Modeling Buried Hot Water Thermal Energy Stores

F. Ochs[1], *W. Heidemann*[2], *H. Müller-Steinhagen*[2,3]
[1)] *Universität Innsbruck, Institut für Konstruktion und Materialwissenschaften, Arbeitsbereich Bauphysik*
Technikerstr. 13, 6020 Innsbruck
Tel. +43 512 507 6616, Fax: +43 512 507 2901
Email: Fabian.Ochs@uibk.ac.at
[2)] *Universität Stuttgart, Institut für Thermodynamik und Wärmetechnik (ITW)*
Pfaffenwaldring 6, D-70550 Stuttgart
[3)] *DLR, Institut für Technische Thermodynamik*
Stuttgart

SYNOPSIS

Thermal losses of buried medium and large-scale TES depend on the construction type and the boundary conditions. It is found that available coarse-structure TES models simplify the real processes such that a detailed analysis with the objective to enhance TES design is not possible. Accurate TES modelling for transient energy simulations requires detailed description of heat and moisture transfer processes in the envelope and in the surrounding soil. In this paper, exemplarily, essential features of the new hygrothermal model are demonstrated.

ABSTRACT

Aspects of modelling buried hot water thermal energy stores (TES) are discussed in this paper. Thermal losses of buried medium and large-scale TES depend on the construction type and the boundary conditions. It is found that available coarse-structure TES models simplify the real processes such that a detailed analysis with the objective to enhance TES design is not possible [2], [3].

Optimization of TES design and construction requires detailed insight in the processes related to heat and moisture transfer in the envelope of TES. Knowledge about relevant material properties, i.e. thermal conductivity and permeation resistance and material functions, eg.. sorption isotherm, are required in order to explain the processes in the envelope of TES.

An analytical model for the thermal conductivity depending on temperature and moisture content presented in [1] yields good results. However, it represents a simplification of the real processes in the envelope of a TES. Hence, a model was established that accounts for coupled heat and moisture transport at elevated temperatures. In this paper, exemplarily, calculations are performed to demonstrate essential features of the model.

Introduction and Motivation

Actual thermal losses of tank and pit TES are too high in most cases. In some cases measured losses are 30 % to 50 % higher and in one case even more than four times higher than the predictions on which the original design had been based. There are several reasons for the high thermal losses compared to the design:

- high mean storage temperature due to changed building development and/or system configuration;
- high return temperatures of the heating net resulting in higher thermal losses to the ground especially at the bottom of the TES, which is not insulated in most cases;
- the thermal conductivity of the insulation was assumed too low. The thermal conductivity of porous material increases with increasing moisture content and with increasing temperature. The assumption of constant effective thermal conductivity of the insulation material according to DIN 4108 leads to wrong predictions;
- Insufficient quality/accuracy of available simulation tools;

While the first three reasons for the high thermal losses depend on the system and thus can only hardly be calculated in advance during the design phase, the increase of the thermal losses due to high temperatures and high moisture contents can be modelled - at least theoretically.

To assess heat and moisture transfer processes in the envelope of a TES a both thermodynamics and building physics have to be considered. Degradation of the insulation within the required operation time of at least 20 to 40 years can only be prevented with a high quality construction with well-matched materials. The insulation has to be protected from moisture penetration from the storage medium inside by diffusion and from the surrounding soil, outside, i.e. from ground or surface water, see Fig. 1.

