time step, to the total energy transferred (for the smallest time step). Since we are studying evaporative cooling and the energy required for evaporation, the heat flux is found to be an appropriate variable for error evaluation in this study.

Fig. 5.7 shows the relative error during the drying of the windward wall for the first 24 hrs. Initially, the relative error ranges between 100% for the largest considered exchange time step \((1920\text{ sec})\) and 10% for the exchange time step size of 60 sec. The error is largest at the beginning of the drying process and gradually decreases as the simulation proceeds. At the start of the second drying phase (marked by the dashed line in Fig. 5.7), when the dry material layer at the surface forms an additional resistance to liquid water removal, the error increases for the exchange time steps of 1920 sec, 960 sec, 480 sec and 240 sec, while it continues to decrease for the exchange time steps of 120 sec and 60 sec. The time step of 120 sec results in an initial error of 20% while this error drops to 8% during the 24 hrs drying. We believe
that this exchange time step (120 sec) provides a good trade-off between accuracy and computational cost, therefore it is chosen for all coupled simulations in this section.

5.3 Boundary conditions and geometry

The cases studied are all situated in Zürich, Switzerland. The considered period is the 21st of June of a Typical Meteorological Year (TMY) or a day in the hottest week during the heat wave of summer 2003. The month of June is chosen as a typical hot month during summer. The 21st day of the month is chosen since in Ashrae (ASHRAE, 2009) averaged data for the calculation of the solar radiation intensity is provided for the 21st of each month (for more detailed information please refer to Sec. 3.4). For this day of the year, the solar radiation intensity is shown in Fig. 5.8a, by the solid black line. This solar radiation intensity is also used for the study of the heat wave case. The temperature and relative humidity of the air is different for each of the case studies and will be presented later.

The studied geometry is a 1:1 2D street canyon with an east-west orientation (Fig. 5.8b). For this orientation, the sun illuminates the top of the leeward wall first, then moves towards the bottom of the leeward wall and to the ground and windward wall, with the entire height of the windward wall being exposed to direct sun from approx. 8:00 to 16:00 (Fig. 5.8a). The solar radiation intensity for a point in the middle of each of windward wall, leeward wall and ground, is shown in Fig. 5.8a, for a 24 hr cycle. It can be seen that the radiation intensity is highest on the ground, due to its position relative to the sun.
5.4 Description of the case studies

For demonstrating the applicability of the proposed coupled model, the drying behavior of various cases, for a duration of 48 hrs, is studied and mutually compared. Different parameters are varied in these cases. These are:

1. Climate: conditions for June 21st for a typical meteorological year (TMY) in Zürich, or a day in the hottest week during the heat wave (HW) condition in Zürich (summer 2003) where data is provided by MeteoSchweiz.

2. Wind speed at the height of 10 m above ground (U_{10} reference location): 5 m/s or 1.5 m/s.

3. Location of the wet surface: windward wall or ground (leeward wall is always assumed dry).

4. Albedo of the surfaces: dark colored material (low albedo) or light colored material (high albedo).

5. Material of the surface: windward wall and leeward wall being ceramic brick, calcium silicate or outside plaster.

6. Thickness of the material at the walls or the ground: for the wall, 1 cm vs. 9 cm thick brick cladding, and for the ground, 10 cm vs 50 cm concrete cover.

Different cases are studied by the combination of the above mentioned parameters. The cases are described in Table 5.1. For each case, the table shows the climate (TMY or HW), the position of the wet surface (ground or windward wall), the material chosen for the wet surface (ceramic brick, calcium silicate or mineral plaster), the thickness

Figure 5.8: a) Total solar radiation intensity (W/m²) variation on June 21st of a TMY, as well as radiation intensity at a point in the middle of the ww wall, lw wall and ground b) schematic overview of the studied cases showing the top view of the street canyon and the sun path
of the material (9 cm or 1 cm walls and 10 cm or 50 cm cover over soil), wind speed at the reference height (1.5 m/s or 5 m/s), and the albedo of each surface. Albedo of 0.4 for the walls and 0.1 for ground (ground assumed to be a dark colored material), represents the base case. Albedo of 0.1 for the walls and 0.04 for ground, represents a case where dark colored materials are used. Albedo of 0.7 for both walls and the ground represents a case where light colored materials are used.

Table 5.1: Description of different studied cases. TMY is typical meteorological year, HW is heat wave, ww is windward wall, lw is leeward wall, gr is ground, CB is ceramic brick, CS is calcium silicate and MP is mineral plaster.

<table>
<thead>
<tr>
<th>case</th>
<th>climate</th>
<th>wet-surface</th>
<th>$U_{10}$</th>
<th>ww-albedo</th>
<th>lw-albedo</th>
<th>gr-albedo</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TMY</td>
<td>9cm-ww(CB)</td>
<td>5.0</td>
<td>0.4</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>2</td>
<td>TMY</td>
<td>9cm-ww(CB)</td>
<td>1.5</td>
<td>0.4</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>3</td>
<td>HW</td>
<td>9cm-ww(CB)</td>
<td>1.5</td>
<td>0.4</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>4</td>
<td>TMY</td>
<td>9cm-ww(CB)</td>
<td>5.0</td>
<td>0.1</td>
<td>0.1</td>
<td>0.04</td>
</tr>
<tr>
<td>5</td>
<td>TMY</td>
<td>9cm-ww(CB)</td>
<td>5.0</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>6</td>
<td>TMY</td>
<td>10cm-gr(CB)</td>
<td>5.0</td>
<td>0.4</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>7</td>
<td>TMY</td>
<td>9cm-ww(CS)</td>
<td>5.0</td>
<td>0.4</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>8</td>
<td>TMY</td>
<td>9cm-ww(MP)</td>
<td>5.0</td>
<td>0.4</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>9</td>
<td>TMY</td>
<td>1cm-ww(CB)</td>
<td>5.0</td>
<td>0.4</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>10</td>
<td>TMY</td>
<td>50cm-gr(CB)</td>
<td>5.0</td>
<td>0.4</td>
<td>0.4</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Initially, to show a typical scenario, the drying behavior in case 1 is presented. Case 1 here is referred to as the ‘base case”. Afterwards, the influence of the climate, wind speed, albedo of the surfaces (dark and light colored material), position of the wet surface, the material of the wet surface, and the thickness of the surfaces, on the conditions in the street canyon and the cooling potential are shown.

5.5 Base case

For this case, the temperature and relative humidity of the environment is taken from a typical meteorological year (TMY) in Zürich, for 21st of June (Fig. 5.9). The temperature varies between 13.5°C and 19°C and the relative humidity varies between 62% and 86%, during a day cycle. The windward wall is assumed to be wet after a rain shower (RH $\approx$ 100%) while the other surfaces are dry. In order to avoid division by zero for calculation of the $CHTC$ and the $CMTC$, the temperature of all surfaces are 0.01°C higher than the air temperature at the start of the simulation being 12:00 pm at midnight, where the air temperature equals 13.5°C. The walls of the canyon are 9 cm thick, made of ceramic brick and have an albedo value of 0.4. The ground cover is 10 cm concrete, assumed to be dark colored with an albedo value of 0.1. The reference wind speed at 10 m height ($U_{10}$) is 5 m/s. Drying of the wall is simulated for 48 hours.
We monitor the drying behavior of the windward wall. Fig. 5.10 shows the surface temperature and relative humidity as a function of time at four locations on the outer surface of the windward wall, being 0.5, 3.5, 6.5 and 9.5 m from the ground. Comparing with the variation of the incoming air temperature (Fig. 5.9), we can see that the wall surface temperature follows the variation of the incoming air temperature. The surface relative humidity stays rather constant for the first day of drying. The wall surface temperature rises above the incoming air temperature due to radiation. The windward wall is exposed to direct radiation everyday from

Figure 5.9: Temperature and relative humidity variation for a typical meteorological year (TMY) on June 21st for Zürich

Figure 5.10: Surface temperature and relative humidity at four points on the surface of windward wall
8:00 to 16:00. At 8:00, as the sun falls on the windward wall, a sudden increase and change in the slope of the surface temperature curves can be observed. The change in the slope of the surface temperature curves can also be noted at 16:00 as the sun leaves this wall. It can be seen that for the top of the wall (height of 9.5 m from the ground) the second drying phase starts on the second day after approx. 36 hrs from the start of the drying. This can be distinguished by a drop in the relative humidity and a change in the slope of the temperature curve. For the next point at the height of 6.5 m, the second drying phase starts two hours later compared to the point at 9.5 m. The other two considered points (at heights of 3.5 m and 0.5 m) do not reach the second drying phase during the first 2 days of drying. Comparing the surface temperatures during the first and the second day of drying, it can be noted that for the locations which enters the second drying phase on the second day (at height of 9.5 m and 6.5 m), the surface temperature is higher on the second day. This is due to the fact that after start of the second drying phase, less energy is required for evaporation and therefore surface temperature increases. It can be seen that the surface temperature at the height of 9.5 m was the lowest on the first day due to highest evaporation rate, while on the second day, after it enters the second drying rate, the surface temperature at this point rises above all other points.

To evaluate the influence of evaporative cooling, we compare the surface temperature at the top point (height of 9.5 m), and bottom point (height of 0.5 m) of the windward wall, as well as the average temperature and relative humidity in the street canyon, for two cases: (i) when the windward wall is initially wet (at capillary moisture content), and (ii) when the windward wall is initially dry (Figs. 5.11a, b, c and d). It can be seen that evaporative cooling results in a maximum surface temperature drop of 15°C at the top location and 13°C at the bottom location of the wall, during the first day of drying. On the second day the temperature difference is less because the wall at this location has reached the second drying phase and therefore less energy is required for evaporation. The average air temperature in the street canyon is approx. 3°C lower in the case with the wet wall, due to evaporative cooling, while the average relative humidity is approx. 15% higher, compared to the dry case, due to mixing of moisture evaporated from the wall with the air in the canyon.

