POSTER 13

Analysis of Mathematical Heat Transfer Models for free-flowing Vacuum Insulation Materials

S. Lang[a*]
D. Bestenlehner[a]
H. Drück[a]
R. Marx

[a] Research and Testing Centre for Thermal Solar Systems (TZS), Institute of Thermodynamics and Thermal Engineering (ITW), University of Stuttgart, Pfaffenwaldring 6, 70569 Stuttgart, Germany
* Corresponding author:
Tel. +49 711-685-63614
lang@itw.uni-stuttgart.de

Keywords:

Free-flowing vacuum insulation,
mathematical models,
perlite,
fumed silica.

Abstract

In this work published mathematical models describing heat transfer mechanisms through porous materials were analyzed and compared respectively fitted to measured thermal conductivities of three different free flowing vacuum insulation materials. These materials were coarse grained and fine grained expanded perlite and opacified fumed silica. The models described in [2, 4, 7, 9] showed good results in terms of predictability and deviation from the measurements.

Introduction

Free-flowing vacuum thermal insulation materials can be utilized where rigid and vacuum tight walls surround the insulation volume, which can stand the forces induced by the vacuum pressure. Utilizing free-flowing materials, a smaller mass of thermal insulation material is needed compared to compressed thermal insulation materials with higher bulk densities, as e.g. used in vacuum insulation panels.
In this paper some results of the analysis of different mathematical models, describing the different heat transfer mechanisms through porous media are presented. These models were analyzed with regard to their suitability to describe the heat transfer mechanisms in free-flowing expanded perlites and opacified fumed silica by comparing the calculation results with measured values determined by the author and from available measurement results described in the literature.

The aim of this work is to identify respectively develop a mathematical model that can determine the ideal mixture of different thermal insulation materials for a certain application, depending on temperature, vacu-um pressure and bulk density. This mathematical model will also be applied to design the thermal insulation for an ultra-high temperature energy store within the research project "AMADEUS", supported by the European Union (s. Acknowledgements).

Investigated Models and Materials

A widespread method to describe the effective thermal conductivity λ_{eff} [W/(m·K)] of porous media is the superposition of thermal conductivities representing the occurring heat transfer mechanisms (s. Eq.1).

$$\lambda_{eff} = \lambda_g + \lambda_s + \lambda_r + \lambda_c \qquad \text{(Eq. 1)}$$

with:

λ_g Thermal conductivity representing the heat transfer through the gas phase [W/(m·K)]
λ_s Thermal conductivity representing the heat transfer through the solid phase [W/(m·K)]
λ_r Thermal conductivity representing the heat transfer by thermal radiation [W/(m·K)]
λ_c Thermal conductivity representing the heat transfer by coupling effect [W/(m·K)]

Investigated models:

The following list shows sources of some of the most promising models investigated:

> Thermal conduction through gas: [1], [2], [3], [4]
> Thermal conduction through solid: [5], [6], [7]
> Heat transfer by thermal radiation: [8], [9]
> Coupling effect: [4]

Thermal Insulation Materials:

The insulation materials used to analyze the mathe-matical models were coarse grained expanded perlite (cep), s. Fig. 1, measured values from [10], fine grained expanded perlite (fep), s. Fig. 2, measured by the author and opacified fumed silica (ofs), s. Fig. 3, measured values from [11]. Relevant material properties are listed in Table 1.

Fig. 1
Coarse grained expanded perlite (cep)

Fig. 2
Fine grained expanded perlite (fep)

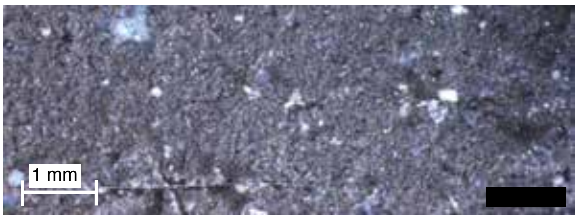

Fig. 3
Opacified fumed silica (ofs) [11]

Material	mean pore size [µm]	bulk density [kg/m³]	Rosseland mean extinction coefficient [m²/kg]
cep	44	76 [4]	43 [4]
fep	30	183	43
ofs	13 [11]	45 [11]	90 [11]

Tab. 1
Some relevant material properties of the investigated thermal insulation material

Results and discussions

To examine the capability of the different models to predict the effective thermal conductivity of the three investigated thermal insulation materials, the results of the calculations are compared with measured data. These measured data of the effective thermal conductivities are either determined by the author or taken from [10] and [11]. The models described in [2] for the heat transfer in gas phase, in [7] for the heat transfer in solid phase and in [9] for the heat transfer by thermal radiation show the best results compared to the other investigated models. The coupling effect was modeled according to [4]. The models for the heat transfer in the solid phase and the coupling effect contain adjustment parameters that cannot be determined by material properties. Thus, these models are not predictive. These parameters were determined by fitting to the measured thermal conductivities at the highest and lowest air pressure. The results of measurements and calculations are shown in fig. 4 for cep and in fig. 5 for fep.