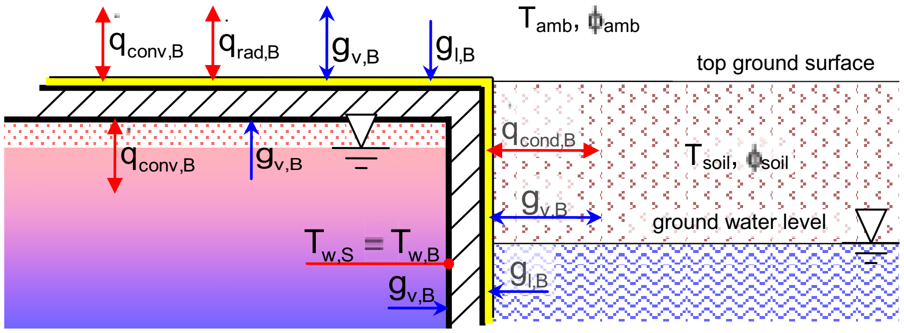

Fig. 1: Boundary conditions for a covered and for an exposed wall of a buried seasonal thermal energy store, convective (conv) conductive (cond) or radiative (rad) heat transfer (q), mass transfer consisting of vapour (g_v) or liquid water (g_l) transfer via boundary (B)

Desiccation should be enabled in case the thermal insulation is already wet e.g. due to rain during construction or if delivered in moistened condition.

With the following example it can be impressively demonstrated that models for coupled heat and moisture transport are required for realistic description of the thermal losses of TES. The assumption that moisture in the insulation is considered to cause at least a major share of the high thermal losses of realised pilot and research TES could be proved by analysis of specimens of the insulation of the tank TES in Hamburg that were taken in 2007. Specimens were taken at three positions in the envelope by core hole drilling. Thus specimens could be taken across the height of the cylinder. As shown in Fig. 1. Relatively high moisture contents of up to 20 Vol.% have been determined.

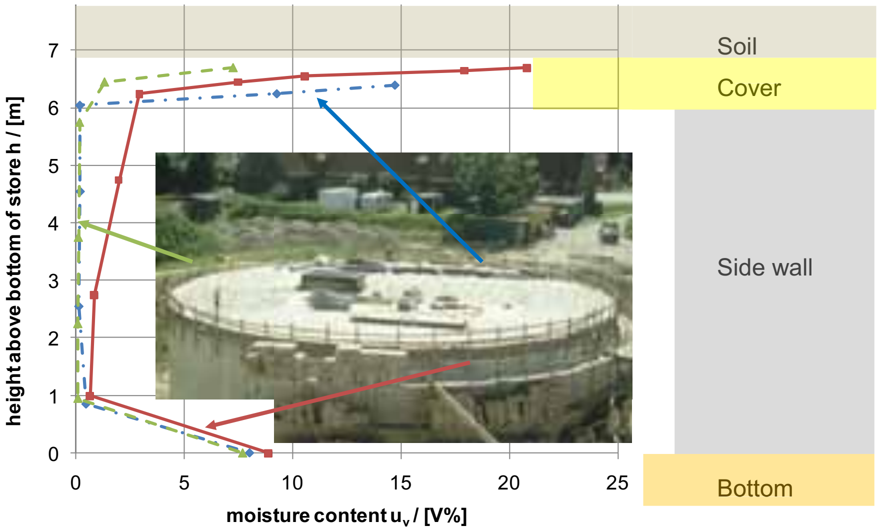

Fig. 1: Volume related moisture content (u_V) vs. height above bottom of TES determined at three different locations in the envelope of the tank TES in Hamburg;

These moisture profiles may be explained by the position of the sampling points. In order to avoid an injury of the HDPE membrane a sampling point next to the concrete cylinder had to be chosen, as is illustrated in Fig. 2. However, increased moisture content towards the soil may be expected due to the temperature gradient from the TES to the soil. Accordingly, at the cover, the highest moisture contents may be expected at the very top. This corresponds to the observations. In the course of the year changing moisture distribution due to changing temperature gradients may be expected.