Finally 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 chose to evaluate the universal thermal climate index (UTCI). For details about the calculation of UTCI refer to Sec. 3.6. Fig. 5.12a shows the UTCI for a person standing 1 m away from the windward wall, for the 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, in the case when evaporative cooling is present. 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
5.5. BASE CASE

Figure 5.11: Comparison of cases with and without moisture for 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 during the 48 hr drying, for cases with and without moisture, is shown in Figs. 5.12b, c, d, e and f. It can be seen that for the case with moisture, the air temperature and \( T_{\text{mrt}} \) at the studied location are approx. 2°C and 8°C lower in comparison to the case without moisture, respectively, while the vapour pressure is approx. 2 hPa (relative humidity approx. 15%) higher and the wind speed is approx. 0.2 m/s lower. Higher wind speed for the case without moisture can be due to small changes in the flow field due to higher surface temperatures. Resulting lower air temperature and \( T_{\text{mrt}} \), due to evaporation, corresponds to higher comfort while resulting higher relative humidity and lower wind speed, corresponds to lower comfort. More comfortable conditions during the second day is due to the fact that during this day, some points on the wall become locally dry at the surface (enter the second drying phase), therefore the vapour pressure in the street canyon is lower (Fig. 5.12d) which results in higher comfort.
5.6 The influence of wind speed

In this section, the influence of the wind speed on the evaporative cooling potential of the street canyon is studied. The boundary conditions are the same as in the base case,
with the temperature and relative humidity of the environment taken from a typical meteorological year (TMY) in Zürich, for 21st of June (Fig. 5.9). The difference between the current case and the base case is the wind speed. For the current case, the reference wind speed at 10 m height ($U_{10}$) is lower than the base case, being 1.5 m/s. 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 9 cm thick, made of ceramic brick and have an albedo value of 0.4. The ground cover is 10 cm concrete, assumed to be dark colored with an albedo value of 0.1. Drying of the wall was simulated for 48 hours.

Looking at the variation of temperature and relative humidity at four points at the surface of the windward wall, we can see that only the top point of the wall (at height of 9.5 m) shows a second drying phase, towards the end of the second day (Fig. 5.13). Comparing with the base case (Fig. 5.10), we can see that the drying of the wall for the current case is slower and that more points remain longer in the first drying phase.

![Figure 5.13: Surface temperature and relative humidity at four points on the surface of windward wall](image)

In order to study the effect of evaporative cooling, we compare this case with the same case but when the windward wall is dry. It can be seen that the surface temperature at the top point of the windward wall is approx. 20°C higher and at the bottom of the windward wall is approx. 14.5°C higher for the case without moisture (Figs. 5.14a and b). The magnitude of the temperature drop at these two points due to evaporative cooling is higher in comparison to the base case (Figs. 5.11a and b). This is due to less convective removal of heat which results in higher evaporative cooling effect. The average temperature and relative humidity in the street canyon are approx. 3°C higher and 15% lower for the case without moisture (Figs. 5.14c and d), which are similar to the base case.
Further, we look at the UTCI for a person standing 1 m away from the windward wall (Fig. 5.15a). The UTCI for the case with evaporative cooling is approx. 4.5°C and 5.5°C lower for the first and second day respectively, for the case with evaporative cooling. The drop in the UTCI due to evaporative cooling is higher in comparison to the base case, where the maximum drop was approx. 2.5°C to 2.7°C. Looking at the individual factors effecting the UTCI (Fig. 5.15), we can see that the drop of both air temperature and $T_{mrt}$ at the studied position due to presence of evaporation is larger (Fig. 5.15b and c), while the increase of vapour pressure due to evaporation is higher (Fig. 5.15d), in comparison to the base case. The higher cooling potential of the case with lower wind speed, hence more buoyant case, is due to the fact that for such a case, less air exchange is happening at the top of the canyon. Therefore the air in the street canyon, which has a higher temperature and higher vapour pressure, is less mixed with the air above and remains more trapped in the canyon. So in such a case, evaporative cooling has a higher potential than in a case with more ventilation at the top of the canyon. Fig. 5.16 shows the exchange flux at a line at the top of the canyon, for the two cases (lower and higher wind speed). It can be seen that the
5.6. THE INFLUENCE OF WIND SPEED

Figure 5.15: Comparison of cases with and without moisture for a) UTCI b) air temperature c) $T_{mrt}$ d) vapour pressure e) relative humidity and f) wind speed, at the position of a person standing 1 m from the windward wall

exchange flux is lower for the case with lower wind speed with exception of some hours in the evening. To explain this higher exchange flux after approx. 18 hrs and 42 hrs of drying, for the case with lower wind speed, we look at the average velocity profiles for this case at the two mentioned times (Fig. 5.17). It can be seen that the average
velocity is higher in the street canyon at 18 hr (6:00 in the evening) in comparison to 30 hr (6:00 in the morning). This can be due to buoyancy which is more significant during the day time. Further, Fig. 5.18 shows the y-velocity along the line at top of the street canyon, where the exchange flux is calculated, after 18 hrs of drying, for cases with 1.5 m/s and 5 m/s reference wind speed. It can be seen that the y-velocity at this time of the day is higher for the case with lower wind speed, which is due to buoyancy. This explains the higher exchange flux at this time of the day, observed earlier.

Figure 5.16: Exchange flux through the top of the street canyon

Figure 5.17: Flow field in the street canyon, for case with moisture, after 18 hr and 30 hr of drying

Looking at the variation of the wind speed at the location of the pedestrian (Fig. 5.15f), we notice that for the case with moisture, the wind speed is in general higher except for some hours during the day. The lower wind speed for the case without moisture is attributed to the difference in buoyancy. Looking at the typical flow field of the case with lower wind speed without moisture (Fig. 5.19, left figure), we can see that in the street canyon, besides the main vortex, the corner vortex seen for the
case with moisture is blow up and forms a counter-rotating secondary vortex. This is due to buoyancy where the air rises at the heated building surface, here being the windward wall for most of the day time (between 8:00 and 16:00) (Allegrini, 2012). This counter-rotating vortex results in less mixing of the air in the canyon with the air above, resulting in lower velocities in the street canyon.

Figure 5.18: y-velocity along the line at top of the street canyon

Figure 5.19: Typical flow field in the street canyon, for case with lower wind speed, with and without presence of moisture

Further, to investigate the cause of the drop of the wind speed during certain times of the day (at approx. 14 hr, and 38 hr) (Fig. 5.15f) for the case with moisture, we look at the flow field in the street canyon for three specific times during drying, i.e. after 14 hr, after 24 hr and after 38 hr of drying, for cases with and without moisture (Fig. 5.20). In these figures, the position of the person 1 m from the windward wall is shown.
by a black dot. First it can be seen that the overall air velocity in the street canyon is lower for the case without moisture, and the shape of the vortex looks different in comparison to the case with moisture, with a secondary vortex forming in the street canyon. The cause of these lower velocities and different flow field is buoyancy which was explained above. The noted lower wind speed at the pedestrian location for the case with moisture at 14 hr and 38 hr, can be explained by looking at the flow field at these times. It can be seen that in this case, a large vortex is formed in the street canyon while small corner vortices are formed at the corner of the walls, specially at the windward wall. The location chosen for representing the pedestrian falls in this corner vortex. It can be seen that the shape of this corner vortex changes slightly between the three chosen times which results in a slightly different velocity at the pedestrian position. At 14 hr and 38 hr, the specific point lies in a region with lower wind speed. In conclusion, the local wind speed at a certain location is very sensitive to the specific flow field and the shape of the main and the corner vortices.

Figure 5.20: Flow field in the street canyon, for cases with and without moisture, after 14 hr, 24 hr and 38 hrs of drying

Further we study the effect of lower wind speed (current case) on the temperature and moisture conditions in the street canyon as well as on the comfort of a pedestrian. Fig. 5.21a compares the UTCI of a person standing 1 m from the windward wall,
as well as the average air temperature, average vapour pressure and average relative humidity, in the street canyon, for the current case ($U_{10} = 1.5 \text{ m/s}$) and the base case ($U_{10} = 5 \text{ m/s}$). It can be seen that more comfortable conditions during day time (lower UTCI by 3°C) are experienced by a pedestrian for the case with higher wind speed (reference case). Also the average temperature, average vapour pressure and average RH in the street canyon drop lower for the case with higher wind speed which are all in favor of more comfortable conditions for the pedestrian (Fig. 5.21b, c and d, respectively), however the differences are rather small.

Figure 5.21: Comparison of base case ($U_{10}=5\text{m/s}$) and case 2 ($U_{10}=1.5\text{m/s}$) for a) UTCI for a person standing 1 m from the windward wall b) average air temperature c) average vapour pressure and d) average relative humidity, in the street canyon

To investigate the cause of the higher UTCI for the case with lower wind speed, we look at the variation of air temperature, mean radiant temperature, vapour pressure and wind speed, at the pedestrian location, for cases with higher and lower wind speed (Fig. 5.22a to d, respectively). It can be seen that the $T_{mrt}$ for the two cases is very similar, although the air temperature is approx. 2°C higher, and the vapour pressure is approx. 1 hPa higher, for the case with lower wind speed. This is due to lower air exchange at top of the canyon for this case. Higher values of air temperature and vapour pressure, combined with lower wind speed at this location contribute to
higher values of the UTCI.

