uhiSolver
Developing an effective transient Multi-Physics solver for prediction and mitigation of Urban Heat Island dynamics

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Motivation

- Temperature significantly higher in summer nights
  - in (large) cities
  - compared to the countryside
- The urban heat island (UHI), [...] is often regarded as the most well documented example of anthropogenic climate modification [1]
- People living in cities are directly affected and suffering from UHI effects
  - 2005: 50% of the population
  - 2050: 66% (estimated)

Motivation

Night time IR image from Vienna, Austria


Temperatures measured on a typical summer day in Vienna

1950: 8.9°C  
2017: 11.6°C

Yearly average temperature in Vienna

source: zamg.at
Motivation

- Generalisation and quantification of UHI effects is a difficult problem.
- Every city, every neighbourhood is a unique “prototype” with specific balances and boundary conditions.
- Small changes in local temperature, humidity and air movement can feel very different.
- Goal:
  - CFD tool based on OpenFOAM
  - Prediction of PET (Physically Equivalent Temperature)
  - Potential mitigation of UHIs via numerical, comparative experiments
Motivation

● Goal:
  ○ CFD tool based on OpenFOAM
  ○ prediction of PET (Physically Equivalent Temperature)
  ○ potential mitigation of UHIs via numerical, comparative experiments

● Additionally implemented models in OpenFOAM (v1712)
  ○ Temperature dependant relative humidity and advection of water (humidity)
  ○ Evaporative cooling effects
  ○ Evaporative mass fluxes of humidity induced by vegetation and water bodies
Theoretical description - fluid

- Conservation of mass
  - Continuity equation

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0 \]
Theoretical description - fluid

- Conservation of mass
  - Continuity equation

- Conservation of momentum
  - Navier-Stokes equations
  - Buoyancy

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0
\]

\[
\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot (2\mathbf{S}) + F_{\text{buoyant}} + F_T
\]
Theoretical description - fluid

- Conservation of mass
  - Continuity equation
- Conservation of momentum
  - Navier-Stokes equations
  - buoyancy
- Conservation of energy
  - enthalpy
  - kinetic energy
  - buoyancy
  - radiation
  - phase change

\[
\begin{align*}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) &= 0 \\
\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) &= -\nabla p + \nabla \cdot (2\mathbf{S}) + F_{\text{buoyant}} + F_T \\
\frac{\partial \rho h}{\partial t} + \nabla \cdot (\rho \mathbf{u} h) + \frac{\partial \rho \left( \frac{u^2}{2} \right)}{\partial t} + \nabla \cdot \left( \frac{u^2}{2} \right) &= -p \nabla \cdot \mathbf{u} + \nabla \cdot \left( \frac{k}{c_v} \right) \nabla h + \rho \mathbf{u} \cdot \mathbf{g} + H_{\text{turb}} + \dot{Q}_{\text{rad}} + \dot{Q}_{\text{evap}}
\end{align*}
\]
Theoretical description - solid

- Heat conduction in solid
- Heat transfer between fluid and solid
  - shared boundary

\[
\frac{\partial \rho h}{\partial t} = \Delta \alpha h
\]
Evaporation, condensation

- Definition of mass loading $X$
  - in kg water vapor per kg
- Calculation of saturation pressure
  - Antoine equation
  - $p_s = p_s(T)$
- Relative humidity with saturation pressure
  - $\text{rh} = \text{rh}(p, p_s(T), X)$
- Compressibility
  - $\psi_i = \psi_i(X, T)$

source: Acker S.: “Raumlufttechnik - Das h.x Diagramm nach Mollier”
Evaporation, condensation

- Relative humidity with saturation pressure
  - $\text{rh} = \text{rh}(p, \text{ps}(T), X)$
- $\text{rh} > 1$
  - condensation of liquid volume fraction
- $\text{rh} < 1$
  - no condensed liquid present - nothing
  - condensed liquid present - evaporation

source: Acker S.: “Raumlufttechnik - Das h,x Diagramm nach Mollier”
Validation of phase change

- „Weighing“ of water condensation and evaporation on a smooth metal surface
- Planning, designing of phase change experiment at Vienna University of Technology
- Defined conditions of (T,U,rh)
  - defined flow speeds
  - defined temperature
  - defined humidity (mass loading)
- Comparison to transient simulation
Validation of phase change
Validation of phase change
Validation of phase change
Validation of phase change
Validation of air flow

- Simulation of urban air flow patterns around free standing model buildings
- Down-scaled wind tunnel experiments of a free standing building block with Re=12500 LES (Smago) turbulence modeling [2]
- Building model height $h=0.05$ m

Validation of air flow

- Simulation of urban air flow patterns around free standing model buildings
- Up-scaled wind tunnel experiments of a free standing building block with Re=2500000 RAS (kEpsilon) turbulence modeling [2]
- Building model height h=10 m

Application - Kabelwerk

- „Kabelwerk“ Project in Vienna, Austria
- Trees, water fountain, pool, varying level of shade, etc. included in simulation.
Application - Kabelwerk

- Wind inlet velocity profile
- Temperature profile
- Loading (i.e. humidity) profile
- Sun (solar angles)
Application - Kabelwerk

- Comparison of two full simulation runs (72h real time, 72h wall clock time).
  - full evaporation modeling (A)
  - without evapotranspiration and evaporation from water bodys (B)
Application - Kabelwerk

- Simulation of
  - vegetation
  - green roofs

roof level

street level

Humidity

Temperature

Evaporation

- 55% relative humidity
- 45% relative humidity

- Concrete roof
- Green roof
- Wind direction
- Sun direction

- ≥28°C air temperature
- ≤28°C air temperature
- ≥30°C air temperature
- ≤25°C air temperature

- No evaporation
Localized evaporation cooling effects

Temperature drop depends on
- wind direction and speed
- radiation at night
- sun path and shade

"Memory effect" of building's heat latency is clearly shown by daily increasing temperature

Complex and coupled effects of flow, sun/shade, and evaporation are seen in the temperature samples

Application - Kabelwerk
Summary

- Model for simulation of Urban Heat Islands
- Energy balances (conduction, advection, radiation, humidity, evaporation)
  - implemented and tested in a realistic model
- UHI “memory effect” on night time temperatures
- Solver runs in real-time for smallish geometries (a few buildings) on affordable hardware
- Scale-up and performance improvements in EU financed POP-COE project
  - 300x300m case with detailed building geometry in real time on HPC
Outlook

- Validation of evapotranspiration models and tuning of parameters
  - Introduction of different plant types and modeling of environmental interaction
- Creating a building database
  - average values of latent heat
  - albedo of wall materials
  - for different types of buildings (old, new, low energy)
  - creating a database for soil material properties (e.g. concrete vs. soil)
- Goal: a tool usable by engineers to do comparative simulations
  - for UHI mitigation in the planning phase of large master plans
  - compare PETs for different scenarios
    - Green roofs and green walls
    - Tree positions, parks, hedges, grass
    - water surfaces
Contact

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