SUPER-INSULATED LONG-TERM HOT WATER STORAGE

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1. Introduction

Today, solar installations with collector areas from 10 to 20 m² and storage volumes from 0.5 to 1 m³ provide only a small solar fraction (maximally 30 %) of the total domestic heat demand. Simultaneously, especially the field of conventional domestic heat supply generates a big fraction of the world wide CO_2 emission. In order to reach higher solar fractions (50 % or more) in solar supported buildings, larger and better insulated storage tanks are necessary to achieve seasonal heat storage in the ideal case. But also for the intermediate storage of district heat (80℃ - 130℃) or industrial process heat at even higher temperatures, storage tanks with improved thermal insulation are necessary to use energy more efficiently.

For many years, the technique of vacuum super insulation (VSI) with expanded perlite has been used for cryogenic applications, especially for the storage of liquid gases at temperatures between 20 K and 90 K. Expanded perlite is an amorphous, highly porous, granular material of volcanic origin, see figure 1. Its two main components are SiO_2 (70 %) and Al_2O_3 (15 %). Due to the small pore diameters and the small distances between the grains, gas conduction in the pores and in the intergranular spaces is suppressed already in the regime of fine vacuum (p = 0.01 mbar). As a consequence of the filigree structure of the material, solid conduction is inhibited to a great extent. Furthermore, thermal radiation is efficiently blocked by multiple absorption and re-emission in the opaque solid. Due to these properties and as a consequence of the temperature dependency of the radiative heat transport, which scales with T^4, effective thermal conductivities λ_{eff} as low as 3 to 5 mW/mK have been realized at cryogenic temperatures. Compared to conventional insulation materials like polyurethane or rock wool at ambient temperature, the thermal conductivity is lowered by a factor of 6 to 10. Moreover, perlite super insulations are more space-efficient compared to conventional insulation materials, and they have no problems regarding humidity or shrinking during their lifetime. In real cryogenic tanks, the perlite is homogenously filled into the annular gap between two concentric steel cylinders and subsequently evacuated to 0.01 mbar or lower, see figure 2.

In a current federally granted research project at ZAE Bayern (grant number 0325964A, German ministry of environment), the approach is pursued to apply perlite-based VSI also at higher temperatures. Primarily, the long-term and seasonal storage of hot water up to T = 100 ℃ in solar thermal heating systems is considered, although other fields of application like the storage of industrial process or district heat could benefit even more from VSI because of the higher temperatures.

Figure 1: Raw perlite (a) and technically expanded perlite powder (b).

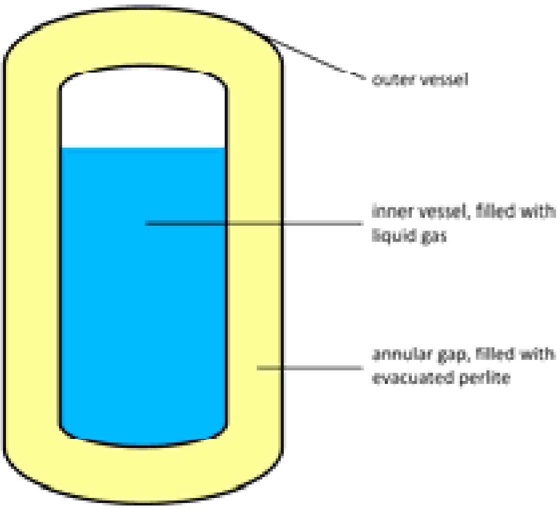

Figure 2: Schematic sketch of a typical cryogenic storage for liquid gases.

2. Laboratory Experiments on Evacuated Perlite

So far, experimental data for the effective thermal conductivity λ_{eff} of evacuated perlite at higher temperatures has been very rare. Furthermore, the single heat transport mechanisms have never been quantified. Also the effect of moisture, which is present during the transport, loading and evacuation process at ambient conditions, and its behaviour at higher temperatures has not been investigated yet. Therefore, various experiments have been performed in order to determine λ_{eff} at different temperatures (20 °C - 150 °C), vacuum pre ssures (0.001 - 1000 mbar), bulk densities (55 kg/m³ - 95 kg/m³) and grain structures. Effective thermal conductivity measurements have been done in an existing parallel plate setup (figure 3) and in a cut-off cylinder apparatus, which has been specially designed and set up during the research project, see figure 4. The central component of both devices is an electrically heatable plate or tube, and the electrical heating power P_{el} is measured, which is needed to keep the heating element at a constant temperature. In the stationary case, P_{el} is equal to the heat flux through the sample material to the colder surroundings (plates or cylinder). The respective temperatures are measured and controlled to constant values. For the experimental investigation of the thermal conductivity, the commercially available perlite "Technoperl C1,5" from the Austrian manufacturer Europerl, Stauss-Perlite GmbH has been used.

