universität innsbruck

Modelling of convective heat and moisture transfer in porous bulk insulation for large-scale thermal energy storage

Alice Tosatto, Fabian Ochs, Michele Bianchi Janetti

Overview

- Integration of large scale Thermal Energy Storage (TES)
- TES envelope performance
  - degradation of thermal insulation
  - design
- Numerical model of TES cover
  - selection of simulation results
- Laboratory-scale tests
  - dry conditions
- Conclusions & Outlook

Large-scale seasonal Thermal Energy Storage (TES)

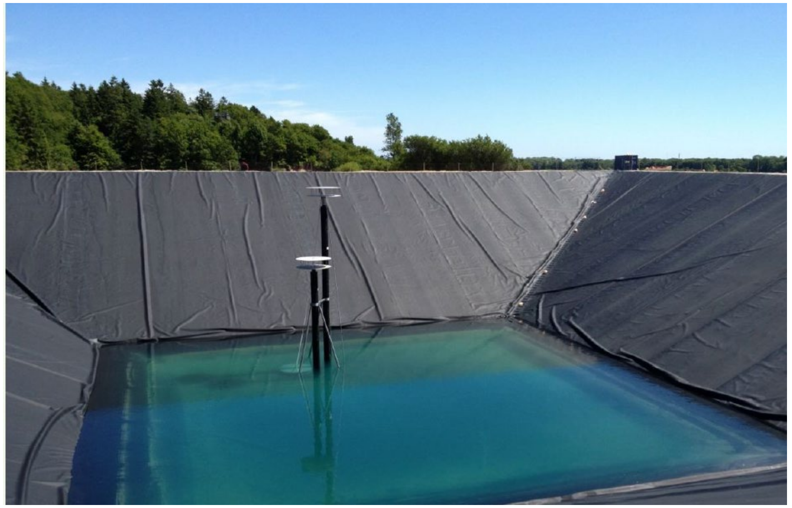
- Task
  - increase the share of renewables in the energy system
  - support the energy transition
  - enhance the sector coupling
- Applications
  - District heating networks
- Types of large-scale TES
  - Tank
  - (Danish) pit

Vojens pit TES (https://www.gigates.at/index.php/de/)

Berlin tank TES (https://group.vattenfall.com/de)

Integration of large scale TES in energy systems
Challenges

1. High construction costs
2. Liner durability
3. Envelope performance
   - Cover insulation
   - Wall insulation
4. Stratification decay


Pit TES in Dronninglund (source: PlanEnergi, 2017).


Tank TES in Munich.

Envelope performance
Degradation of TES insulation

- Convection in porous media
- Moisture penetration
  - Failure during construction (i.e. liner welding).
  - Diffusion from storage water through the liner or through leakages.
  - Moisture penetration from snow and rain.
  - Construction moisture.
  - Air bubbles in case of floating insulation cause an uneven surface in contact with the water.

Solutions to remove cover insulation moisture

- permeable upper liner
- forced ventilation through the insulation layer
- ventilation pipes

Envelope performance

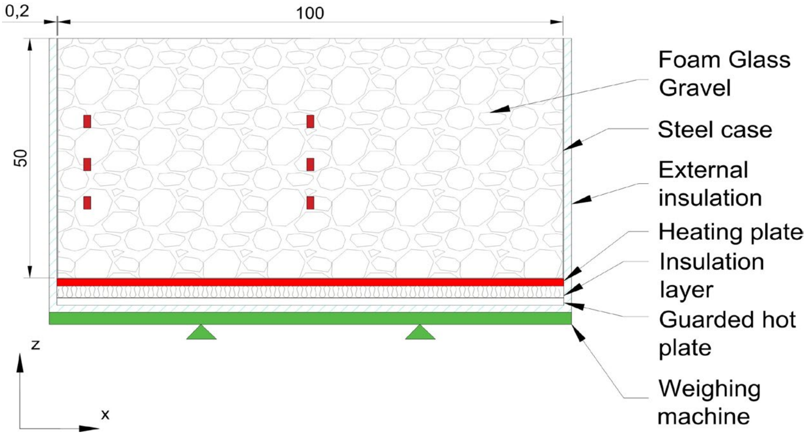
How to improve the design and thus the performance of TES envelope (i.e. insulation)?

