

EFFECTIVE THERMAL CONDUCTIVITY OF THE INSULATION OF HIGH TEMPERATURE UNDERGROUND THERMAL STORES DURING OPERATION

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1. INTRODUCTION

At the Institute of Thermodynamics and Thermal Engineering (ITW), University of Stuttgart, experiments on different concepts of pit heat stores are carried out in the framework of the research project „Further Development of the pit heat store technology“, which is funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. The main objective is the development of energy efficient and economic hot water pit heat store for temperatures up to 95 °C for solar assisted district heating systems (cf. Ochs 2005 and Ochs 2005a).

Suitable materials for thermal insulation, liner, geotextiles and vapour barrier, are selected together with the manufacturers. Indoor experiments are carried out to rate the selected materials, i.e. thermal conductivity of insulation materials and vapour diffusion resistance of liners. The processability and practical feasibility (robustness, weldability or sensitivity to moisture) are studied in outdoor laboratory experiments. For this purpose two research pit heat stores have been built at ITW (see figure 1). The storage and ground temperature as well as the heat flow through different wall designs or wall assemblies is monitored continuously. The determination of the thermal conductivity of the thermal insulation of the bottom, of the walls and of the cover during operation is in the focus of this work. Based on the measured results recommendations for optimised wall constructions shall be derived for buried thermal energy stores - pit heat stores as well as buried tank stores.



Figure 1: Outdoor laboratory: research store at ITW; top laboratory 1: hot-water pit heat store with floating cover, laboratory 2: gravel-water-store; bottom laboratory 1 after deconstruction

2. THERMAL INSULATION OF THERMAL UNDERGROUND STORES

Thermal losses of most of the pilot projects of solar assisted district heating systems with buried seasonal heat store are higher than the design values. One reason for the thermal losses can be explained by changes in the temperature levels (mean storage temperature) compared to the design stage due to modified system configurations or modifications concerning the heat loads. Secondly poor stratification causes higher internal losses. Higher thermal losses to the ground resulting from increased temperature at the bottom region of the store are a further consequence. The bottom of seasonal heat stores is not insulated in most of the pilot projects.

Insufficient knowledge about the material properties (thermal conductivity of insulation and of surrounding ground, water vapour resistance index of liner) and about the boundary conditions (ground water level and flow) frequently contributes to an underestimation of the thermal losses. Additionally the quality of the wall design with respect to resistance against moisture penetration is often inadequate. Table 1 shows a comparison of calculated values and measured values for thermal losses of some pilot projects during operation.

Table 1: Thermal losses of thermal underground hot water tank and pit heat stores – comparison of design and measured data of selected projects

		Volume in m	Measurement in MWh/a	$Q_{\text{measured}}/Q_{\text{design}}$
tank heat stores				
Friedrichshafen	Benner 2004	12 000	320 – 360	1.46-1.64
Hamburg	Benner 2004	4 500	360 – 430	3.79-4.53
Hannover	Benner 2004	2 750	90 – 100	1.29-1.43
pit heat stores				
Stuttgart	Giebe 1989	1 000	27	n/a
Chemnitz ¹⁾	Urbanek 2003	8 000	n/a	1.44
Steinfurt ²⁾	Benner 2004	1 500	70 – 90	n/a

1) extrapolation of 8 week data

2) incl. connecting pipes

The comparison indicates that there is need for optimisation concerning the design especially with respect to the wall assembly of buried thermal stores. On the one hand a wall design is required that assures the protection of the thermal insulation from moisture penetration from the inside by diffusion and from the soil by convection and diffusion. On the other hand the wall construction has to enable desiccation when the thermal insulation is already wet. Additionally a fast and consequently economic construction process must be guaranteed by the selected wall design and the construction materials.

Due to contamination and due to influences resulting from increased temperature and moisture content, the measured in-situ thermal resistance of the insulation decreases in comparison to the values determined in the indoor laboratory. Protection from rain and surface water is of importance when choosing a suitable construction or installation method. Furthermore the insulation has to remain dry and undamaged during installation. Especially in the case of large heat stores the installation of the thermal insulation takes several days. Therefore the thermal insulation has to be installed in a fast and cost effective way.