So it can be seen that the cooling potential for a pedestrian at a distance of 1 m from the windward wall is higher in a case with lower wind speed, where buoyancy is more pronounced, but in comparison to the base case, higher UTCI (less comfort) at the pedestrian location is predicted.

![Figure 5.22](image)

**Figure 5.22:** Comparison of base case \(U_{10}=5\text{ m/s}\) and case 2 \(U_{10}=1.5\text{ m/s}\) for a) air temperature b) \(T_{mrt}\) c) vapour pressure and d) wind speed, at the location of a person standing 1 m from the windward wall

### 5.7 The influence of climate

In this section, we study the influence of the climate on the potential of evaporative cooling when a windward wall is initially wet (case 3). The temperature and relative humidity for the boundary conditions are chosen to be a day in the hottest week during a heat wave in Zürich (summer 2003) (Fig. 5.23). The climatic data are provided by MeteoSchweiz. Temperature varies between approx. 20°C and 33°C and the relative humidity between 24% and 75%. The windward wall is initially wet after
5.7. THE INFLUENCE OF CLIMATE

a rain shower (capillary saturated) while the other surfaces are dry. The walls of the canyon are 9 cm thick, made of ceramic brick and have an albedo value of 0.4. The ground cover is 10 cm concrete, assumed to be dark colored with an albedo value of 0.1. The reference wind speed at 10 m height \((U_{10})\) is 1.5 m/s which is the average wind speed during the chosen week (data provided by MeteoSchweiz). Drying of the wall is simulated for 48 hours.

![Graph](image.png)

**Figure 5.23:** Temperature and relative humidity variation in 24 hour for the average of the hottest week during a heat wave condition in Zürich (summer 2003)

We monitor the drying behavior of the windward wall. Fig. 5.24 shows the surface temperature and relative humidity as a function of time at four locations on the outer surface of the windward wall. We can see that for the top of the wall (height of 9.5 m) the second drying phase starts on the second day after approx. 34 hrs, characterized by a sudden drop in the relative humidity and a change in the slope of the temperature curves. For the next point at the height of 6.5 m, the second drying phase starts an hour later compared to the point at the height of 9.5 m. For the point at height of 3.5 m, the second drying phase starts 4 hrs after the point at 6.5 m.

Figs. 5.25a, b, c and d show the surface temperature at the top and bottom of the windward wall, and the average temperature and relative humidity in the street canyon, respectively, for cases with and without moisture. Looking at the surface temperatures for this case, we can see that the surface temperatures are high compared to the base case (on the second day, top point is 26°C and bottom point is 14°C higher in the heat wave case), while the evaporative cooling at these two points is not necessarily more effective. At the top point (height of 9.5 m), the temperature drop is approx. 18°C (3°C more than the base case), although at the bottom point (height of 0.5 m) the temperature drop is 9°C on the first day and 12°C on the second day (4°C and 1°C less than the base case, respectively).
Studying the average air temperature and relative humidity in the street canyon (Figs. 5.25c and d), it can be seen that for the case with wet wall, the temperature goes as high as 35°C at around 15:00, when the relative humidity is approx. 33%. It can be seen that although the average temperature in the street canyon is higher for the heat wave case, compared to the design year case, the temperature drop due to evaporative cooling is 2°C less during the day (approx. 1°C) but 1.5°C higher during the night (approx. 2.5°C).

To further evaluate the effectiveness of evaporative cooling we study the comfort conditions of a person standing in the street canyon, 1 m from the windward wall. Fig. 5.26a shows the UTCI at the studied location, for the two cases, i.e. with and without moisture. It can be seen that the person can feel up to max. 2°C cooler during the first day (2.5°C during the second day). The cooling potential is higher during night with a maximum of 4°C although this is less important since a low temperature are experienced during the night, however this can create comfortable conditions for sleeping when using outside air ventilation. The cooling potential of heat wave case is during the day is lower compared to what was observed for the design year case by 0.5°C for the first day and 0.2°C for the second day.

Further we look at the variation of the four parameters influencing the UTCI, being the air temperature, mean radiant temperature ($T_{mrt}$), vapour pressure (relative humidity) and wind speed at the location where the UTCI is evaluated (Fig. 5.26b, c, d, e and f, respectively), for cases with and without moisture. We can see that, during the day, while the air temperature and $T_{mrt}$ are both lower for the case with moisture (by max of 1.5°C and 9°C, respectively), the vapour pressure, and relative humidity, at this location are higher. Knowing that comfort of a person in the canyon (UTCI), is influenced not only by temperature but also by vapour pressure, it can be
seen that in this case, during the day, the cooling effect of lower air temperature and $T_{mrt}$ which is a result of the evaporative cooling, is to some extent canceled out by the higher vapour pressure (increase of approx. 7 hPa). During the night, a larger drop of air temperature and $T_{mrt}$ is occurring, while the increase of vapour pressure is lower (approx. 1 hPa). This results in a more significant drop of UTCI during the night than during the day.

In order to study the influence of each of the four parameters, i.e. air temperature ($T$), mean radiant temperature ($T_{mrt}$), vapour pressure ($p_v$) and air velocity ($v$), on the UTCI for the heatwave case, the following parametric study is conducted. The case without moisture is chosen as the reference case and new UTCIs are calculated by changing one parameter at a time. The new values given for each parameter for this study is what is achieved from the study with the presence of moisture. Fig. 5.27 shows the difference between the UTCI achieved using a parameter ’a’ from the moist case (UTCI$_a$) and the UTCI of the base case (dry case), UTCI$_{dry}$. So a positive value means that applied change results in an increase of the UTCI$_{dry}$ while
a negative value means it results in decrease of the UTCI$_{dry}$. The combination of all the changes achieved using each individual parameter will provide the total difference between the UTCI of the dry case and UTCI of the moist case. It can be seen that lower air temperature and $T_{mrt}$ of the moist case result in a drop of UTCI$_{dry}$. The
factor that cancels out this cooling effect is the vapour pressure, as it can be seen that specially during the hottest hours of the day, it results in an increase of the UTCI\textsubscript{dry}. Therefore the overall cooling effect achieved from evaporative cooling for the heatwave case during the day, for the person standing 1 m from the windward wall, is not very large.

**Figure 5.27:** Parametric study on the influence of each of the four parameters on the UTCI of the dry case

The observed drop in wind speed at the pedestrian location for the case with moisture, as seen in Fig. 5.26f, is due to the same phenomena as described in Sec. 5.6.

Further, we look at the UTCI for a person standing 1 m away from the leeward wall (Fig. 5.28). It can be seen that the difference of the UTCI at this location for cases with and without moisture is insignificant during the day, while it is approx. 3°C during the night time. Lower cooling potential at this location compared to the location close to the windward wall is due to the fact that this location is further away from the windward wall which is being dried.

If we compare the UTCI for a person standing 1 m from the windward wall and for a person standing 1 m from the leeward wall (Fig. 5.29a), for the case with moisture, it can be seen that, during the day, the UTCI for a person close to the windward wall is approx. 8°C higher than for a person close to the leeward wall, while there is no difference between the two during the night. To understand this, we look at the individual parameters effecting the UTCI, and compare them for the two locations (Figs. 5.29b to f). It can be seen that there is a large difference between the \( T_{mrt} \) at the two locations (Fig. 5.29c). During the time that the leeward wall is exposed to direct solar radiation (between 5:00 and 8:00 and 15:00 to 18:00) (as shown in Fig. 5.8), high \( T_{mrt} \) is experienced for the person standing close to this wall but as soon as the sun leaves this wall and falls on the windward wall, the \( T_{mrt} \) for the
person standing close to the leeward wall drops and the one for the windward wall increases. The duration when the windward wall is exposed to direct solar radiation is longer and the radiation intensity during this period is higher (Fig. 5.8) which results in higher $T_{mrt}$ compared to the leeward wall. Comparing the values of air temperature and vapour pressure, and their combined effect (relative humidity), for the two locations, we can see very similar values for the two locations. So the main cause of the difference between the UTCI at the two locations is the mean radiant temperature.
5.8 The influence of albedo of the surfaces

In this section, the influence of the color of the walls on their drying behavior and on the comfort conditions in the street canyon, is studied. The boundary conditions are...
for a typical meteorological year (TMY) in Zürich (Fig. 5.9). The day considered is the 21st of June and the reference wind speed at 10 m height \( (U_{10}) \) is 5 m/s. cases 1, 4 and 5, are compared to one another, where the walls are 9 cm thick made of ceramic brick and the ground is 10 cm thick concrete cover. The windward wall is assumed to be wet. The difference between the three cases is the value of the albedo for cladding and ground material. For case 1 (the base case), an albedo value 0.4 for the walls and 0.1 for the ground, is used. For case 4 (the dark colored case), the albedos represent darker colored materials (an albedo value of 0.1 for the walls and 0.04 the ground), thus absorbing more shortwave radiation. For case 5 (the light colored case), the albedos represent lighter colored materials (an albedo value of 0.7 for both walls and ground), therefore absorbing less shortwave radiation.

To compare the effect of evaporative cooling in these three cases, we study the variation of the average temperature in the street canyon, the surface temperature and relative humidity at the top of the windward wall and the UTCI for a person standing 1 m away from the windward wall (Figs. 5.30a, b, c and d respectively).