→ design of cost-optimal and efficient envelope components

- deep knowledge of insulation materials behaviour at TES operating conditions
- support of (multi-physics) numerical tools

Experimental set-up

Porous cover



Loose uncompacted FFG

Experimental set-up: stainless steel container with lateral insulation (vacuum insulation panel).

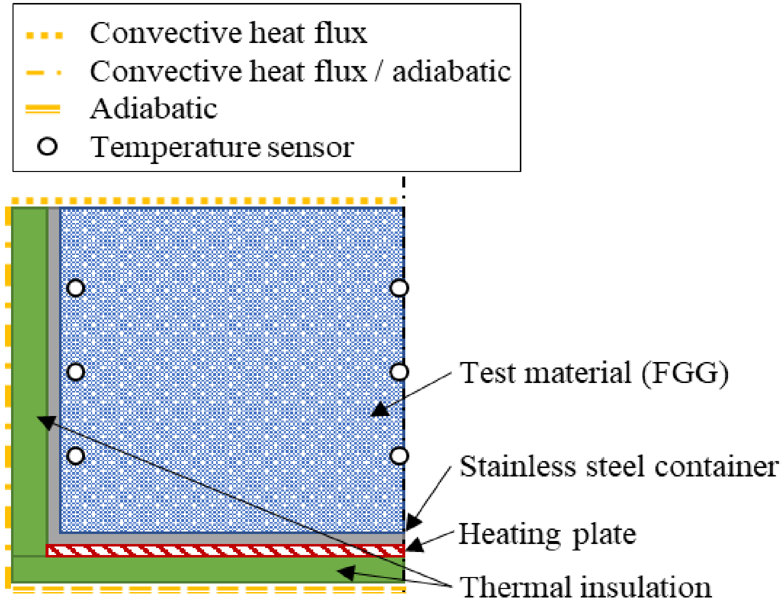
Compacted FFG (30 %)

Compaction process

universität innsbruck

Numerical model of TES cover

Equations



Heat transfer

$$(\rho C_p)_{eq} \frac{\partial T}{\partial t} = \nabla \cdot (\lambda_{eq} \nabla T) - (\rho C_p)_{eq} u \cdot \nabla T$$

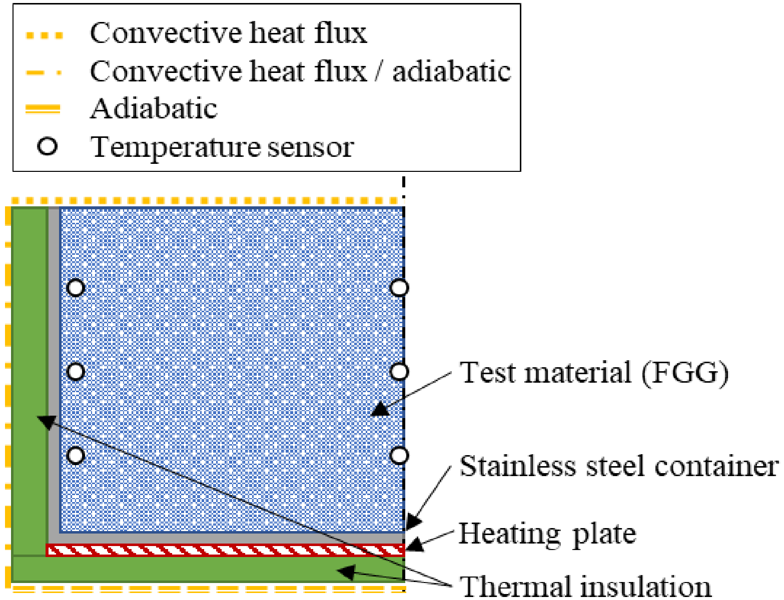
Momentum equation (Brinkman)

$$\rho \frac{du}{dt} = \nabla \cdot \left[-pI + \frac{\eta}{\psi} (\nabla u + (\nabla u)^T) + \frac{2}{3} \frac{\eta}{\psi} (\nabla u) I \right] + \rho g \beta (T - T_c) + \frac{\eta}{K} u$$

