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Thermal conductivity of foam glass gravels: a comparison between experimental data and numerical results

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Abstract

In this study the equivalent thermal conductivity of foam glass gravels is investigated by means of measurements with guarded hot plate devices. Firstly the thermal conductivity of the foam glass corns is determined. Following experiments are performed on random generated gravel beds varying the mean temperature, the temperature difference between hot and cold plate, the gravel compression degree and the heat flux direction. The influence of these parameters on the effective thermal conductivity is investigated. An empirical model based on the Krischer approach for determination of thermal conductivity in porous media is proposed and validated against the experimental data. In addition, results from numerical simulations are presented.

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Nomenclature

a	[-]	Volumetric fraction	γ	[°]	Rotation angle
C_p	[J/(Kg K)]	Heat capacity	λ	[W/(m K)]	Effective heat conductivity
C_s	[W/(m K^4)]	Radiation coefficient	μ	[Kg/(m s)]	Dynamic viscosity
g	[m/s^2]	Gravitational acceleration	ρ	[Kg/m^3]	Density
h	[m]	Sample thickness	ψ	[-]	Porosity
k	[m/s]	Hydraulic conductivity	**Subscripts**		
K	[m^2]	Permeability	0		At the cold surface
$\dot{q}$	[W/m^2]	Heat flux	a		Air
T	[K]	Temperature	c		Corn
α	[W/(m^2 K)]	Conv. heat transfer coefficient	m		Arithmetic mean value
β	[1/K]	Coefficient of thermal expansion	I, II		Parallel, series
V	[m^3]	Sample volume	w		Water

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1. Introduction

Foam glass gravel is a thermal insulation material with many advantages and used in different applications such as thermal insulation of building foundation and cellar plates, as backfilling of voids or overflows in structural engineering or as cost-effective insulation for large-scale thermal energy stores (TES) [1][2]. The main advantages are that it is made of recycled glass; it is light, dimensionally stable, ageing-resistant and is ideally suited to load-dissipating insulation. Foam glass gravel serves for drainage of the aggregate layer, can replace frost barriers and strip foundations and simultaneously acts as external heat insulation from the soil.

For this reason in the last years the interest on this material is increasing and further knowledge on its behavior as thermal insulation is required. In particular the effective thermal conductivity of gravels under different application conditions needs to be determined. The influence of different parameters such as temperature, porosity and heat flux direction (i.e. presence of convective heat transfer) on the apparent thermal conductivity is of interest.

The present study represents a step forward to in extending such knowledge. In particular natural convection is taken into account using the approach proposed by [3]. Measured data, obtained by means of hot plate devices are analyzed and used for calibration of empirical and numerical models. This work results from cooperation between the University of Stuttgart, Institute of Thermodynamics and Thermal Engineering (ITW), the Research and Testing Center for Thermal Solar System (TZS) and the University of Innsbruck, Unit for Energy Efficient Buildings (EEB).

2. Experimental setup

The guarded hot plate apparatus used in the present study is suitable for measurement of the thermal conductivity of gravels according to the standard [4]. The device is fixed on a steel frame through a pivot, allowing complete or partial rotation as shown in Figure 1 a) (rotation angle: $0 < \gamma < 180°$). In case the rotation angle is equal to zero, downward directed heat flux occurs through the gravel, principally due to conduction and radiation. In the opposite case (rotation angle equal to 180°) the heat flux is upward and natural convection may be relevant. The specimen thickness can be reduced through mechanical compression of the gravel using a hydraulic press. In this way, the gravel porosity can be varied.

A second smaller apparatus (guarded hot plate: 15 cm x 15 cm, specimen surface: 30 cm x 30 cm) has been employed for measuring the thermal conductivity of the single corns as explained in section 4.1. Further measurements have been performed with a third device at the University of Stuttgart (ITW).