In addition to the effective thermal conductivity measurements, the radiative heat transfer has been examined separately using Fourier transform infrared (FTIR) spectroscopy. In particular, the spectral mass-specific extinction coefficient has been measured. According to the theory of diffuse radiation heat transport in powder insulations, this quantity determines the radiative thermal conductivity, together with the application temperature and the corresponding Planck-spectrum, see figure 5. As a consequence, the radiative thermal conductivity λ_{rad} of the perlite powder can be calculated for a wide range of temperatures.

From measurements in the high vacuum range, where gas heat conduction is totally suppressed, the sum of radiative and solid conduction has been experimentally determined. Subtracting λ_{rad}, one obtains the solid conduction, see figure 6.

At higher vacuum-pressures, one can subtract the solid and radiative contributions from the total effective thermal conductivity, which yields the thermal conductivity λ_{gas} that describes gas conduction (figure 7).

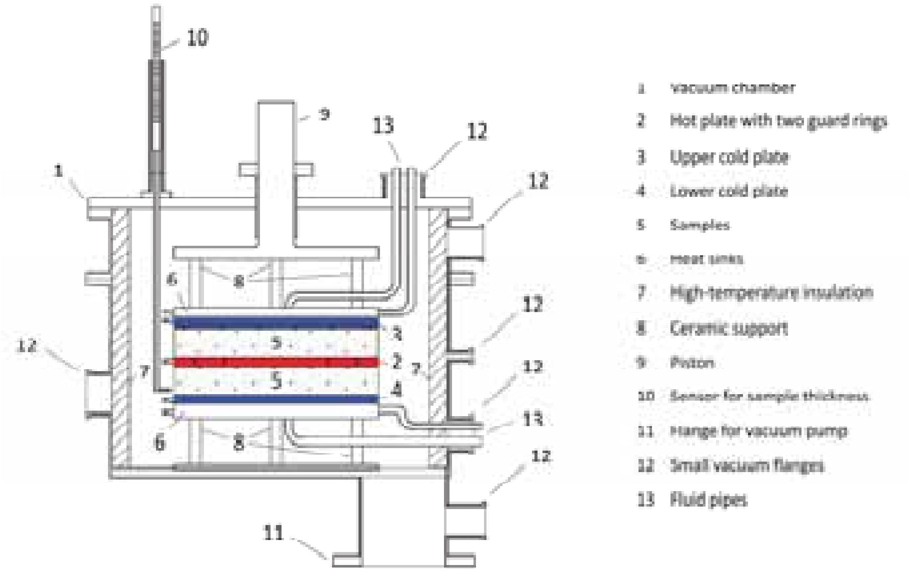

Figure 3: Parallel plate setup of the ZAE Bayern for measuring effective thermal conductivities as a function of temperature, vacuum pressure and density, which is varied by an external load applied via the piston (9).

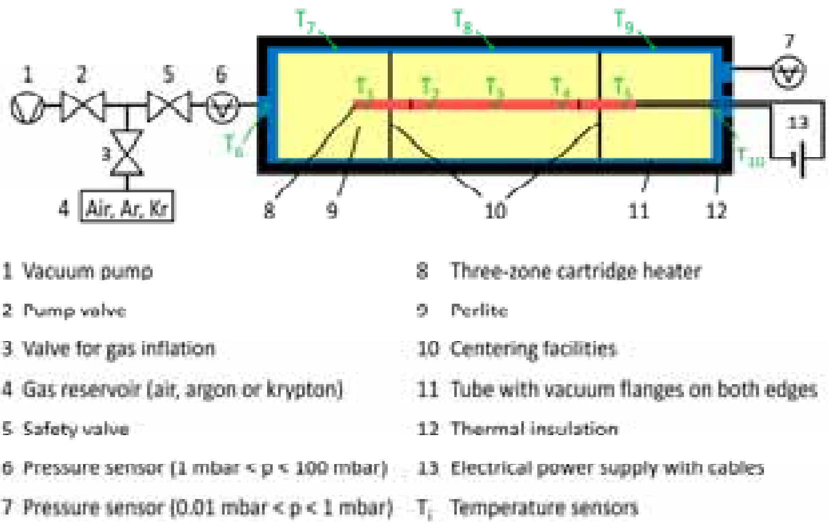

Figure 4: Cut-off concentric cylinder apparatus of the ZAE Bayern to determine thermal conductivities of powder insulations at different temperatures and vacuum pressures.