Simplification $$(\rho C_p)_{eq} \frac{\partial T}{\partial t} = \nabla \cdot (\lambda_{eq} Nu \, \nabla T)$$ where $$h = \frac{Nu \, \lambda}{\Delta x}$$

Numerical model of TES cover

Equations



Heat transfer

$$(\rho C_p)_{eq}\frac{\partial T}{\partial t} = \nabla\cdot(\lambda_{eq}\nabla T) - (\rho C_p)_{eq}\, u\cdot\nabla T + \nabla\cdot\left(L_v\left(\frac{D_{av}}{RT\mu_{diff}}\right)\nabla(\varphi\, p_{sat})\right)$$

Momentum equation (Brinkman)

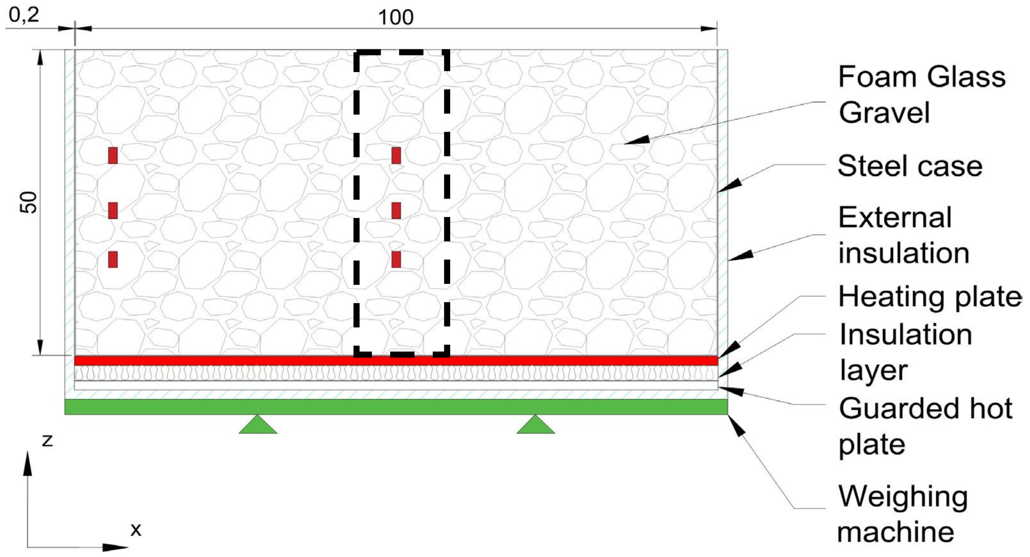
$$\rho\frac{du}{dt} = \nabla\cdot\left[-pI + \frac{\eta}{\psi}(\nabla u + (\nabla u)^T) + \frac{2}{3}\frac{\eta}{\psi}(\nabla u)I\right] + \rho g\beta(T - T_c) + \frac{\eta}{K}u$$