Figure 2: Construction methods for the installation of bulk thermal insulation in lost formwork. From left to right: installation of the insulation by blowing from a silo-truck (air injection), mounting prefabricated formwork elements, geotextile during filling and (jute-) membrane formwork (compare Ochs 2005a)

Pressure resistant bulk materials, suitable for installation by air injection, are advantageous. The installation of bulk insulation by pouring or blowing from a silo-truck is in comparison

more time and cost effective to the installation of sheet material particularly in the case of large seasonal heat stores with long slopes. Due to the fast installation process the risk of water penetration can be minimised. Table 2 shows a collection of important properties of bulk materials that may be used as thermal insulation.

Table 2: Thermo-physical properties of bulk thermal insulation (see Ochs 2004)

Property		Unit	EGG type I	EGG type II	EGG type II	FGG ³⁾ type I	ECG type I	ECG type II
grain size	d	mm	2-4	2-4	4-8	0-90	4-8	1-4
density	ρ	kg/m ³	200	190	185	150	270	300
porosity	Ψ	m ³ /m ³	0.92	0.93	0.93	0.94	0.90	0.89
TC10 ¹⁾	λ	W/(m K)	0.070	0.080	0.080	0.06	0.100	0.08
TC10 _{mess} ²⁾	λ	W/(m K)	0.065	0.060	0.060	0.065	0.090	0.075
TC80 _{mess} ²⁾	λ	W/(m K)	0.080	0.075	0.080	0.090	0.105	0.095
free saturation	u_{fs}	kg/m ³ ⁴⁾	550	510	500	460	300	235

- EGG: expanded glass granules
 - ECG: expanded clay granules
 - FGG: foam glass gravel
 - TC: thermal conductivity
- 1) Manufacturer specification
 - 2) Own measurement at 10 °C and 80 °C, guarded heating plate, according to DIN 52612 or ASTM C 177, respectively
 - 3) Measured thermal conductivity for uncompacted 0-20 mm FGG, λ_{0-90} = 0.08 W/(m K) for 0-90 mm
 - 4) Drain weight according to DIN EN 13755

3. MEASUREMENT AND MODELLING OF THE EFFECTIVE THERMAL CONDUCTIVITY

Using measured data obtained with a guarded heating plate device according to DIN 52612 or ASTM C 177, respectively, a model for the description of thermal conductivity as a function of temperature and moisture content is developed. The influence of moisture on the thermal conductivity mainly depends on the pore size and pore distribution or pore structure of the material (see Ochs 2004). In figure 3 measured data of the effective thermal conductivity of expanded glass granules and expanded clay granules are compared with calculated values. For the calculation an extended layer model based on a model proposed by Krischer and Kast (Krischer 1992) is applied.

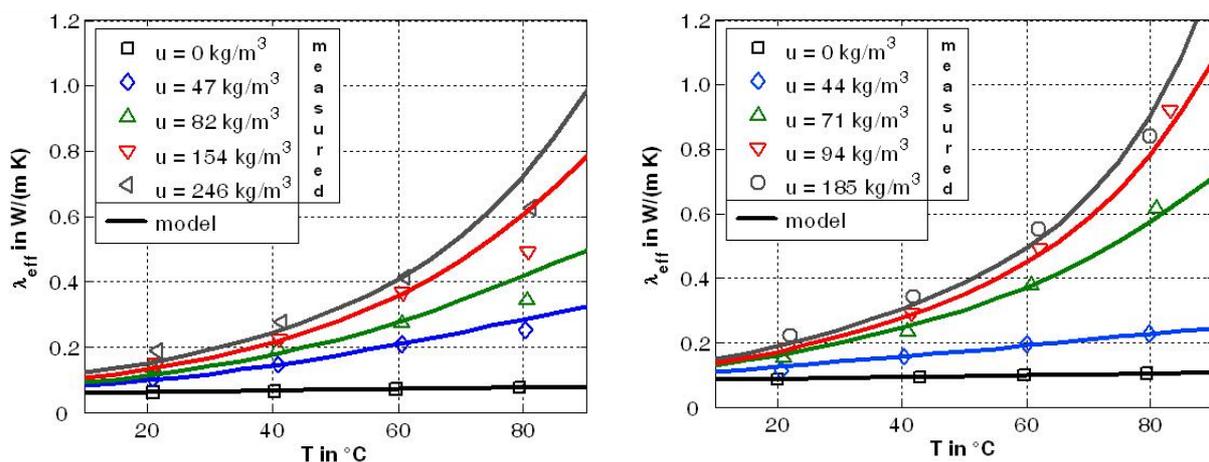


Figure 3: Measured data and model predictions of the effective thermal conductivity as a function of temperature (T) and moisture content (u) of expanded glass granules left and expanded clay granules right diagram (both 4-8 mm grain size), model predictions are calculated according to a modified layer model based on the model proposed by Krischer and Kast (compare Krischer 1992)