The heat flux through the specimen is described by the following equation:

$$\dot{q} = \lambda \frac{\Delta T}{h} \tag{1}$$

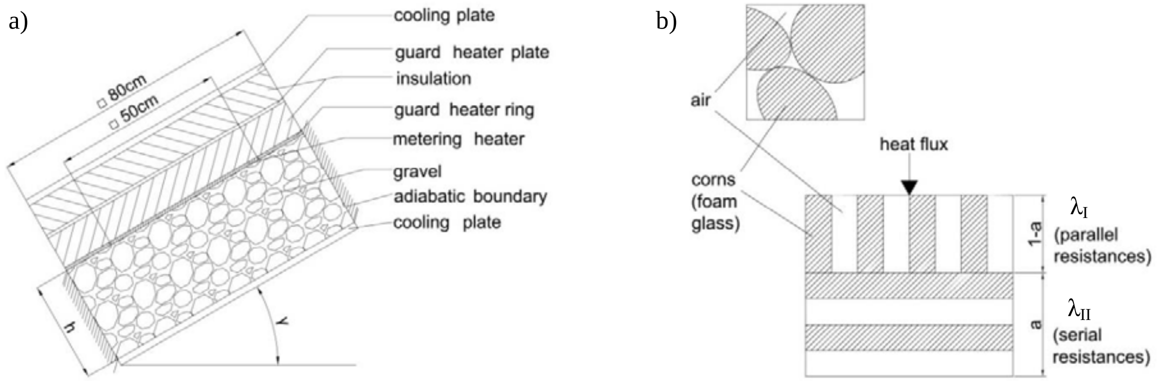

Figure 1 a) schematic representation of the experimental setup for measurement of the thermal conductivity of gravel beds. b) gravel phases (top) and Krischer model (bottom)

According to equation (1), the apparent thermal conductivity λ can be directly calculated if the heat flux, the temperature difference between metering heater and cooling plate ($\Delta T = T_{hot} - T_{cold}$) and the thickness of the sample (h) are known.

The effective thermal conductivity includes the contribution of heat conduction in the two phases (air and solid) present in the gravel, as well as radiation inside the cavities between the corns. In case macroscopic convective flow occurs, equation (2) has to be employed instead of equation (1):

$$\dot{q} = \alpha \, \Delta T \tag{2}$$

Where the convective heat transfer coefficient α depends on the Nusselt number Nu as follows:

$$\alpha = \frac{Nu \, \lambda}{h} \tag{3}$$

If the Nusselt number approximates the unity, convection has no significant influence on the total heat transfer and equation (2) turns into (1). In general, for porous materials the Nusselt number can be calculated as a function of the Darcy-modified Rayleigh number defined as follows:

$$Ra = \frac{g \, \varrho_{a,0} \, \varrho_{a,m} \, \beta_{a,m} \, \Delta T \, h \, K \, Cp_{a,m}}{\lambda \, \mu_{a,m}} \tag{4}$$

The relation connecting the Nusselt number to the Rayleigh number is determined in the following of this study by means of experimental data. For calculation of the Rayleigh number with equation (4), the gravel permeability K has to be known. This parameter is not directly measured within this study, but derived by inverse simulation by means of a numerical model as shown in the following.

3. Analytical model describing the effective thermal conductivity of gravels

The effective thermal conductivity is assumed to be a material specific property depending from temperature, porosity and porous structure of the gravel whereas influence of moisture is not object of this study. Furthermore, it is assumed that only the air cavities between the corns may be reduced after compression whereas the corn volume and the corn porosity do not change.

For describing the thermal conductivity, the model proposed by Krischer [5], suitable for general porous materials, is employed. This model includes the heat transfer due to conduction and radiation, whereas the influence of convection, which may locally occur in the small air cavities, is neglected.