Moisture transfer

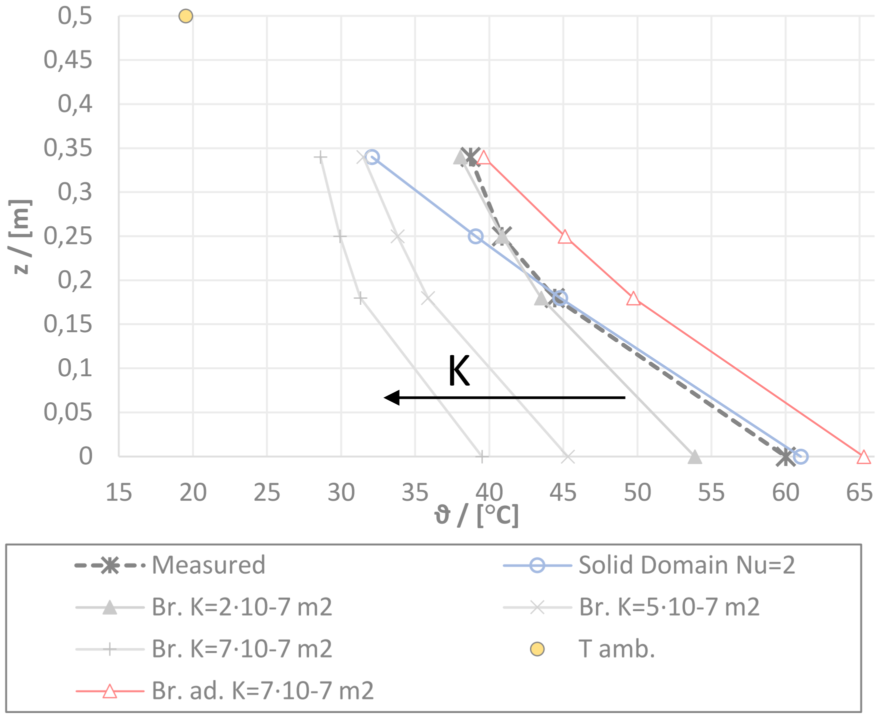
$$\frac{\partial w}{\partial t} + u\cdot\nabla w = -\nabla\cdot\left(\frac{\mathrm{D_{av}}}{\mathrm{RT}\mu_{\mathrm{diff}}}\nabla(\varphi\, p_{sat})\right)$$