Above moisture contents of about 50 kg/m³ (corresponding to about 5 vol.%), an exponential increase of the thermal conductivity can be recognised. For expanded glass granules, the effective thermal conductivity exceeds the rated value of 0.08 W/(m K) according to DIN 4108 by a factor of five at a temperature of 60 °C and a moisture content of about 200 kg/m³ (20 vol.%) and at 80 °C even by a factor of 10. A similar behaviour can be recognised in the case of expanded clay.

4. THERMAL CONDUCTIVITY OF THE INSULATION DURING OPERATION

The two research stores and the outdoor laboratory heating central are equipped with an extensive measurement system consisting of temperature sensors, heat flux sensors, flow sensors and level sensors. By continuous monitoring of the storage and the insulation temperatures as well as the surrounding ground temperatures and by the measurement of the heat flux the thermal losses can be determined during operation. Based on these measured data, the effective thermal conductivity of the insulation layer can be calculated.

For a period of six months with alternating heating and cooling cycles the influence of moisture penetration can be demonstrated (see figure 4). The effective thermal conductivity increases slightly with increasing storage (average) temperature analogue to the indoor measured results.

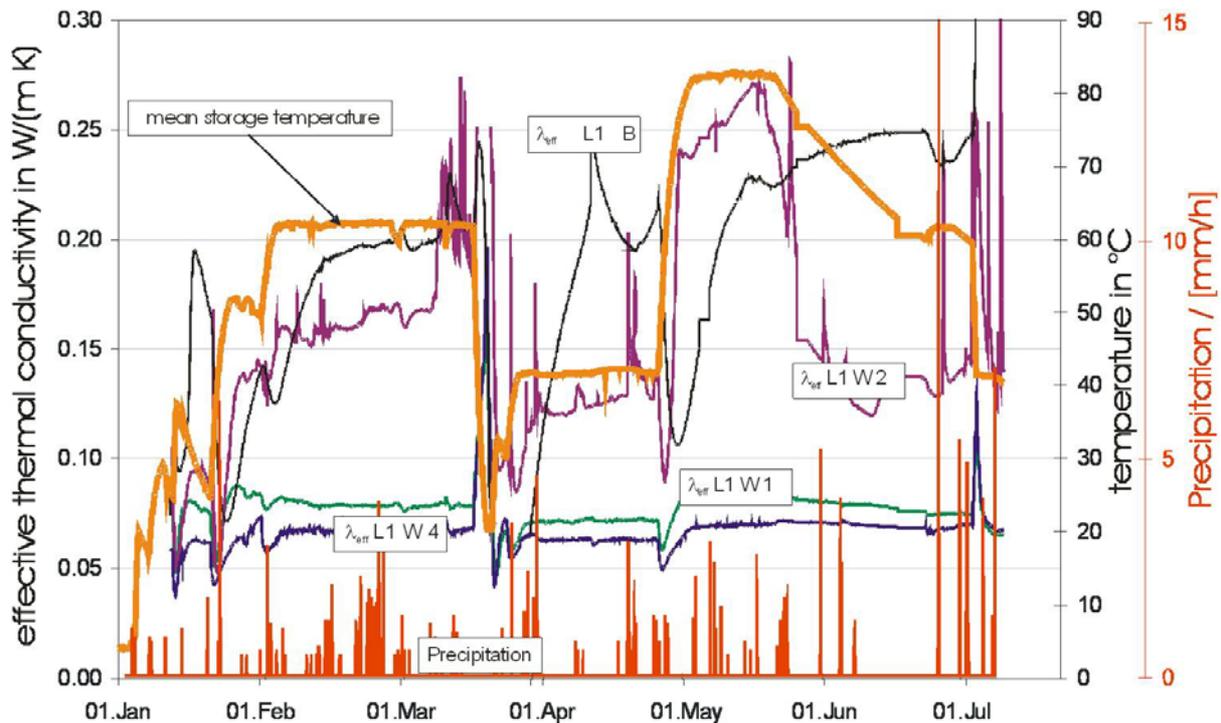


Figure 4: Effective thermal conductivity of the bottom insulation (expanded glass granules, 2-4 mm) as well as of three of the four wall insulations (west: L1 W1, north: L2 W2 and south: L1 W4) during operation; influence of rain on the thermal insulation

Obviously, the effective thermal conductivity of the bottom insulation (L1 B) and of the north wall (L1 W2) immediately increases with almost every precipitation peak, whereas the thermal insulation of the west (L1 W1) and south (L1 W4) wall remain unaffected. This effect is more pronounced with increasing average storage temperature.