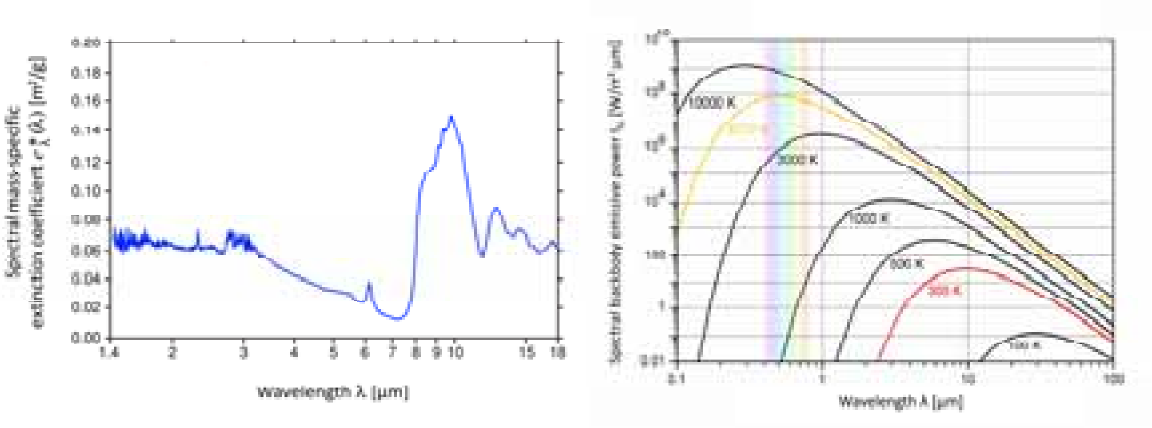

Figure 5: Experimental wavelength-dependent, mass-specific extinction coefficient of perlite (left) and Planck spectra (right, [1]), by which the spectral extinction has to weighted to get the integral extinction.

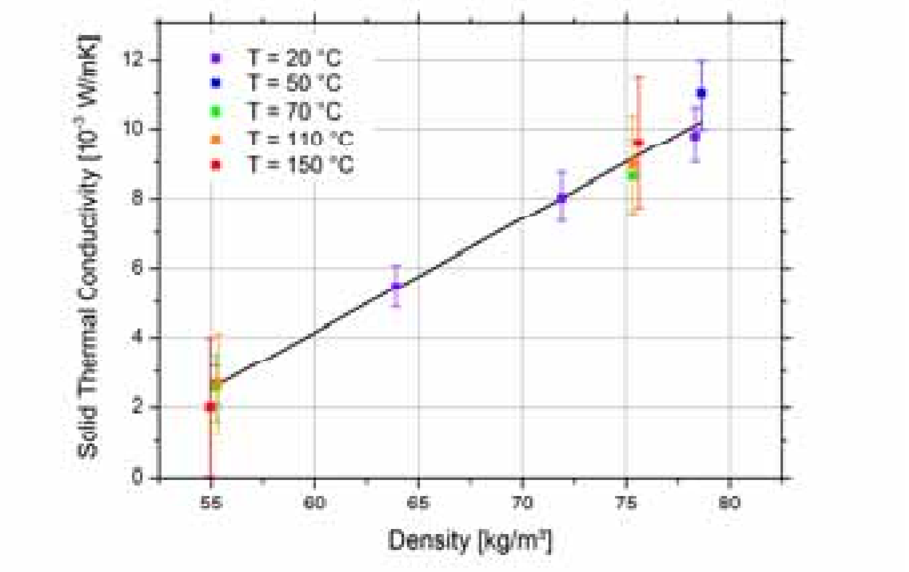

Figure 6: Experimentally determined solid thermal conductivity as a function of bulk density and temperature of the sample. Starting from the density of 55 kg/m³, the higher densities have been realized by external pressure in the parallel plate apparatus.