Results

Central sensors



Vertical temperature profile: measured and simulated profile

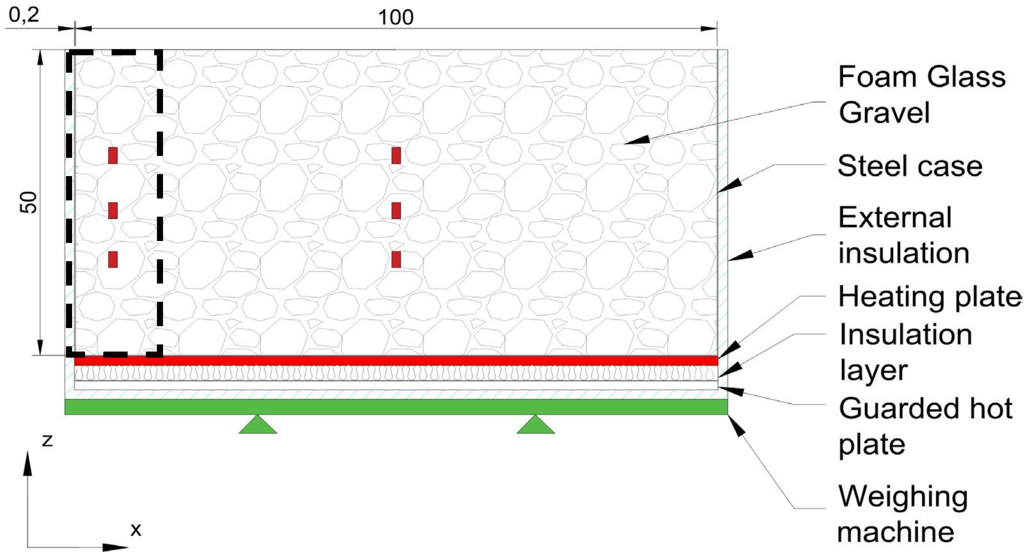


Br: with Brinkman model

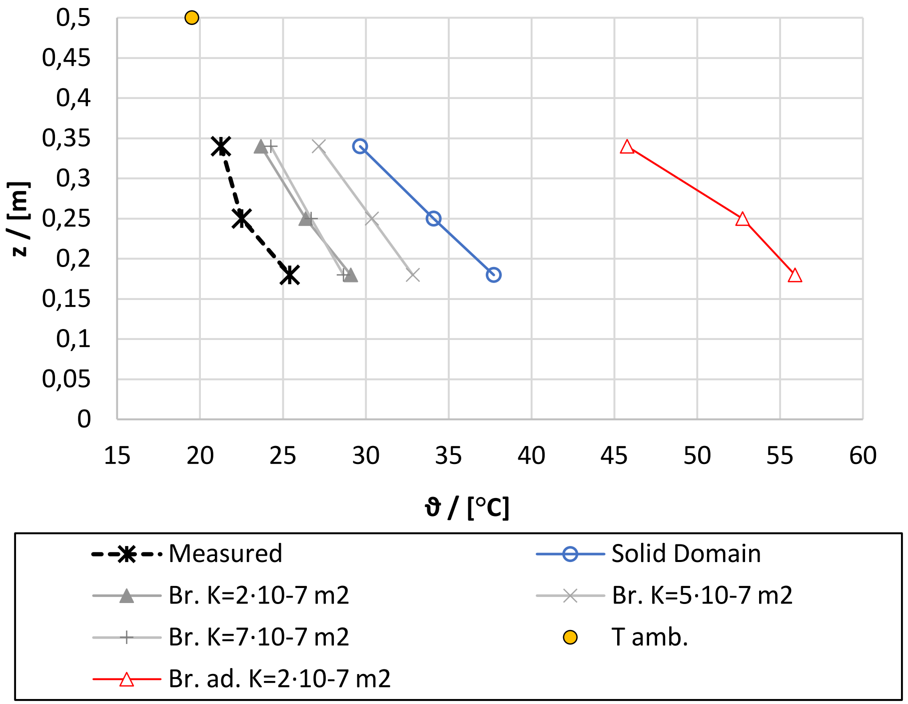
Br. ad.: Brinkman model with adiabatic boundary conditions