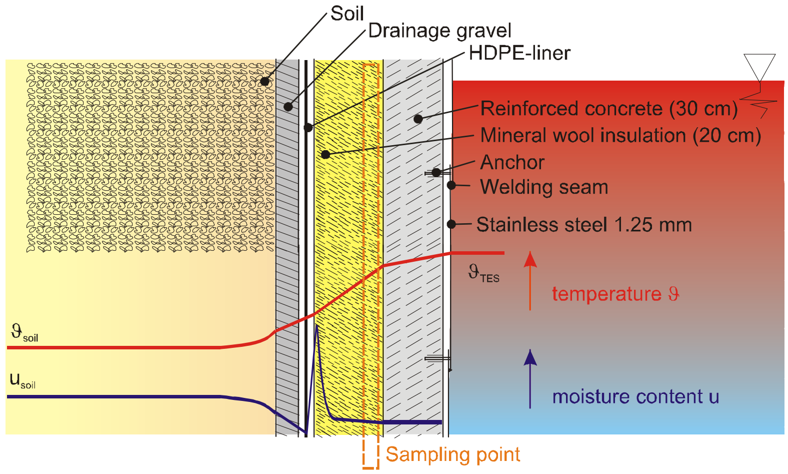

Fig 2.: Schematic diagram of moisture distribution due to temperature gradient in the insulation of the envelope (side wall)

The reason for the high moisture contents at the very bottom of the side wall could not be explained completely. Possible reasons are capillary soil moisture (ground water) or moisture transport and condensation at the bottom of the side wall due to the temperature gradient in the store and accordingly in the envelope.

Modeling Seasonal Thermal Energy Stores

Design of solar assisted district heating systems with seasonal TES requires (multi-) annual system simulations. The simulation environment TRNSYS was nearly exclusively applied for calculation of energy systems with seasonal TES. Several models are available for the calculation of TES in TRNSYS. A very flexible model is the multiport-store-model (MST, type 340). Like most TES models in TRNSYS, the multiport-store-model can be only applied for free-standing cylindrical TES. For modelling of buried TES only two so-called non-standard types are available in TRNSYS: The XST-model (type 342) and the ICEPIT-model (type 343). However, with available TES models coupled heat and moisture processes cannot be considered.

Basically, models can be distinguished into detailed models (CFD) and coarse models. Detailed or CFD models enable the exact representation of the real geometry in a discretized fashion (FDM, FEM, FVM). All transport phenomena occurring in reality can be considered. CFD models require the solution of partial differential equations (PDE) for the physical values such as temperature, pressure and velocity. It is possible to integrate CFD models, which predict the thermo-hydraulic behaviour in a detailed way, into system simulation tools. However, the computational effort is enormous. (Multi-) annual system simulations with CFD models are not feasible with today's computing facilities. A further disadvantage of CFD models is that every change of the geometry requires a time-consuming mesh generation.

Coarse models apply simplifying assumptions with respect to geometry, material properties and boundary conditions. Depending on the problem, the computational effort can be significantly reduced. However, there is only little degree of freedom with respect to geometry and discretization. Generally, in coarse structure models the flow in the TES is considered one-dimensionally (plug flow).

The decision for detailed or coarse models depends on the objective of the investigation. In system simulations it may be sufficient that the energy balance is fulfilled in the majority of cases. Predicting temperature distribution in the TES or the surrounding soil in a realistic fashion may consequently not be required for this purpose. Contrariwise, optimization of the envelope design requires detailed knowledge of temperature (and moisture) fields.

In [3] an analytical model for the thermal conductivity as a function of temperature and moisture content was developed which yields good results. However, it represents a simplification of the real processes in the envelope of a TES. Hence, a model was established that accounts for coupled heat and moisture transport at elevated temperatures.

Hygrothermal Simulation

Despite the availability of several simulation tools the method developed by Glaser is still applied as a standard procedure to calculate and predict the hygrothermal behaviour of building materials and to evaluate the moisture performance of building envelopes. Numerical codes for the calculation of coupled heat and moisture transfer were developed since 1960. At least since the 1980s and 90s performance of computers is sufficient to conduct simulations. Different tools are commercially available such as CHAMPS/DELPHIN and WUFi, which are based on models described in recent standards (EN 15026**)**.