The west and the south wall have a slope of 80° and are steeper than the north wall, which has a slope of 60°. The steeper walls are protected against slide off using soil nails and a shotcrete layer. The shotcrete layer prevents surface water penetrating into the insulation. In

the slope area (L1 W2) the thermal insulation desiccates after a short period of time – the effective thermal conductivity nearly goes back to the original value. Contrariwise the thermal conductivity of the bottom insulation (L1 B) remains at the high level indicating that a considerable amount of moisture remains in the insulation due to insufficient drainage. In figure 5 the values of the effective thermal conductivity obtained by the outdoor experiments (fig. 4) are plotted over the mean insulation temperature. The measured data show significant fluctuations due to transient effects and due to changes in the moisture content of the insulation. However, some trends can be identified.

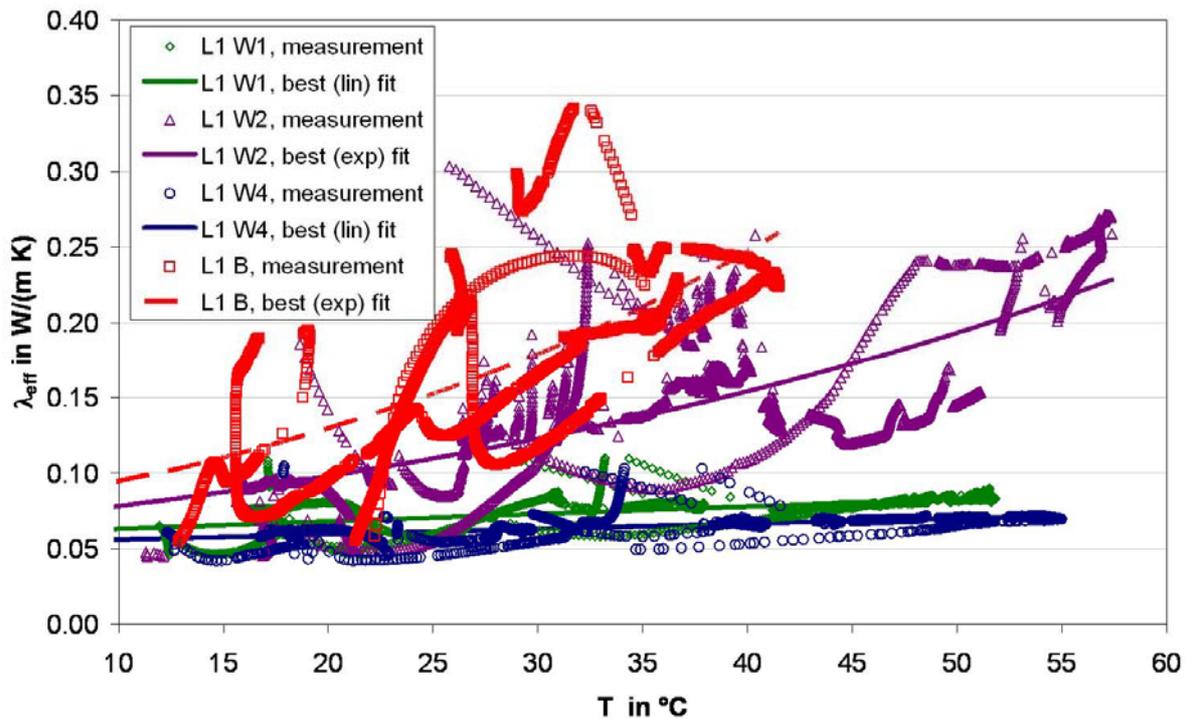


Figure 5: Effective thermal conductivity of bottom insulation (L1 B) and the wall insulation during operation as a function of the mean insulation temperature (values according to figure 4)

The conclusions that have been drawn from the analysis of the measured data could be confirmed after the deconstruction of the research store (see figure 6).