Results

Lateral sensors



Vertical temperature profile:
measured and simulated profile

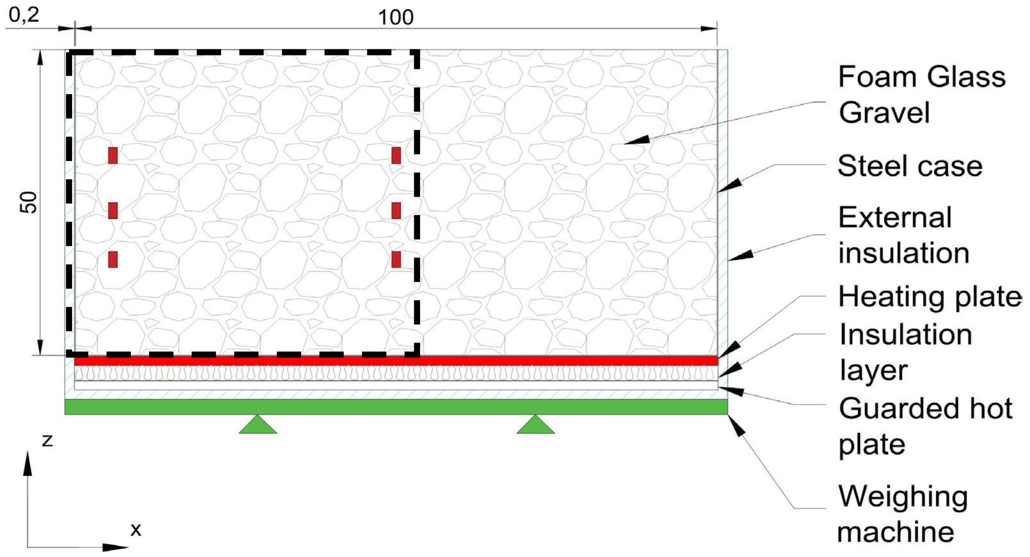


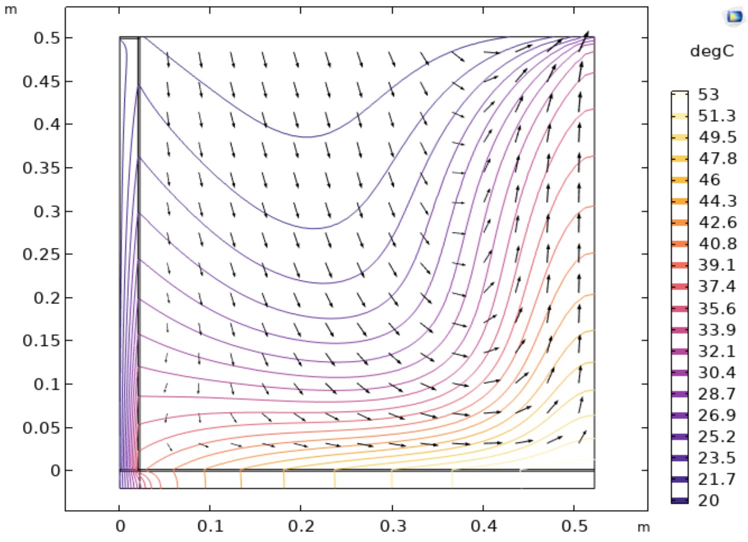
Br: with Brinkman model

Br. ad.: Brinkman model with adiabatic boundary conditions

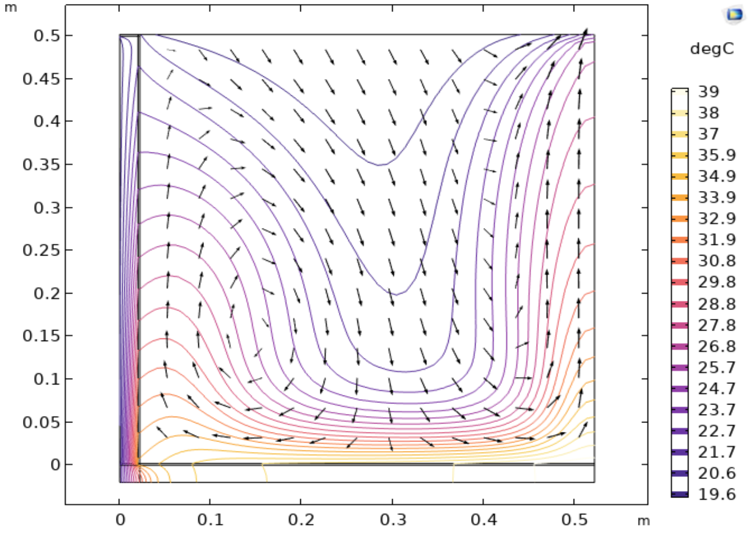
Results

Temperature contour plot and velocity field for the case with realistic boundary conditions.





$K=2\cdot10^{-7}$ m/s



$K=7\cdot10^{-7}$ m/s

Results

Influence of moisture

In presence of porosity, however, both heat and moisture transport are enhanced by the air and moisture fluxes driven by the density gradients.

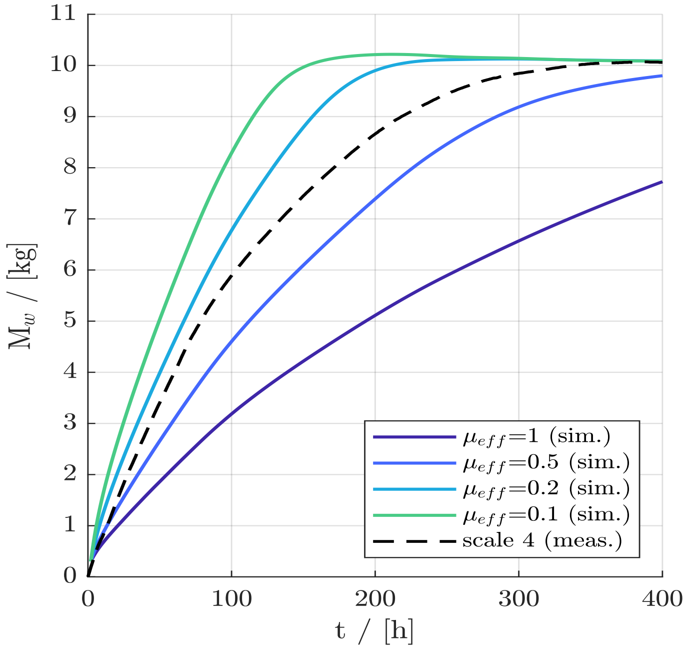
$$(\rho c_p)_{eq} \frac{\partial T}{\partial t} = \nabla \cdot (\lambda Nu\, \nabla T) + \nabla \cdot \left(L_v \left(\frac{D_{av}}{RT\mu_{eff}} \right) \nabla(\varphi p_{sat}) \right)$$