Krischer assumes the material as constituted by thermal resistances disposed serially and in parallel with respect to the heat flux direction (Figure 1, b). The parallel resistances present equivalent thermal conductivity λ_I (theoretical minimal value), described by equation (5). The serial resistances present equivalent thermal conductivity λ_{II} (theoretical maximal value), described by equation (6):

$$\lambda_I = \psi \cdot (\lambda_a + C_s \, T^3) + (1 - \psi) \cdot \lambda_c \tag{5}$$

$$\lambda_{II} = \frac{1}{\frac{\psi}{(\lambda_a + C_s \, T^3)} + \frac{1 - \psi}{\lambda_c}} \tag{6}$$

In equations (5) and (6), ψ and λ_c represent the macro porosity (volume fraction of the air cavities between the corns) and the corn thermal conductivity respectively. The value of λ_c is measured and reported in the next section whereas the porosity ψ is given by the following equation:

$$\psi = \frac{V - V_c}{V} \tag{7}$$

Where V is the total sample volume and V_c is the corn volume, which can be calculated if the corn density and the total mass of the gravel bed are known. The radiative contribution to heat transfer is included through the parameter C_s. This parameter is material specific and is determined by interpolation with experimental data.

The total effective thermal conductivity of the gravel bed can be calculated by means of equation (8), where the parameter a is a weighting factor which has to be determined in experimental way:

$$\lambda = \frac{1}{\frac{1-a}{\lambda_I} + \frac{a}{\lambda_{II}}} \tag{8}$$

4. Results

The experimental results reported in this section concern foam glass gravels produced by two different manufacturers. In the following we refer to them as gravel 1 and gravel 2.

4.1. Effective thermal conductivity of the corns

The thermal conductivity of the corns has been measured using foam glass specimens cut from single gravel´s corns. In Figure 2 a), the measured values are reported as function of the average temperature of the specimens. The two different gravels are compared. These results confirm that the dependence of thermal conductivity from the temperature is linear and pronounced. More uncertainty presents the dependence of thermal conductivity from the corn density ρ_c shown in Figure 2 b). A slight increasing of the thermal conductivity can be observed by increasing corn density ρ_c, what is verisimilar since heat conduction in the solid matrix (glass) is much higher as heat conduction in air.

4.2. Effective thermal conductivity of the gravel

The effective gravel thermal conductivity has been measured varying the compactness i.e. degree of compression, in order to observe the influence of this parameter on the heat transfer. The experimental data are interpolated with results obtained from the model described above (equations (8), (5) and (6)), determining the parameters a and C_s. After calibration, the model shows satisfactory agreement with the measured data (Figure 3 and Figure 4).

Firstly measurements with downward heat flux are performed. In this case, radiation and conduction represent the main contributions to the total heat flux, whereas natural convection is nearly negligible. The results show that the thermal conductivity is decreasing by raising the degree of compression. This can be explained considering that heat transfer due to radiation becomes lower if the air cavities between the corns are reduced. Due to the corn stability, the total corn volume is supposed to remain the same after compression. For gravel 1, measurements have been performed on four different compression levels, starting from specimen thickness of 30cm (uncompressed), as shown in Figure 3. In case of gravel 2, only data measured without compression are available till now. The thermal conductivity is slightly higher as that of gravel l (Figure 4).

In order to investigate the influence of the temperature, all the specimens are measured on different temperature levels between 10 and 35°C (referring to the steady state mean-temperature T_m inside the specimens). The results show that the equivalent thermal conductivity increases with increasing temperature, as expected according to the theory of heat transfer. This trend has been observed for all the measured specimens.

4.3. Influence of natural convection and comparison with numerical data

In this section influence of natural convection on the total heat transfer is investigated. This intention requires measurements with upward directed heat flux (γ=180°). Gravel 1 is measured applying maximal compression degree (h = 0.235m) whereas gravel 2 is uncompressed (h = 0.3m). In the second case, the determinant parameter for heat transfer results to be the temperature difference between hot and cold surface, whereas the mean temperature of the specimen plays a minor role. ΔT is varied between 5 K and 15 K. The Nusselt number is calculated by means of equations (2) and (3) from the measured heat flux and temperature difference.