The state of the art of hygrothermal models and simulation tools was analysed and evaluated by a comprehensive literature review. It was found that the specific issue of the influence of higher temperature on the heat losses from the TES via the ground was left completely unattended in the literature, although a strong coupling between heat and moisture transport, both in the soil domain and at the envelope of the TES is expected.

Hence, all approaches are limited to applications in the „normal" temperature range from about -20 °C to 40 °C. For the simulation of the coupled heat and moisture transport at higher temperatures (up to 95 °C) the transport equations have to be modified (e.g. mass flow factor, see [3]) and the material properties and transport coefficients have to be modelled as a function of temperature and moisture content.

The aim of this work was not to develop just another model. The objective is rather to highlight necessary modifications and to improve existing models with respect to high temperature applications as required for calculation of thermal losses of buried TES.

Based on existing approaches physical model equations were developed numerically transformed and implemented in a computer program. The partial differential equations for the moisture balance

$$\frac{\partial u}{\partial t} = \frac{\partial}{\partial x}(g_v + g_l) \quad (1)$$

and for the energy balance

$$\frac{\partial H}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial \vartheta}{\partial x}\right) - \frac{\partial}{\partial x}(h_v \cdot g_v + h_l \cdot g_l) \quad (2)$$

are coupled as on the one hand the water and water vapour fluxes g_v and g_l appear in both equations and on the other hand, the material properties may be a function of temperature and moisture content. In particular the thermal conductivity (λ) is a function of temperature (ϑ) and moisture (u). In equations (1) and (2) t is the time, x the spatial coordinate and h_l and h_v are the enthalpies of water and water vapour.

The coupled partial differential equations have to be solved numerically. After several transformations and rearrangements the transient moisture and temperature fields can be calculated. The enthalpy and the moisture content depend on the temperature and on the suction or capillary pressure. The model was implemented and solved using own Matlab code, see [3].

Example

In the following using a typical example for a buried tank TES the features of the hygrothermal model are presented. For a construction similar to Fig. 2, desiccation of construction moisture is simulated. For the simulation the envelope of the TES is reduced to two layers: only the concrete (30 cm) and the insulation (20 cm) will be considered. The soil temperature on the right hand side is assumed to be constant at 30 °C. A periodic storage temperature between 10 °C and 80 °C is assumed on the left hand side. Initially the moisture content of the concrete is 150 kg/m³, which is rather realistic construction moisture content for standard concrete, while the mineral wool insulation is with 5 kg/m³ nearly dry.

Due to the temperature and consequently partial pressure gradient a diffusion flux establishes. Construction moisture in the concrete tank will diffuse into the insulation and condenses at the cold side of the envelope (at the outer HDPE liner). If the thermal energy store is discharged to temperatures below ambient or soil temperature the direction of the diffusion turns and water vapour is transported back in the direction of the concrete. However, due to the relatively high water vapour diffusion resistance of concrete it condensates at the mineral wool concrete interface, see Fig. 3. In this case, water vapour is remaining in the insulation and transported back and forth, back and forth and thus significantly enhancing the thermal transport or thermal losses.

After 1 year the moisture content of the concrete decreased to about 60 kg/m^3 and at the right hand side of the insulation a steep moisture front can be recognised. The total moisture content of the envelope remains nearly constant.

Now, what can we learn with this example. On the one hand thermal losses can be better explained with the suggested model. On the other hand and even more important with the suggested model, TES can be designed with enhanced envelopes that enable the desiccation in such cases!