Looking at the average temperature in the street canyon, we can see lower air temperature for the light colored case compared to the two other cases (approx. 2°C). This is due to the fact that light colored materials absorb less heat and the walls have lower surface temperatures, therefore there is lower convective heat transport to the air. For the base case and the dark colored case, we observe that the average air temperatures are very close to each other with only a difference of 0.5°C during the second day. From Fig. 5.30b, it can be seen that the difference in surface temperature at the top of the windward wall for the different cases is approx. 1.5°C for the first day, while the temperature difference increases to 3°C for the second day when the second drying phase starts. In Fig. 5.30c, the drop in surface relative humidity below 100% indicates the development of a dry surface layer and marks the start of the second drying phase. It can be seen that the wall of the dark colored case dries faster in comparison to the light colored case. This is due to the fact that the wall with dark color absorbs more heat which is used for the evaporation of water.

Observing the UTCI variations (Fig. 5.30d), we can see that the UTCI is 2.6°C lower for the light colored case in comparison to the base case. If the surfaces have a darker color, the UTCI is slightly higher in comparison to the base case. This study shows that the color of the surfaces of a street canyon can be an important factor in how a pedestrian in the street feels.

In general, the color of the material can affect the conditions in the street canyon in two opposite ways: A light colored material does not absorb a lot of heat, therefore results in lower surface temperature and a lower air temperature in the canyon. On the other hand, due to lower heat absorption of light colored material, less drying occurs which results in a smaller drop of surface temperature and air temperature due to evaporative cooling. Same discussion can be made for a dark color case. A dark colored material absorbs more heat, which results in a higher surface temperatures and higher air temperature in the canyon. On the other hand, higher absorption
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Figure 5.30: Variation of a) average temperature in the street canyon, b) surface temperature at the top of the windward wall (height of 9.5 m) c) surface relative humidity at the top of the windward wall (height of 9.5 m) and d) the UTCI for a person standing 1 m away from windward, for the three cases of heat results in higher evaporation, therefore lower surface and air temperatures due to evaporative cooling. In this study, when the three cases with wet walls and different colors are compared, we see that the effect of heat absorption is larger than evaporative cooling effect: the light colored case results in lower surface temperature, lower average air temperature in the canyon and lower UTCI values, compared to the darkened color case.

Now we look at the cooling effect of the light and dark colored cases, by comparing the UTCI for the person standing 1 m from the windward wall, for the cases with and without moisture (Figs. 5.31a and b). It can be seen that although the light colored case results in lower UTCI in comparison to the dark colored case, the evaporative cooling effect of the dark colored case is higher (drop of the UTCI by 3°C for the dark colored case in comparison to 2°C for the light colored case).

Looking at the variation of air temperature, \( T_{mrt} \) and vapour pressure, for cases with and without moisture, at the position where UTCI is studied, for the the two cases
Figure 5.31: The UTCI for a person standing 1 m from the windward wall, for cases with and without moisture for a) light colored case, and b) dark colored case.

(Figs. 5.32a to f), we can see that drop of both air temperature and $T_{mrt}$ with the presence of moisture is larger for the dark colored case. Also the increase of vapour pressure is higher at this location for the case with dark colored material. Higher surface temperatures due to high absorption of heat by dark colored material results in higher $T_{mrt}$ (and eventually higher air temperature), more evaporation and therefore higher vapour pressure. We can see that the effect of the $T_{mrt}$ due to evaporation for the two cases is the largest compared to the effect of the other variables, therefore this factor is the main cause of the higher evaporative cooling effect for the dark colored case.
Figure 5.32: Comparison of air temperature for a) light colored case and b) dark colored case, comparison of $T_{mrt}$ for c) light colored case and d) dark colored case, and comparison of vapour pressure for e) light colored case and f) dark colored case, for cases with and without moisture, at the position of a pedestrian standing 1 m from the windward wall.
5.9 The influence of location of the wet surface

In this section, we study the influence of the location of the wet surface on the conditions in the street canyon and on pedestrian comfort. First we consider case 6, where the ground is wet while the wall surfaces are dry. The walls have 9 cm of ceramic brick with an albedo of value of 0.4. The ground covered with 10 cm ceramic brick, with an albedo value of 0.1. Choice of ceramic brick as the material of the ground for this case is for the purpose of direct comparison with the base case, where the ceramic brick walls were used, and the windward wall was wet. The boundary conditions are for a typical meteorological year in Zürich (Fig. 5.9). The day of the study is the 21st of June and the reference wind speed at 10 m height \( U_{10} \) is 5 m/s. Fig. 5.33 shows the variation of the surface temperature and surface relative humidity of the ground during 48 hrs of drying at four points 0.5 m, 3.5 m, 6.5 m and 9.5 m from the leeward wall.

![Figure 5.33: Surface temperature and relative humidity at four points on the upper surface of the ground](image)

It can be seen that the surface of the ground reaches the second drying phase at two of the four considered locations, namely at 9.5 m and 6.5 m from the leeward wall, after approx. 12 hr and 15 hr, respectively. After entering the second drying phase, the surface temperature at these two points increases to approx. 47°C and the relative humidity at the surface drops to approx. 60%. During the night, the relative humidity at the surface of the wall at these two points reaches approx. 100% again, while on the second day of drying, both points as well at the point at 3.5 m from the leeward wall enter the second drying phase.

The observed temperature drop at approx. 8 hr and 9.5 hr for the points 0.5 m and 3.5 m from the leeward wall, respectively, corresponds to the time when these locations become shadowed. This part of the ground again becomes sunlit in the afternoon,
resulting in a temperature rise.

To study the influence of evaporative cooling, Figs. 5.34a and b compare the ground surface temperature at points 9.5 m and 0.5 m from the leeward wall, respectively, for the two cases: when the ground surface is initially wet and when it is initially dry. It can be seen that evaporative cooling results in a temperature drop of maximum 26°C on the second day at the point 9.5 m from leeward wall and approx. 10°C for the point 0.5 m from the leeward wall. Figs. 5.34c and d show that the average temperature in the street canyon drops by approx. 2°C and the average RH in the street canyon increases by approx. 10% for the case with moisture. Comparing with the base case, when the windward wall is wet, we can see that the average temperature drop in the street canyon is larger for the base case (3°C in comparison to 2°C for the current case).

![Figure 5.34: Comparison of ground surface temperature at a location a) 9.5 m from the leeward wall, b) 0.5 m from the leeward wall, c) average temperature in the street canyon and d) average RH in the street canyon, for cases with and without moisture](image)

Further we compare the effect of evaporative cooling on the drop of the UTCI for the location of a pedestrian standing 1 m away from the windward wall (Fig. 5.35a). It can be seen that the UTCI drops by approx. 2.5°C on the first day and approx.
1.5°C on the second day, due to evaporative cooling. In comparison to the base case (Fig. 5.12a), the drop of the UTCI is similar on the first day of drying, although it is less for the second day of drying, for the case with the ground being wet, due to higher surface temperatures, at both the windward wall and the ground.

We further look at the variation of the parameters influencing the UTCI, being air temperature, $T_{mrt}$, vapour pressure (relative humidity) and wind speed (Figs. 5.35b to f). It can be seen that evaporative cooling causes an air temperature drop of 1.5°C and a $T_{mrt}$ drop of 8°C during the first day and 4°C during the second day. For the base case (Fig. 5.12), we noted an air temperature drop of 2°C and a $T_{mrt}$ drop of 8°C for both days. The higher $T_{mrt}$ during the second day, for the case with the ground wet, is the main cause of the lower UTCI drop and it is due to higher surface temperatures at the ground after some locations have entered the second drying phase.

Finally we compare the UTCI value, as well as air temperature, $T_{mrt}$ and vapour pressure, at the pedestrian position, of the current case, with the base case when the windward wall was wet (Fig. 5.36a to d, respectively). It can be seen that during the first day, the UTCI of the case with the wet ground is slightly lower than the base case. This trend is the same for the first half of the second day, although towards the end of the second day, the UTCI for the case with the wet ground goes slightly higher than the base case (by approx. 1°C). We can see that the air temperature at this point is always higher for the case with the ground wet, although the difference in the $T_{mrt}$ changes from first to second day. For the first day, the case with the wet ground shows slightly lower $T_{mrt}$ compared to the base case. This is due to the fact that in this case, the ground surface temperature is lower due to evaporative cooling, which was not the case for the base case, where high ground surface temperatures were experienced. It should be noted that due to the geometry of the street canyon, the ground receives a higher solar radiation intensity in comparison to the walls, which results in higher surface temperatures. This also results in a faster evaporation of water from the ground surface when its wet. During the second day of drying, when most locations on the ground surface have entered the second drying phase, surface temperature at the ground goes up, which results in a higher $T_{mrt}$. The higher $T_{mrt}$ during the second day contributes to higher UTCI for the case with ground wet. Also it can be seen that for the current case, the vapour pressure at the pedestrian position decreases on the second day (Fig. 5.36d), since most of the points on the ground have entered the second drying phase. This lower vapour pressure is in favor of lower UTCI, therefore the influence of a higher $T_{mrt}$ on increasing the UTCI is reduced.

From this study, we conclude that the evaporative cooling potential of a case with wet ground is very close to the case with the a wet windward wall during the period when evaporative cooling is more pronounced (first day of drying), although it reduces as the surface of the ground is locally dried out.
Figure 5.35: Comparison of cases with and without moisture for a) UTCI b) air temperature c) $T_{mrt}$ d) vapour pressure e) relative humidity and f) wind speed, for a person standing 1 m from the windward wall.
5.10 The influence of the material of the surfaces

In this section, the influence of the material of the wet surface, on the conditions in the street canyon and on the evaporative cooling effect, is evaluated. For this purpose, three different materials are chosen for the windward and leeward walls, being 9 cm ceramic brick (base case), calcium silicate (case 7) and mineral plaster (case 8). The capillary moisture content for the materials is 130 kg/m³, 894 kg/m³, and 231 kg/m³, respectively. The liquid permeability, sorption (hygroscopic) curve, and moisture retention curve of the three materials are shown in Fig. 5.37. More transport properties of the three material are provided in the appendix. Calcium silicate is a coarse porous material with very high liquid permeability and high capillary moisture content. Mineral plaster is a very hygroscopic porous material showing a low liquid permeability. Ceramic brick is non-hygroscopic coarse porous material showing an average liquid permeability and low capillary moisture content.