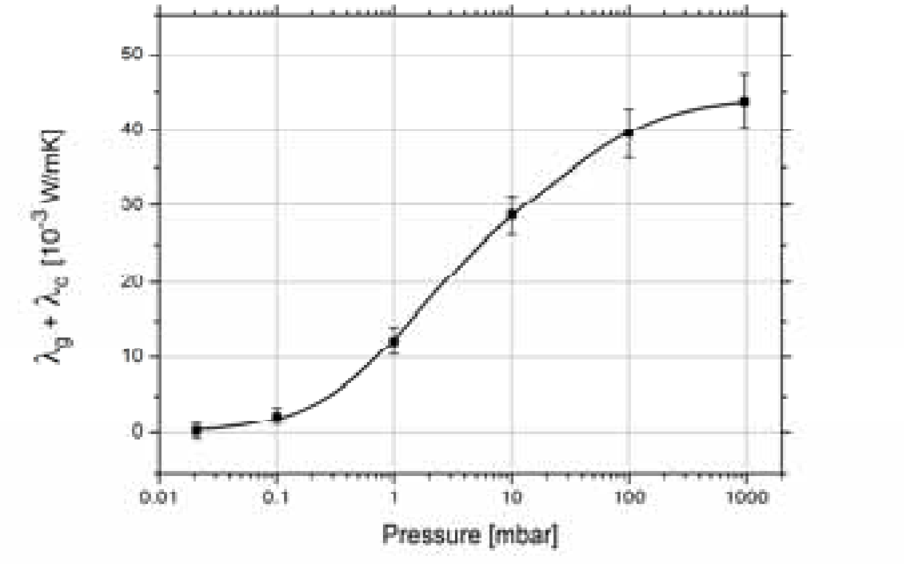

Figure 7: Pressure-dependent gaseous thermal conductivity of evacuated perlite at ρ = 55 kg/m³, measured in the cut-off cylinder apparatus at temperatures of T = 150℃ for the interior hot tube and T = 50℃ for the cold exterior cylinder.

3. Theoretical Treatment of the Heat Transport in Evacuated Perlite

In order to interpret and compare the extensive measurement data, a comprehensive theoretical understanding of the different heat transport mechanisms contributing to the effective thermal conductivity of evacuated perlite has been developed, and it has been possible to explain the results of all different measurements in a consistent way. It is not possible to go in details here, but summarizing, it can be said that for this theoretical description, conventional approaches and models have been used, which have successfully been applied to similar super-insulating systems during the last decades, and which can be found in literature [2]: The pressure dependency of gaseous conduction has been characterized using the Sherman interpolation between the continuum at high pressures and the regime of free molecular flow at low pressures. Regarding the solid thermal conductivity, a linear dependency on density has been derived from the experimental data. This result is in agreement with other empirical findings. However, the initially assumed dependency of solid conduction on temperature has not been observable. Radiative heat transport has been treated using the heat diffusion model, which describes absorption and scattering of thermal radiation within a material and allows the introduction of a radiative thermal conductivity. For the gas conduction in the intergranular spaces, also referred to as coupling effect, a special new model for perlite has been developed, based on approaches, which have originally been applied to particle beds in general, and have also been adapted to aerogels in particular [3].

4. Experiments on a Real-Size Prototype

To transfer the results from the laboratory experiments and the theoretical calculations into a practical application and to verify the predictions, a real-size cylindrical storage prototype with a water storage volume of $V = 16.4$ m³, an outer diameter of 2.4 m and a 20 cm thick insulation layer of evacuated perlite has been constructed by the industrial project partner Hummelsberger GmbH in Mühldorf, Germany (figure 8). This prototype allows experiments under practical conditions. The bulk density of the homogenously distributed perlite in the annular gap is 92.4 kg/m³. The storage has been loaded with hot water (86.5 °C), and the cooling rate has been determined over a total interval of 10 days in December 2010 at a mean ambient temperature of -2.3 °C. The water temperature has been measured via 6 equidistantly distributed Pt-1000 temperature sensors, which have been installed in a small vertical tube with a distance of 30 cm to the inner storage tank wall. The difference between the average water temperature and the ambient temperature was $\Delta T = 88.8$ K, and the mean vacuum pressure inside the insulation was 0.08 mbar. From CFD simulations, it has been proven that the sum of thermal losses due to supply pipelines and suspension amounts to only 1.3 % of the total storage losses. In conventional storages in contrast, the heat losses via the pipes can reach 70 % of the envelope losses via the insulation material [4].