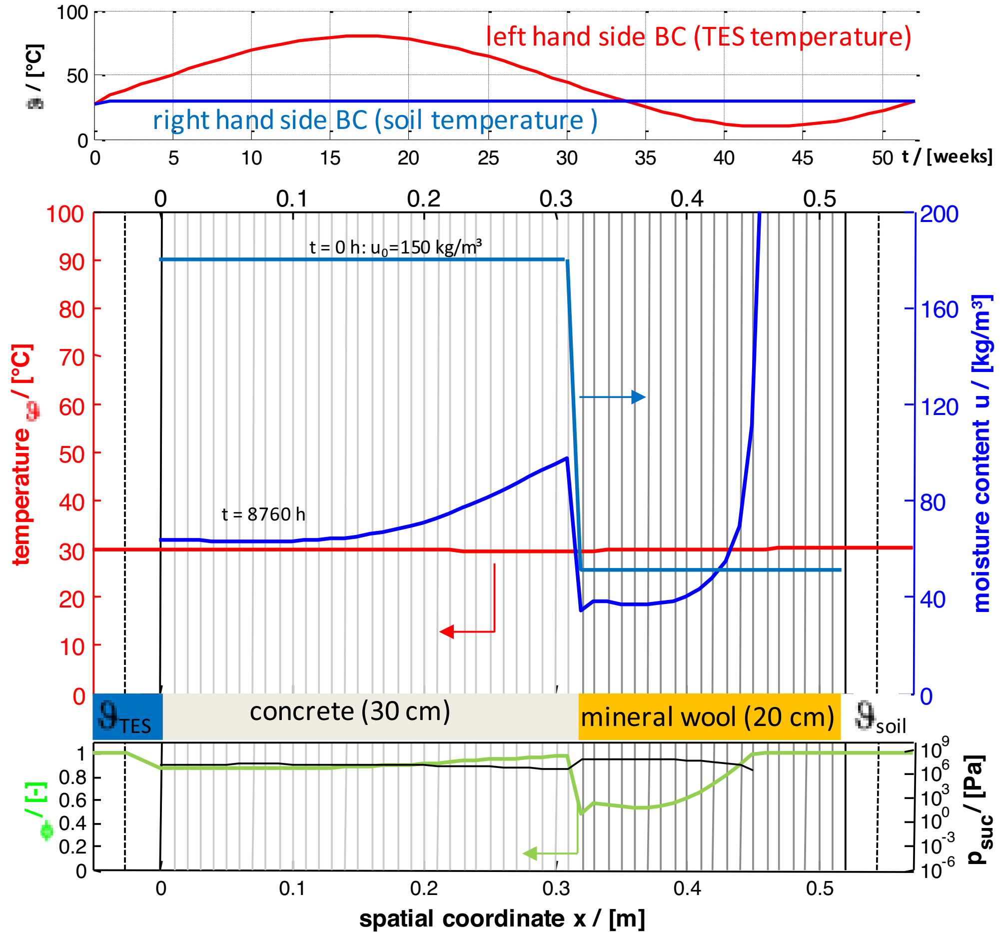

Fig. 3: Profile of temperature (ϑ), moisture content (u) as well as relative humidity (Φ)and corresponding suction pressure (p_{suc}) after 8760 h for a periodic TES temperature

Summary and Conclusions

Available coarse-structure TES models simplify the real processes such that a detailed analysis with the objective to enhance TES design is not possible. The developed model allows predicting the coupled heat and moisture transport in the envelope of buried TES. Thus, thermal losses of seasonal TES can be predicted more accurately. However, due to the relative high computational effort of the numerical solution of the problem, the application of such a model is not recommended for multi-anual system simulation. Depending on the objective of the investigation different approaches (detailed and coarse structure models) are required.

Literature

[1] Ochs F., Heidemann W., Müller-Steinhagen H., Effective Thermal Conductivity of Moistened Insulation Materials as a Function of Temperature, International Journal of Heat and Mass Transfer, 2007.

[2] Ochs F., Heidemann W., Müller-Steinhagen H., Berechnung der Wärmeverluste erdvergrabener Wärmespeicher, OTTI, 17. Symposium Thermische Solarenergie, Kloster Banz, 2007.

[3] Ochs, F. Modeling Large-Scale Thermal Energy Stores, Diss. Universiät Stuttgart 2009, Shaker Verlag, Aachen, Reihe: Energietechnik, 978-3-8322-8834-1, 2010.