Initially, a study is conducted to evaluate the drying behavior of the three materials
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Exposed to constant boundary conditions. A 3 cm thick material is considered. A 1D structured grid, consisting of 340 finite elements is constructed based on a grid sensitivity analysis, with gradual mesh refinement toward the air-porous material interface. The material is drying from one side while the other side is considered adiabatic and impermeable to moisture. For the boundary conditions, a temperature of 23°C and a relative humidity of 40% is chosen, representing a typical day of the year. The materials are considered initially saturated and at 23°C. The CHTC and the CMTC at the interface are chosen as 10 W/m²K and $2.17 \times 10^{-7}$ s/m, respectively, based on previous simulations. The materials are allowed to dry for 200 hrs.

From Figs. 5.38a and b, it can be seen that mineral plaster dries much slower than ceramic brick and calcium silicate. While the average saturation reaches zero after approx. 80 hrs for ceramic brick and after approx. 180 hrs for calcium silicate, mineral plaster still has a saturation of 0.5 after 200 hrs of drying. Fig. 5.38c shows that mineral plaster has a high drying rate at the beginning, decreasing fast and after approx. 20 hrs, it reaches a plateau which remains constant until the end of the

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**Figure 5.37:** a) Liquid permeability as a function of capillary pressure b) sorption (hygroscopic) curve and c) moisture retention curve, for ceramic brick, calcium silicate, and mineral plaster
Figure 5.38: Comparison of a) average moisture content, b) average saturation, c) drying rate, d) relative humidity at the surface, and e) temperature at the surface, as a function of time, for calcium silicate, ceramic brick and mineral plaster.

This shows that mineral plaster has a very short first drying phase and that the material enters the second drying phase very shortly after start of the drying. On the other hand, calcium silicate has a very long first drying phase, which lasts for approx. 150 hrs. Start of the second drying phase can be distinguished also by
studying the relative humidity and temperature at the surface of the material (Figs. 5.38d and e). It can be seen that for mineral plaster with a very short first drying phase, the temperature at the surface drops to 17°C (due to evaporative cooling) and immediately starts to increase as the material enters the second drying phase when less heat of evaporation is required (Fig. 5.38f). This is also marked by the sudden drop of relative humidity below 100% (Fig. 5.38e). For calcium silicate with a much longer first drying phase in comparison to calcium silicate and ceramic brick, surface temperature drops to approx. 11°C and stays at this value until the material enters the second drying phase after 150 hrs of drying. At this point, the surface temperature starts to increase and relative humidity at the surface drops below 100%. The same behavior can been for ceramic brick but after approx. 20 hrs of drying.

The observed behavior of the three material can be explained by their moisture transport properties. Calcium silicate with high liquid permeability allows for continuous water supply from the inside of the material towards the surface, which causes the surface to remain at 100% RH and prevents the surface from drying out quickly. This results in a long first drying phase. On the other hand, mineral plaster with low liquid permeability, and therefore higher resistance to liquid transport, leads to a faster drop in RH at the surface and faster drying, therefore very short first drying phase. So we expect that calcium silicate to be a material promoting strong evaporative cooling while the mineral plaster has a small evaporative cooling effect.

After studying the drying behavior of these materials, we use them as constructing material for the windward and leeward walls in the street canyon. Here we compare cases 1, 7 and 8 (Sec. 5.4). For these studies, the climatic conditions follow a typical meteorological year in Zürich for June 21st (Fig. 5.9). Only the windward wall is wet while the ground and the leeward wall are dry. The walls of the street canyon have albedo of 0.4 and ground is 10 cm concrete with albedo of 0.1. The reference wind speed at 10 m height \( U_{10} \) is 5 m/s.

To compare the three cases, initially, we look at the average air temperature and relative humidity in the street canyon as well as the surface temperature and surface relative humidity of the windward wall, at a heights of 9.5 m and 0.5 m (Figs. 5.39a to f, respectively).
Figure 5.39: Variation of a) average temperature and b) average relative humidity in the street canyon, c) surface temperature and, d) surface relative humidity at the top of the windward wall (9.5 m high), e) surface temperature and f) surface relative humidity at the bottom of the windward wall (0.5 m high), for a person standing 1 m away from windward, for cases with ceramic brick, calcium silicate and mineral plaster as the outside material for the walls.
It can be seen that the average air temperature in the street canyon is lowered by approx. 0.2°C when the walls are made of calcium silicate, in comparison to the ceramic brick case. When the walls are made of mineral plaster, the average temperature is approx. 0.5°C higher than the ceramic brick case. For the surface temperature at a height of 9.5 m, it can be seen that during the first day, the case with mineral plaster has a higher temperature (8°C more than the ceramic brick case), while the case with calcium silicate has a surface temperature approx. 1°C lower than the ceramic brick case. The relative humidity at the surface of the windward wall at the height of 9.5 m, for the case of mineral plaster, drops below 100% after approx. 7 hrs. This shows that the material has entered the second drying phase and therefore the surface temperature can reach high values during the first day. On the second day of drying, when the surface of the wall at the top has also dried for the wall with ceramic brick, the difference between the surface temperatures of the ceramic brick and the mineral plaster case is approx. 6°C, while the difference between the ceramic brick and calcium silicate case is approx. 5.5°C. By the end of the 48 hrs drying, the wall of the case with calcium silicate is still in the first drying phase at the height of 9.5 m. The bottom of the windward wall performs differently that its top. As can be seen in Fig. 5.39e and f, the bottom point does not enter the second drying phase for the ceramic brick or calcium silicate case. This causes the surface temperature for these two cases at this point to stay low and not to increase.

As expected, the case with a material which quickly enters the second drying phase, such as mineral plaster, results in a higher surface temperature at the top of the wall in comparison with a material that remains longer in the first drying phase, such as calcium silicate. The average air temperature and average relative humidity in the street canyon for these two extremes is not significantly different (Figs. 5.39a and b).

Figure 5.40: Variation of a) the UTCI and b) the $T_{mrt}$, for a person standing 1 m away from windward, for cases with ceramic brick, calcium silicate and mineral plaster as the outside material for the walls.

To compare the effect of different materials further, we look at the UTCI for a person standing 1 m away from the windward wall (Fig. 5.40a). It can be seen that the
predicted UTCI for cases with ceramic brick cladding and calcium silicate cladding is very similar, while the case with mineral plaster results in a UTCI of approx. 1°C higher than the ceramic brick case, during the second day of drying. From Fig. 5.40b, we can see that the observed difference of the UTCI for the three cases is attributed to the difference in the $T_{mrt}$. The case with mineral plaster, with the highest surface temperature, also results in the highest $T_{mrt}$, which influences the UTCI. Although the difference in the $T_{mrt}$ of the cases is not so large.

5.11 The influence of thickness of wall cladding

In this section, the influence of the thickness of the wall cladding on the evaporative cooling potential of the street canyon is studied. The boundary conditions are the same as in the base case, with the temperature and relative humidity of the environment taken from a typical meteorological year (TMY) in Zürich, for 21st of June (Fig. 5.9). The difference between the current case and the base case is the thickness of the ceramic brick of the windward and leeward walls. For the current case, the thickness of the ceramic brick for the cladding is 1 cm while for the base case (case 1) it was 9 cm. The windward wall is assumed to be wet after a rain shower (capillary saturated) while the other surfaces are dry. The walls have an albedo value of 0.4 and the ground is 10 cm concrete cover, assumed to be dark colored with an albedo value of 0.1. Drying of the wall was simulated for 48 hrs.

First we look at the variation of the surface temperature and relative humidity at four points at the surface of the windward wall (Fig. 5.41). We can see that in comparison to the base case (Fig. 5.10), the surface temperature reaches higher values and all

![Figure 5.41: Surface temperature and relative humidity at four points on the surface of the windward wall](image)

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locations on the windward wall dry faster. On the first day of drying, the point at the height of 9.5 m enters the second drying phase after approx. 14 hrs of drying, followed by the point at 6.5 m and 3.5 m. The lower point on the wall enters the second drying phase during the second day of drying. It can be seen that at the points which enter the second drying phase, the relative humidity suddenly drops below 100%. The relative humidity at these points increases again during the night and drops again during the second day of drying.

In order to study the effect of evaporative cooling, we compare this case with a similar case but when the windward wall is dry (Fig. 5.42). We can see that the surface temperature at the top point of the windward wall is maximum 20°C lower for case with moisture before it enters the second drying phase. On the second day, the temperature at this point for cases with and without moisture is very similar since there is no evaporative cooling effect anymore (Fig. 5.42a). At the bottom of the windward wall (Fig. 5.42b), the temperature is approx. 18°C higher for the case without moisture during the first day, and after the point enters the second drying

![Figure 5.42](image_url)

**Figure 5.42:** Comparison of case with and without moisture for a) surface temperature at the height of 9.5 m b) surface temperature at the height of 0.5 m at the windward wall, c) average air temperature and d) average relative humidity in the street canyon
phase, the temperature difference drops to approx. 8°C on the second day. For the current case, the magnitude of the temperature drop at these two points due to evaporative cooling is higher before entering the second drying phase in comparison to the base case (Fig. 5.11a and b). Due to the faster drying on the second day, the temperature difference between wet and dry cases is smaller, in comparison to the base case.