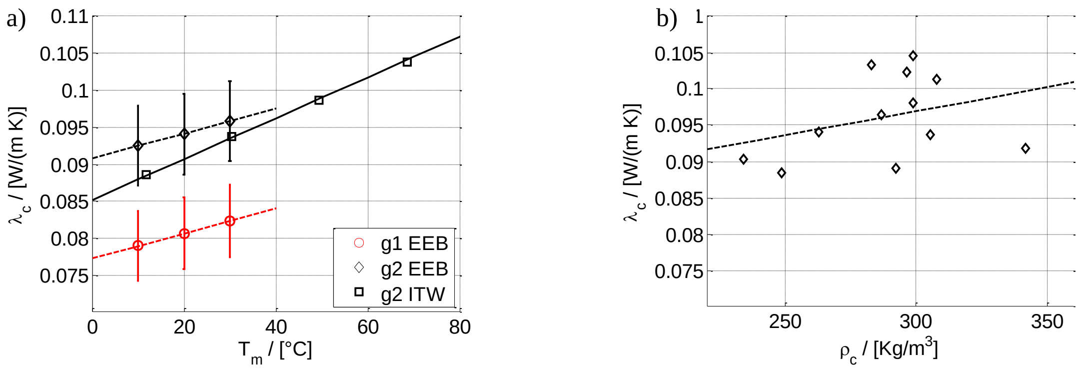

Figure 2 a) corn thermal conductivity as function of temperature measured at EEB (ΔT=10K, gravels 1 and 2) and at ITW (gravel 2). b) corn thermal conductivity as function of gravel density (mean temperature 20°C, ΔT=10K, gravel 2, measured by EEB)

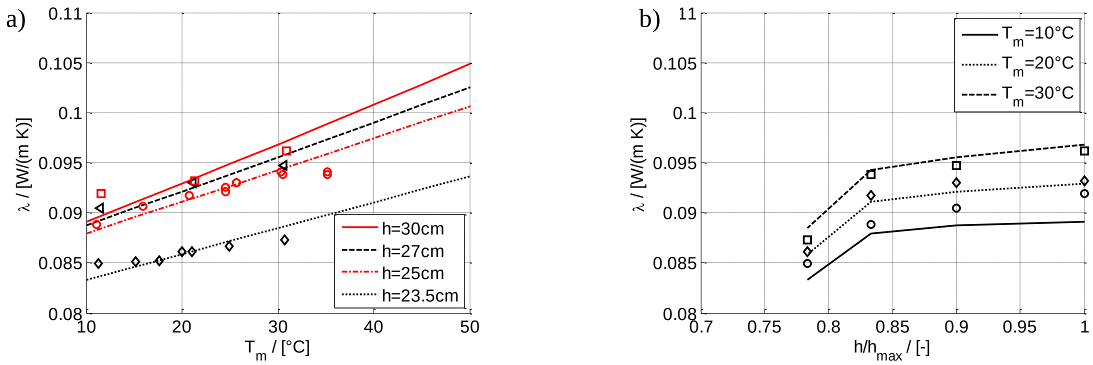

Figure 3: Measured data of thermal conductivity of gravel 1 and results calculated with the Krischer-model for different mean temperatures and compression degrees (uncompressed gravel corresponds to h= 30cm)

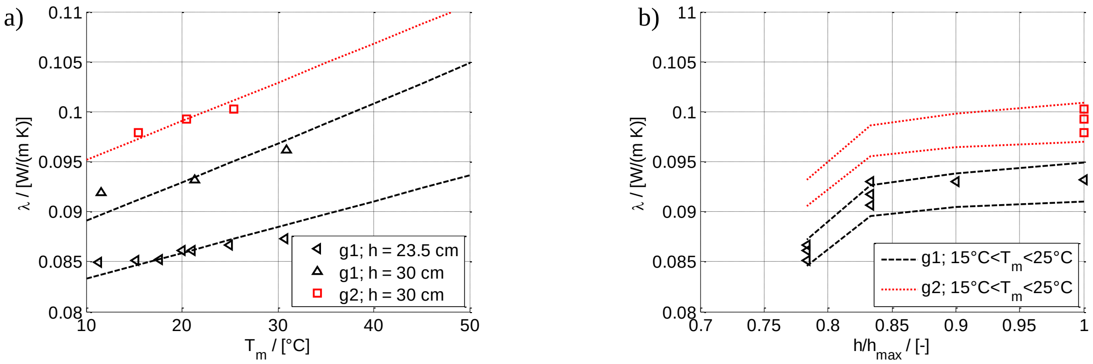

Figure 4: Comparison between thermal conductivity of gravels 1 and 2. a) thermal conductivity as function of the mean temperature. b) thermal conductivity range as function of compression degree with h_{max}=30 cm. The gravel 2 range (dotted lines) is traced assuming the both gravels presenting similar behaviours.