With the models described above, the measured values can be reproduced very precisely. The highest deviations occur between 1 and 10 mbar, at the highest slope of the curve. This could be explained with inaccuracies of the pore size determination or the model for the heat transfer in the gas phase. The influence of the coupling effect is higher for fep compared to cep due to the smaller grain sizes and thus more contact spots where the coupling effect can occur.

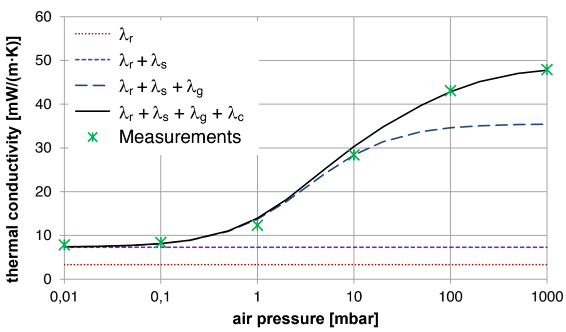

Fig. 4
Results of measurements and calculations for cep at 53°C

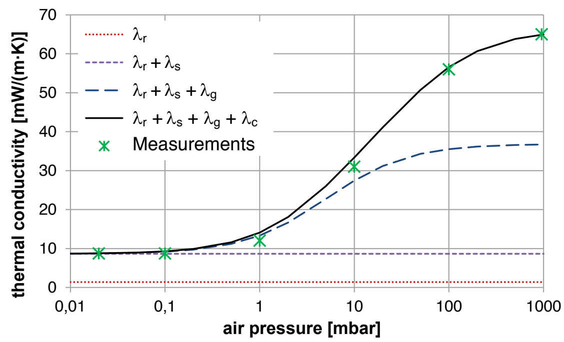

Fig. 5
Results of measurements and calculations for fep at 48°C

Conclusions and outlook

The selected models suitably quantify the heat transfer mechanisms in free-flowing vacuum thermal insulation materials. However, it is necessary to find measurable or predictable parameters to create predictive models for the heat transfers through the solid phase and for the coupling effect.

Acknowledgements

The project AMADEUS has received funds from the European Union's Horizon2020 research and innovation program, FET-OPEN action, under grant agreement No 737054. The sole responsibility for the content of this publication lies with the authors. It does not necessarily reflect the opinion of the European Union. Neither the REA nor the European Commission are responsible for any use that may be made of the information contained therein.

References

[1] Kennard, E. H. Kinetic theory of gases with an introduction to statistical mechanics, 1938
[2] Schwab, H. Vakuumisolationspaneele- Gas- und Feuchteeintrag sowie Feuchte- und Wärmetransport, Eq. 2-7, Dissertation, Würzburg, 2004
[3] Krause, M. et al. Icarus 214 (2011) 286-296, Eq. 5
[4] Demharter, M. Heat Transport in Evacuated Perlite Powder Insulations and Its Application in Long-Term Hot Water Storages, Eq. 4-7 and 4-31. Master Thesis, München, 2011
[5] Bouquerel, M. et al. Energy and Buildings 54 (2012) 320–336, Eq. 25
[6] Kwon, J.-S. et al. International Journal of Heat and Mass Transfer 52 (2009) 5525–5532, Eq. 9
[7] Kaganer, M. G. (1969). Thermal insulation in cryogenic engineering, Jerusalem, ISBN 13: 9780706506075
[8] Jelle, B. Journal of Building Physics 34, 2 (2010) 99-123, Eq. 4
[9] Fricke, J. et al. Vacuum 82 (2008) 680–690, Eq. 7
[10] Beikircher, T. et al. Superisolierter Heißwasser- Langzeitwärmespeicher, project report, Garching, 2013
[11] Kim, J.; Song, T. International Journal of Heat and Mass Transfer 64 (2013) 783–791.