The average temperature and relative humidity in the street canyon are approx. 2.5°C higher and 15% lower for the case without moisture (Fig. 5.42c and d). The drop of the average temperature due to evaporative cooling is about 0.5°C lower in comparison to the base case.

Evaporation also influences the comfort (the UTCI) for a person standing 1 m away from the windward wall (Fig. 5.43a). The UTCI is approx. 3°C lower on the first day and 1.5°C on the second day, for the case with evaporative cooling. The drop of the UTCI on the first day is slightly higher in comparison to the base case, where the maximum drop was approx. 2.5°C. On the second day, the drop of the UTCI is higher for the base case (2.7°C for the base case in comparison to 1.5°C for the current case).

Figs. 5.43b to f show the individual factors affecting the UTCI being the air temperature, the mean radiant temperature, the vapour pressure, the relative humidity and the wind speed, at the studied location. We can see that the drop of air temperature due to evaporation is approx. 2°C which is similar to the base case (Fig. 5.12). The drop in the \( T_{\text{mrt}} \) due to evaporative cooling is approx. 9°C during the first day which is higher in comparison to the base case. Also we can see that the vapour pressure at this point is higher by approx. 2.5 hPa during the first day of drying for the case with moisture. On the second day, when all the locations on the windward wall have entered the second drying phase, the value of vapour pressure is similar to the case without moisture. The vapour pressure at this point for the case with moisture during the first day is larger than what was observed for the base case (approx. 2 hPa).

Further we study the influence of a thinner material (brick) at the walls on the temperature and moisture conditions in the street canyon as well as the comfort of a pedestrian. Figs. 5.44a to d compare the cases with 1 cm and 9 cm thick brick cladding, for the UTCI of a person standing 1 m from the windward wall, the average air temperature, the average vapour pressure and the average relative humidity in the street canyon, respectively. It can be seen that for the case with a thinner material, the material enters the second drying phase faster, therefore the cooling effect of evaporation is lower especially in the second day. This can be seen by higher UTCI during the second day of drying for the case with the thinner material, as well as higher average air temperature in the street canyon. Also it can be seen that for the thinner wall, the average vapour pressure is initially higher than the case with the thicker wall (same relative humidity), but after the wall dries, the vapour pressure drops below. In conclusion, the thinner material has similar evaporative cooling effect
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as the thick material, as long as it remains in the first drying phase.

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**Figure 5.43:** Comparison of cases with and without moisture for a) UTCI b) air temperature c) $T_{mrt}$ d) vapour pressure e) relative humidity and f) wind speed, at the position of a person standing 1 m from the windward wall
CHAPTER 5. CASE STUDIES

Figure 5.44: Comparison of base case (9 cm brick) and case 9 (1 cm brick) for a) the UTCI at the position of a person standing 1 m from the windward wall b) average air temperature c) average vapour pressure and d) average relative humidity, in the street canyon

5.12 The influence of thickness of ground

In this section, the influence of the thickness of the ground material on the evaporative cooling potential of the street canyon is studied. The boundary conditions are the same as in the base case, with the temperature and relative humidity of the environment taken from a typical meteorological year (TMY) in Zürich, for 21st of June (Fig. 5.9). The difference between the current case and the base case is the thickness of the concrete cover at the ground which is 10 cm for the base case and 50 cm for the current case (case 10). The windward wall is assumed to be wet after a rain shower (capillary saturated) while the other surfaces are dry. The walls of the canyon are 9 cm thick made of ceramic brick and have an albedo value of 0.4 and the ground, assumed to be dark colored with an albedo value of 0.1. Drying of the wall was simulated for 48 hrs.

To study the influence of evaporative cooling on the temperature and comfort conditions in the street canyon, we compare this case with a similar case but when the windward wall is dry. Figs. 5.45a and b show the UTCI for a person standing 1 m from
5.12. THE INFLUENCE OF THICKNESS OF GROUND

It can be seen that the the drop in the UTCI is between 1°C to 1.5°C. This drop is less in comparison to the base case where the UTCI drop due to evaporative cooling was 2.5°C on the first day. The drop of the average air temperature is approx. 2°C on the first day which is also lower in comparison to the base case.

Further we compare the UTCI at the pedestrian location, and average air temperature, average relative humidity and average vapour pressure in the street canyon, of the current case (50 cm ground) with those of the base case (10 cm ground) (Figs. 5.46a to d, respectively). It can be seen that the UTCI for a person standing 1 m from the windward wall is about 2.5°C higher for the case with thinner ground material. Also the average air temperature in the street canyon is increased by approx. 1.5°C for this case, which results in a lower average relative humidity in the street canyon.

To investigate the source of the cooler conditions observed for the case with the thicker ground material, in Figs. 5.47a and b we compare the ground surface temperature at two positions, 9.5 m and 0.5 m from the leeward wall, for cases with thinner and thicker ground. It can be seen that the surface temperatures at these two positions are significantly higher (by 10°C and 9°C, respectively), for the case with thinner ground material. For the case with thinner material, we assumed that 10 cm thick concrete is placed on 90 cm soil when the soil is modelled as thermal resistance not considering its thermal capacity (assuming an insulation layer between concrete and soil). Increasing the thickness of the ground material results in a higher thermal capacity, therefore the temperature at the ground does not raise to high values. The high ground surface temperatures of the case with thinner material results in higher air temperature (both in the canyon and at pedestrian location), and higher $T_{mrt}$ at the pedestrian location. This can be seen in Figs. 5.47c and d. It can be seen that the air temperature at the pedestrian location is approx. 1°C lower and the $T_{mrt}$ at this location is approx. 9°C lower during the first day, for the case with thicker ground material. On the

Figure 5.45: Comparison of case with and without moisture for a) the UTCI for a person 1 m from the windward wall and b) average air temperature in the street canyon
second day, the $T_{mrt}$ of the case with thicker concrete initially goes above the one of the thinner concrete, and then it drops below again. The increase of $T_{mrt}$ at the first hours of the day is due to higher surface temperature at certain points on the ground such as what was observed for the point at 0.5 m from the windward wall in Fig. 5.47a. This observation is attributed to the dynamic behavior of concrete. The thick concrete cover will remain warmer during the night time explaining the higher temperatures in the morning when heated by the sun. After longer exposure to the sun, the thin concrete layer will however show higher temperatures since it can store less heat.
5.13 THE INFLUENCE OF SKY TEMPERATURE

In the previous case studies, the sky temperature was kept constant at 15°C. This was done in order to limit the cooling effect by long-wave radiative losses to the sky and the focus on cooling due to evaporation. In order to look at a more realistic case, in this section, the influence of the sky temperature on the evaporative cooling potential of the street canyon is studied. The boundary conditions are the same as in the base case, with the temperature and relative humidity of the environment taken from a typical meteorological year (TMY) in Zürich, for 21st of June (Fig. 5.9). The difference between the current case and the base case is the temperature of the sky. For the current case, the sky temperature is calculated from the air temperature ($T_a$) by Eq. 5.7 (Garg and Prakash, 2000). The resulting sky temperature is shown in Fig. 5.48, which is much lower than the 15°C assumed in the other case studies. The windward wall is assumed to be wet after a rain shower (capillary saturated) while the other surfaces are dry. The walls of the canyon are 9 cm thick, made of ceramic brick and have an albedo value of 0.4. The ground cover is 10 cm concrete, assumed
to be dark colored with an albedo value of 0.1. Drying of the wall was simulated for 48 hrs.

\[ T_{sky} = 0.0552 \times T_a^{1.5} \]  \hspace{1cm} (5.7)

**Figure 5.48:** Temperature of the sky

Fig. 5.49a shows the UTCI at the pedestrian position for the current case, and the base case. It can be seen that the maximum difference in the UTCI is approx. 2.5°C during the second day. Lower UTCI for the current case is due to more losses by long-wave radiation to the cooler sky. If we compare the evaporative cooling potential, by looking at the UTCI for cases with and without moisture (Fig. 5.49b), we can see that the drop in the UTCI is approx. 2°C for both days, which is 0.5°C and 0.7°C lower

![Figure 5.49: Comparison of the UTCI for a) the current case with changing sky temperature and the base case, with moisture and b) for the current case, with and without moisture](image)

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than what was observed for the base case (Fig. 5.12a). So we can see that evaporative cooling potential drops if the cooling by radiation to the sky is also considered which is a more realistic case. For realistic prediction of urban micro-climate and comfort, the use of the realistic sky model is therefore important.

5.14 Conclusions

In this chapter, the applicability of the proposed coupled model was demonstrated for studying the influence of evaporative cooling by applying it to different case studies. The model cases are compared to one another in terms of their ability to reduce the temperature in the street canyon due to evaporative cooling and to create more comfortable conditions for pedestrians.

The studied geometry is a 2D 1:1 street canyon with an east-west orientation. The study is performed for Zürich, for a two day period starting on the 21st of June. Ten difference cases were studied by changing the parameters such as the climatic conditions, wind speed, position of the wet surface, albedo of the wet surface, material of the wet surface and thickness of the material. The influence of the mentioned parameters on the cooling potential of the street canyon was evaluated using the UTCI for a person standing 1 m away from the windward wall.

The results achieved studying different cases are summarized in the Table 5.2 where the maximum UTCI value for the wet case ($\text{UTCI}_{\text{wet}}$) and the maximum evaporative cooling potential ($\text{UTCI}_{\text{wet}} - \text{UTCI}_{\text{dry}}$) (the value in the bracket is for the second day), achieved during the 48 hr simulation, is shown. For the cases with calcium silicate (CS) and mineral plaster (MP) for the cladding, no simulation with dry material was performed, therefore no cooling potential is calculated. The values of $\text{UTCI}_{\text{wet}}$ and cooling potential are also shown in Figs. 5.50a and b, respectively.