Figure 6: Moisture penetration of the north slope (L1 W4) and the bottom insulation (L1 B) after the deconstruction of the research store

The comparison of the calculated values of the thermal conductivity of the insulation of the research store with values measured by indoor experiments allows predictions about the water content of the insulation and the functionality of the liner and the wall assembly.

In table 3 measured values from the research store are compared with model predictions. The model data has been calculated applying an extended layer model based on a model suggested by Krischer (Krischer 1992). The water content of the insulation measured after the deconstruction was used as an input for the calculation.

Table 3: Comparison of model data (indoor experiments) and measured data (research store, values of the best fit from figure 5)

Location ¹⁾	material	meas. moisture content kg/m ³	measurement (research store)			model (based on indoor measurements)		
			W/(m K)			W/(m K)		
			20 °C	35 °C	50 °C	20 °C	35 °C	50 °C
west wall (W1)	EGG 2-4	0	0.07	0.08	0.08	0.06	0.07	0.07
south wall (W4)	EGG 2-4	0	0.06	0.07	0.07	0.06	0.07	0.07
north wall (W2)	EGG 2-4	145	0.12	0.15	0.21	0.13	0.19	0.26
bottom (B)	EGG 2-4	383	0.10	0.22	²⁾	0.19	0.26	0.36

1) East wall has not been equipped with sensors, cover sensors failed

2) max. average temperature $T_m = (T_{store,av} + T_{ground})/2$ at bottom: 40 °C

The comparison of the thermal conductivity of the insulation of the research store measured using heat flux and temperature sensors during operation, with the model data obtained by indoor measurements shows that

- a small moisture content in the insulation (<10 vol%) results in a significant increase of the effective thermal conductivity
- calculated values of the thermal conductivity give good agreement with the measured values thus the 'extended layer model' is suitable for the calculation of the thermal conductivity of bulk insulation materials
- the determination of the effective thermal conductivity of the insulation of buried thermal stores with heat flux and temperature sensors is suitable to assess and predict the condition of the insulation.

5. CONCLUSIONS

It is obvious that the calculation of the thermal losses (and thus the dimensioning of the insulation thickness) with the values recommended in DIN 4108 results in significant errors. In comparison to the manufacturer or the DIN specifications the effective thermal conductivity and thus the thermal losses can be higher by a factor of 4 to 10 (see Ochs 2005). The thermal conductivity increases significantly with increasing moisture contents, especially at higher temperatures. Therefore suitable measures have to be taken to guarantee the protection of the insulation from moisture penetration during installation and subsequent operation.

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REFERENCES

Benner M. et al. (2004). Solar unterstützte Nahwärmeversorgung mit und ohne Langzeit-Wärmespeicher, Forschungsbericht zum BMBF-Vorhaben, November 1998 bis Januar 2003, ISBN-Nr. 3-9805274-2-5, in German.

DIN 4108, Teil 4: Wärmeschutz und Energie-Einsparung in Gebäuden, Thermal insulation and energy economy in buildings, in German.

DIN 52612, Bestimmung der Wärmeleitfähigkeit mit dem Plattengerät, in German.

ASTM C 177, Guarded Hot Plate Method

DIN EN 13755, Bestimmung von Wasseraufnahme und Sättigungswert, Determination of water absorption and saturation coefficient, in German.

Giebe, R. (1989) Ein Kies/Wasser-Wärmespeicher in Praxis und Theorie, Dissertation, Universität Stuttgart, in German.

Krischer, O, Kast, W (1992). Die wissenschaftlichen Grundlagen der Trocknungstechnik, Springer, Berlin, in German.

Ochs F. et al. (2005). Außenlaborversuche zur Entwicklung kostengünstiger Erdbecken-Wärmespeicher für Solarwärme, Proc. OTTI, 15. Symposium „Thermische Solarenergie“, Kloster Banz, Bad Staffelstein, in German.

Ochs F. (2005a). Sachstandsbericht zum Projekt „Weiterentwicklung der Erdbecken-Wärmespeichertechnologie“, Status Report, in German.

Ochs F. et al. (2004). Bestimmung der feuchte- und temperaturabhängigen Wärmeleitfähigkeit von Dämmstoffen, Proc. OTTI, 14. Symposium Thermische Solarenergie, Kloster Banz, in German.

Urbanek, T. (2003), Berechnung des thermischen Verhaltens von Kies-Wasser-Speichern, Dissertation, TU Chemnitz, in German.