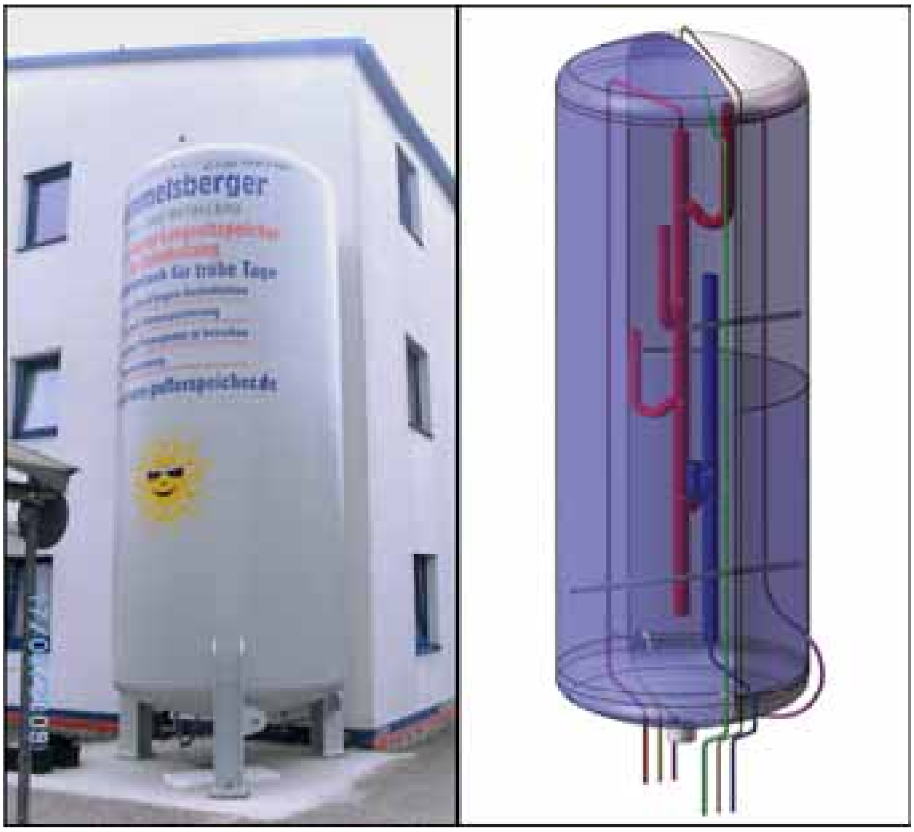

Figure 8: Layout of the real-size storage tank prototype (16.4 m³ storage volume) with VSI-insulation: Photograph of the tank (left), sketch of the inner container with supply pipelines and stratification device (right).

The experimental cooling rate, including pipe-losses, was as low as 0.23 K/day, which is about ten times lower as for conventional storages. The cooling rate corresponds to an effective thermal conductivity λ_{eff} of (9.2 ± 0.2) mW/Km for the insulating evacuated perlite layer, which is in full agreement to the theory and the results of the laboratory measurements. According to the investigation of the different heat transfer mechanisms, λ_{eff} is composed of a radiative part of λ_{rad} = 2.6 mW/mK, a solid thermal conductivity of λ_s = 5.1 mW/mK and a contribution due to gas conduction of λ_{gas} = 1.5 mW/mK. Due to the coincidence of the maxima of the Planck spectrum at T = 300 K and the mass-specific extinction of perlite for thermal radiation, according to fig. 5, λ_{rad} shows an extremely low value. The lower value for λ_s compared to figure 6 results from the different grain structures during both experiments (self-compression of the bulk by space-saving arrangement in a close-packing of spheres during the filling procedure in the real-size application versus application of external mechanical pressure in the parallel plate apparatus, resulting in partial grain destruction and shortening of thermal resistances). From theoretical calculations, it has been derived, that it should be possible to reduce the effective thermal conductivity of the insulation to λ_{eff} = 7.3 mW/mK if a bulk density of around 60 kg/m³ is used and if the gas pressure is lowered to p = 0.01 mbar. This corresponds to the minimum value that can be achieved in practice.

A last experimental task was the determination of the moisture content within Technoperl C 1,5. According to theory, moisture in its liquid or gaseous form can dramatically increase the thermal conductivity of an insulation. However, as a result of the experiments and due to phase diagram considerations, these effects could be proven to be neglectable for practical applications. The maximally measured moisture load was below 2%.

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