In addition to the determination of the effective thermal conductivity by means of the empirical model of Krischer a numerical model in the dynamic simulation program Comsol Multiphysics 4.3b is set up. The aim is to simulate in detail the occurrence of free convection and to calibrate the simulation with the help of the measuring results of grain 2. Finally the effective thermal conductivities should be predictable without running time-consuming real-time measurements. The Comsol model calculates with the physical fully coupled modules “heat transfer in porous media” and the “Brinkman Equation”.

Figure 5 shows the measured and simulated thermal conductivities. For gravel 2 significant influence of natural convection on the total heat transfer is observed. The dependence of the Nusselt number on the temperature difference results to be nearly linear (Figure 5, a). On the contrary, no convection is observed in gravel 1. This deviation between the two gravels can be explained, assuming that the permeability of gravel 1 is significantly reduced after compression.

Since no measured value for air permeability is available, this parameter is obtained by means of comparison of numerical results and measured data. For gravel 2 the permeability value results: $K \approx 1.5\cdot10^{-6}$ m^2. The results present expectable agreement with the empirical theory of Elder ($Nu = Ra/40 \pm 10$ %) [6] (Figure 5, right). The permeability of gravel 1 is estimated to be approximately $K \approx 0.3\cdot10^{-6}$ m^2, in order to obtain $Ra < 40$.

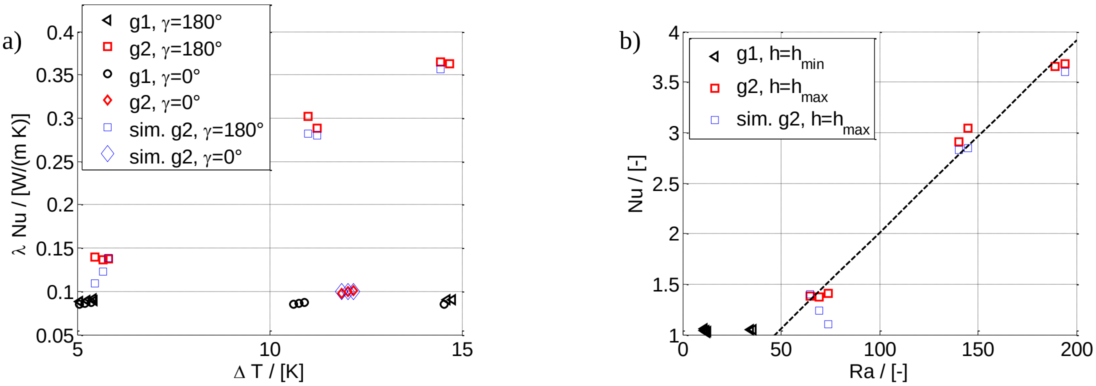

Figure 5: Influence of natural convection with upward heat transfer on gravel 1 (compressed, h = 0.235 m) and gravel 2 (uncompressed, h = 0.3 m). Comparison between simulation (sim.) and experimental results. a) $\lambda\cdot Nu$ vs ΔT. b) Nu vs Ra for $\gamma = 180°$

5. Conclusions and outlook

Both measured foam glass gravel types reveal similar behaviors concerning the effective thermal conductivity. Increasing mean temperature in the specimens leads to higher total heat transfer whereas gravel compression reduces the thermal conductivity. In case of upward directed heat flux, adequate gravel compression may avoid natural convection and reduce heat losses through the gravel bed. Further development of the numerical model should take into account the temperature-dependent fluid properties and more accurate assessment of the gravel permeability.

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