$$\frac{\partial w}{\partial t} = -\nabla \cdot \left(-\frac{D_{av}}{RT\mu_{eff}} \nabla(\varphi\, p_{sat}) \right)$$

$\lambda\, Nu$: effective thermal conductivity / [W/(mK)]

μ_{eff}: effective water vapor resistance factor

Comparison between simulated (continuous lines) and measured (black dashed line) drying curves



A. Tosatto, F. Ochs, A. Dahash, C. Muser, F. Kutscha-Lissberg, and P. Kremnitzer, “Influence of Heat and Mass Transfer on the Performance of Large-Scale Thermal Energy Storage Systems,” in *Proceedings of the International Renewable Energy Storage Conference (IRES 2022)*, 2023, pp. 470–488, doi: 10.2991/978-94-6463-156-2_30

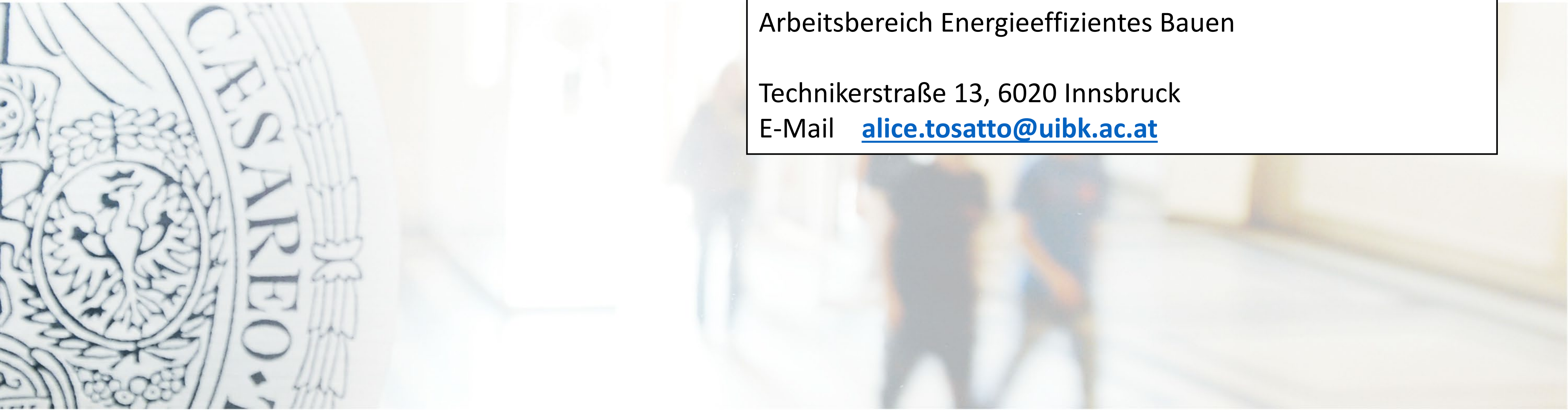
Conclusions

- In the presence of high temperature differences and bulk thicknesses, natural convection is not a negligible factor.
- An in-depth knowledge of the behavior of the insulation materials is essential for the efficient design of thermal insulation solutions.
- The combination of component-based experimental testing and numerical modelling provides important insights for the design of efficient TES envelope solutions.

Alice Tosatto, MSc

Universität Innsbruck
Institut für Konstruktion und Materialwissenschaften
Arbeitsbereich Energieeffizientes Bauen

Technikerstraße 13, 6020 Innsbruck
E-Mail alice.tosatto@uibk.ac.at



www.uibk.ac.at