The highest UTCI is observed for the heat wave case, reaching max. of 38.6°C, which falls in the very strong heat stress UTCI category (Table 3.3). Although much higher UTCI is observed for this case in comparison to the base case, its evaporative cooling potential is lower than the base case. This is due to the fact for this case, evaporation results in a large increase in vapour pressure, which cancels out the cooling effect of the lower $T_{mrt}$ and air temperature.

The next highest UTCI is observed for the case with low wind speed, where the UTCI reaches a max. of 29.4°C (moderate heat stress). More pronounced buoyancy counteracting the forced convection results in lower air exchange at the top of the canyon, entrapment of air in the street canyon and higher temperatures, which in combination with lower wind speed, results in uncomfortable conditions. It can be seen that evaporative cooling potential is the highest for the low wind speed case (max. of 5.5°C), and without evaporative cooling, the UTCI reaches a maximum of approx. 35°C, which falls in the strong heat stress category.
Table 5.2: Comparison of difference cases in terms of the maximum UTCI and the cooling potential (the numbers in bracket are the results for the second day)

<table>
<thead>
<tr>
<th>case</th>
<th>UTCI&lt;sub&gt;wet&lt;/sub&gt; (°C)</th>
<th>cooling potential (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>base case</td>
<td>27.4</td>
<td>2.5 (2.7)</td>
</tr>
<tr>
<td>low wind speed</td>
<td>29.4</td>
<td>4.5 (5.5)</td>
</tr>
<tr>
<td>heat wave</td>
<td>38.6</td>
<td>2.0 (2.5)</td>
</tr>
<tr>
<td>light color</td>
<td>25.2</td>
<td>2.0 (2.0)</td>
</tr>
<tr>
<td>dark color</td>
<td>27.5</td>
<td>3.0 (3.0)</td>
</tr>
<tr>
<td>gr wet</td>
<td>27.8</td>
<td>2.5 (1.5)</td>
</tr>
<tr>
<td>CS ww</td>
<td>27.1</td>
<td>-</td>
</tr>
<tr>
<td>MP ww</td>
<td>27.8</td>
<td>-</td>
</tr>
<tr>
<td>thinner ww</td>
<td>28.5</td>
<td>3.0 (1.5)</td>
</tr>
<tr>
<td>thicker gr</td>
<td>25.6</td>
<td>1.0 (1.5)</td>
</tr>
</tbody>
</table>

The case with light color material results in the lowest UTCI compared to other cases (25.2°C), which falls in the no thermal stress category. In such a case (light color), the material absorbs less heat. Although this results in less drying and hence less drop of surface temperature and air temperature due to evaporative cooling, it also results in lower surface temperature and lower air temperature in the canyon, which seems to be more important than evaporative cooling effects. As can be seen, the cooling potential of this case is not so high (2°C) compared to the base case when the color of the surfaces is darker.

The case with thick ground cover results in the second lowest UTCI (25.6°C). For this case, the ground surface temperatures reach lower values, which results in lower

Figure 5.50: Comparison of case studies for their a) UTCI<sub>wet</sub> and b) cooling potential (for first and second day)
air temperature and $T_{mrt}$, hence more comfortable conditions. It can be seen that the cooling potential of this case is not so high (maximum of 1.5 °C) compared to the base case with thinner ground cover material.

We can see that changing the position of the wet surface from the windward wall to the ground does not influence the comfort (UTCI) or the cooling potential significantly during the first day of drying, although the cooling potential decreases during the second day. This is a result of higher ground surface temperatures and $T_{mrt}$ at different locations on the ground, which have entered the second drying phase, occurring faster in comparison to the windward wall (when wet). Due to the position of the ground (horizontal), the solar radiation intensity is higher on this surface, therefore higher surface temperatures are experienced compared to the windward wall.

Changing the material of the walls does not have a large influence on the comfort conditions in the street canyon, although the case with calcium silicate (CS) results in slightly lower UTCI values. This material dries slower and has a longer first drying phase, therefore its cooling effect on lowering the wall surface temperature stays longer.

Changing the thickness of the wall cladding does not have a large effect on the UTCI in the street canyon during the first day, but the UTCI increases by 3°C on the second day, compared to the base case. This is because the thinner material dries faster and enters the second drying phase earlier, where surface temperatures at the wall increases, resulting in higher $T_{mrt}$ and higher UTCI. Also the cooling potential for this case drops for the second day, due to quicker drying of all location on the wall and therefore shorter first drying phase.

Finally we observed that a person standing close to windward wall, who is exposed to direct sun for 8 hrs during the day compared to a person standing close to the leeward wall, who is in the shadow for some hours in the day, has more comfortable conditions during the day (lower UTCI by approx. 8°C). This is due to the shadowing effect which results in lower temperatures at the surfaces around the person and therefore lower $T_{mrt}$, which is in favor of more comfortable conditions. The cooling potential at this position due to evaporation is less than for the position close to the windward wall.
Chapter 6

Conclusions

6.1 Conclusions

The current trend towards urbanization and climatic change results in a growing interest in the urban climate in cities. A central theme is the study of the heat island effect and its consequences on building energy demand and the health and comfort of the residents.

Some of the methods used for mitigation of the excess heat in an urban environment are: i) use of materials with higher albedo (bright color materials), ii) reduction of anthropogenic heat release, iii) control of urban pollution, iv) taking advantage of evaporative cooling, v) modification of thermal capacity of surface materials, vi) modification of urban geometry, vii) introduction of shading canopies, etc.

In this thesis, we focused on the potential of evaporative cooling to remove excess heat from the city. For this purpose, we developed a coupled model allowing to investigate how the local wind flow pattern induces non-uniform drying of the urban surfaces, and how this drying results in a modification of the local micro-climate and the resulting thermal comfort in the street canyon. The model takes into account the influence of direct solar short-wave radiation, the long-wave radiative exchange between the urban surfaces and the sky (including multiple reflections), the effect of latent heat of evaporation, detailed material properties and buoyancy.

The proposed model consists of three main sub-models. A Computational Fluid Dynamics (CFD) model which solves the convective heat, air and moisture transport in the air, a Building Envelope Heat and Moisture (BE-HAM) model which solves the heat and moisture transport within the porous material, and a radiation model (RAD) which solves the radiative balance for short-wave and long-wave radiative exchange between the building surfaces and the sky. In addition, the model calculates the comfort of a pedestrian in the street canyon.
The results using the coupled model were compared with experiments consisting of the drying of ceramic brick specimens with cavity under controlled conditions. The specimens were scaled down in order to fit in a neutron radiography setup. This downscaling results in differences in the flow pattern in comparison to a real size street canyon as well as differences in the drying behavior of the porous surfaces. The current study is conducted to confirm the accuracy of the coupling procedures between the individual sub-models.

The change of the moisture content in the brick specimens was calculated from the experimental data. Two specimens were tested, one in the shape of a flat plate (FP) and one with a cavity, which resembles the shape of a small-scale street canyon (SC). The results achieved from the coupled simulation and the experiments were compared. For the FP specimen, the agreement was satisfactory, although the drying front was overestimated, while the moisture content towards the bottom surface of the specimen was underestimated. These differences can be attributed to uncertainties in the moisture transport properties, and the 2D assumptions for the simulation.

For the SC specimen, comparing the flow field obtained from PIV and simulations, showed that when the production of turbulent is disabled in the shear layer, the similarity between the experiments and simulations is satisfactory. Comparing the drying behavior of the SC specimen for simulation and experiment shows that the drying rate of the windward section is captured quite well, while for the leeward section and the ground, it is underestimated. The observed differences can be due to a number of factors such as differences in the flow field and turbulent kinetic energy values of experiment and simulation, uncertainties in the moisture transport properties, and 2D assumptions.

The proposed coupled model is then applied to a series of case studies, where the influence of various parameters on the effectiveness of evaporative cooling and on the thermal comfort is studied. The studied parameters are: position, albedo, thickness and material of the porous surfaces, as well as wind speed and climate. The studied geometry is a 2D 1:1 street canyon with an east-west orientation. The study is performed for Zürich, on June 21st. The cooling potential for each case is evaluated by the universal thermal climate index (UTCI) for a person standing 1 m away from the windward wall of a street canyon.

The results showed that the evaporative cooling effect is more important when wind speeds are low which corresponds to the more uncomfortable conditions with UTCI values in the moderate heat stress category. For this case, the presence of buoyancy counteracting the forced convection results in low air exchange at the top of the canyon, the entrapment of air in the canyon and higher temperatures. In this case, evaporative cooling heads to a large reduction of the UTCI.

We also saw that when using light colored material, comfort conditions in the street canyon are much better, although the evaporative cooling potential in such a case is not as large as for a case with dark colored material.
6.2. Limitations and future improvements

In this thesis, a coupled model was proposed in order to study the convective drying of porous materials in a street canyon, and the resulting evaporative cooling effect on the surrounding environment. Using the proposed model, the cooling potential of a few common scenarios was studied, e.g. under strong or light wind conditions, during a heat wave, or the dependency of the cooling potential on the material choice or finishing color. The proposed model has some assumptions and limitations, which are discussed below. Further, we provide suggestions for future improvements to the current model.

i) The present model is 2D, hence it does not include 3D air flow effects or 3D drying behavior of the porous materials. Also we assumed wind flow perpendicular to the main axis of the street canyon, which is an important simplification. Extending the model to 3D will provide more accurate results which however will largely increase the computational cost.

ii) The present model is limited to a street canyon geometry. In an urban environment, there exist different urban geometries where different street canyons may interact with one another. The present model can be adapted to more complex urban geometries by using more detailed radiation and CFD models.

iii) The CFD model uses the steady RANS approach, therefore the unsteady fluctuations in the flow field are neglected which could influence the calculated air exchange flux between street canyon and environment plus the calculated heat and mass fluxes at the porous surfaces. The amount of air exchange between the canyon air and the air above, is an important factor in the heat and moisture conditions in the street canyon, which affects the drying of the surfaces. Using LES modelling can be an improvement although it will increase the simulation time significantly (Louka et al., 2000).

iv) Each of the individual sub-models of the present coupled-model are separate stand-alone programs. Each of the programs need to be opened and executed individually, and pass information to the next program, which increases the overall simulation time. This method is chosen since the Fluent CFD code is a commercial code and not open source. Alternative methods which could reduce the overall computation cost are: using an open source program for the CFD code (i.e. OpenFOAM), and combining all the models into one code (at the cost of being less flexible), or using a method which makes the communication and exchange of data between the individual...
codes possible without having to open and close each individually (i.e. inter process communication (IPC) or Ptolemy project (Eker et al., 2003)).

v) The present model does not consider evaporation or evapo-transpiration from trees or vegetative surfaces. The evaporative cooling effect of green elements in a street canyon can be important, which can be also combined with shadowing effect of trees. Addition of a vegetation sub-model to the present model can improve the model and result in valuable findings.

vi) The current model does not use a soil model at the ground of the street canyon. Thermal capacity of soil as well as take up of rain and evaporation from the wet soil can be important in an urban geometry and can influence the conditions in the street canyon, therefore adding a soil model to the current model can be a future improvement.

vii) The case studies presented in this thesis consider drying of a wet surface for two days after a rain shower. For practical applications, we recommend conducting the simulations for longer duration and under real climatic conditions. Also it is recommended that initially a simulation with dry conditions (without a wet surface) be conducted to reach steady state conditions, and then to apply realistic rain events, including accurate determination of driving rain distributions on the surfaces. In addition, evaporation from a water pond in an urban environment can be added.

viii) The case studies presented consider a fixed sky temperature of 15°C. This was done in order to limit the cooling effect by long-wave radiative losses to the sky and to focus on cooling due to evaporation. It is known that in reality, the sky temperature varies during a day/night cycle. Therefore it is recommended that when a realistic prediction of urban micro-climate and comfort is intended, a realistic sky model should be used.

ix) The current model can be coupled to building energy simulation (BES) models and city energy simulation (CES) models, to study the influence of evaporative cooling on the energy demand in buildings in an urban environment or in an entire city.

x) The model proposed in this thesis enables a detailed study of evaporation from a wet porous surface in a street canyon. In order to study the influence of evaporative cooling on the heat island effect or to do detailed mitigation studies for cooling of an urban environment, this model can be incorporated into a multi-scale approach, e.g. the incorporation of the current model into mesoscopic regional climate models. For this purpose, the lower scale models need to be correct but also fast and thus simplified. The simplifications can be done in a number of ways such as: i) conducting more simplified porous material modeling, where all surfaces in a street canyon are combined into one bulk surface, or ii) conducting more simplified CFD simulations, where for example simplified wall functions are used. In addition, parametric studies can be conducted using the current model, the results of which can be fed to higher-scale models.
Appendix

Material properties

The material properties for the porous material used in this thesis have been determined experimentally: for the ceramic brick measurements by Derluyn et al. (2008) are used, for the concrete data are taken from the HAMSTAD benchmark case 1 (HAMSTAD WP2, 2002), for the mineral plaster in-house measurements are used, and for calcium silicate data by Poupelleer (2007) have been used. Some transport properties are given in Table 4.2, where $\rho_b$ (kg/m$^3$) is the bulk density, $c_p$ (J/kgK) is the specific heat capacity, $\mu_{dry}$ (-) is the vapour resistance factor of the dry material, $\lambda$ (W/mK) is the thermal conductivity, and $w_{cap}$ (kg/m$^3$) is the capillary moisture content.

Table A-1: Material properties of ceramic brick, concrete, mineral plaster and calcium silicate

<table>
<thead>
<tr>
<th>material</th>
<th>$\rho_b$</th>
<th>$c_p$</th>
<th>$\lambda$</th>
<th>$\mu_{dry}$</th>
<th>$w_{cap}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ceramic brick</td>
<td>2087</td>
<td>840</td>
<td>$1+0.0047 \times w$</td>
<td>24.79</td>
<td>130</td>
</tr>
<tr>
<td>concrete</td>
<td>2200</td>
<td>829</td>
<td>$1.5+0.0158 \times w$</td>
<td>200</td>
<td>146</td>
</tr>
<tr>
<td>mineral plaster</td>
<td>1504</td>
<td>1050</td>
<td>1.2</td>
<td>21.1</td>
<td>231</td>
</tr>
<tr>
<td>calcium silicate</td>
<td>270</td>
<td>1000</td>
<td>$0.06+0.00056 \times w$</td>
<td>5.6</td>
<td>894</td>
</tr>
</tbody>
</table>

Vapour diffusion coefficient

The vapour diffusion coefficient, as a function of moisture content, $w$, is calculated for ceramic brick, concrete and mineral plaster by Eq. A-1.
\[
\delta_v = \frac{2.61 \times 10^{-5}}{\mu_{dry} R_v T} \frac{1 - (w/w_{cap})}{0.503(1 - (w/w_{cap}))^2 + 0.497} \tag{A-1}
\]
and for calcium silicate by Eq. A-2:
\[
\delta_v = \frac{2.61 \times 10^{-5}}{\mu_{dry} R_v T} \frac{1 - (w/w_{cap})}{0.8(1 - (w/w_{cap}))^2 + 0.2} \tag{A-2}
\]

The vapour diffusion coefficient is used then to calculate the vapour permeability by:
\[
K_v = \frac{\delta_v \phi P_{v,sat}}{R_v T \rho_l} \tag{A-3}
\]
and the total moisture permeability of the porous material:
\[
K_{mm} = K_v + K_l \tag{A-4}
\]

**Moisture retention curve**

The moisture retention curve for ceramic brick is calculated by:
\[
w(p_c) = w_{cap}\left[0.846(1 + (1.394 \times 10^{-5} p_c)^4)^{-0.75} + 0.154(1 + (0.9011 \times 10^{-5} p_c)^{1.69})^{-0.408}\right] \tag{A-5}
\]

for concrete by:
\[
w(p_c) = w_{cap}\left[1.0(1 + (8.0 \times 10^{-8} p_c)^{1.6})^{-0.375}\right] \tag{A-6}
\]

for mineral plaster by:
\[
w(p_c) = w_{cap}\left[0.6(1 + (7.21 \times 10^{-6} p_c)^{1.4})^{-0.28571} + 0.333(1 + (1.02 \times 10^{-6} p_c)^{1.5})^{-0.3333} + 0.067(1 + (2.04 \times 10^{-9} p_c)^{6})^{-0.8333}\right] \tag{A-7}
\]

and for calcium silicate by:
\[
w(p_c) = w_{cap}\left[0.05(1 + (2.46 \times 10^{-6} p_c)^{1.5})^{-0.3333} + 0.1(1 + (2.00 \times 10^{-6} p_c)^{2.0})^{-0.5} + 0.85(1 + (2.47 \times 10^{-6} p_c)^{4.8})^{-0.79166}\right] \tag{A-8}
\]
Fig. A-1 shows the sorption curve and moisture retention curve for all considered materials.

**Figure A-1:** a) sorption (hygroscopic) curve and b) moisture retention curve, for ceramic brick, calcium silicate, concrete, and mineral plaster

**Liquid permeability**

Fig. A-2 shows the liquid permeability for all considered material.

**Figure A-2:** liquid permeability as a function of capillary pressure for ceramic brick, calcium silicate, concrete, and mineral plaster
Bibliography


Curriculum Vitae

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Name: Saba Saneinejad
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Education

Ph.D., Civil Engineering, ETH Zürich, Zürich, Switzerland, 2009-2013.
Research topic: The influence of evaporative cooling on the micro-climate and thermal comfort in a street canyon

M.A.Sc., Building, Civil and Environmental Engineering, Concordia University, Montreal, Canada. 2007-2009.
Research topic: Solar-driven vapor diffusion in wall assemblies in hot and humid climates

Concentrations: Building Science
Thesis: Test method to study the water shedding effectiveness of drip edge of metal flashing
Employment history

Building Science Laboratory Instructor, Jan 2008 - April 2008
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Course: Building Science

Project Administrator, Nov 2005-April 2006
Halcrow Yolles, Toronto, CA
Responsibilities include: building condition assessments, new construction quality control inspections, building investigation, contract administration for parking garage restoration projects, and contract administration of the restoration project related to building enclosure such as roof repair/replacement, masonry wall repair, window and skylight replacement, etc.

Project Administrator, May 2005-Nov 2005
Construction Control Inc., Woodbridge, CA
Responsibilities include: new construction quality control inspections, and field air and water tightness window tests

Teaching Assistant, Sep 2003 - Dec 2003
Jan 2004 - April 2004
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Ryerson University, Toronto, CA
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Journal Publications


Conference Proceedings


conditions. Proceeding of Nordic Building Physics Symposium, Copenhagen, June 2008, 1015-1022


Grants and Fellowships

Canadian Society of Civil Engineering Building Science Scholarship (for 4th year thesis, 2005), $500 (CAD)

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The influence of evaporative cooling on the micro-climate and thermal comfort in a street canyon

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