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

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INTRODUCTION

In this contribution different mathematical models describing the heat transfer mechanisms through porous materials were analyzed. They were compared respectively fitted to measured thermal conductivities of different free flowing vacuum insulation materials. Thus the models that fit the measured values the best way could be determined.

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, vacuum pressure and bulk density.

THERMAL INSULATION MATERIALS

Fig. 1 *Investigated thermal insulation materials: left: coarse grained expanded perlite (cep); right: fine grained expanded perlite(fep)*

Table 1 *Most relevant material properties of the investigated thermal insulation materials cep and fep*

Material	mean pore size [µm]	bulk density [kg/m³]	Rosseland mean extinction coefficient [m²/kg]
cep	44	76*)	43*)
fep	30	183	43**)

**) Beikircher, T. et al. Superisolierter Heißwasser-Langzeitwärmespeicher, project report, Garching, D, 2013.*
***) assumed to be the same for cep and fep.*

MATHEMATICAL MODELS

A widespread method to describe the effective thermal conductivity λ_{eff} 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)]

Following mathematical models, with air assumed as residual gas, show the best results compared to other investigated models (see corresponding paper):

$$\boldsymbol{\lambda_g} = \frac{\lambda_{air}}{1 + \frac{p_{1/2,air}}{p_{air}}} \qquad \text{(Eq. 2)}$$

with:

$$p_{1/2,air} = \beta \cdot \frac{k_B \cdot T}{\sqrt{2} \cdot \sigma_0 \cdot d} \qquad \text{(Eq. 3)}$$

and:

$$\beta = \frac{5 \cdot \pi}{32} \cdot \frac{2 - \alpha_k}{\alpha_k} \cdot \frac{9 \cdot \kappa - 5}{\kappa + 1} \qquad \text{(Eq. 4)}$$

Schwab, H. Vakuumisolationspaneele- Gas- und Feuchteeintrag sowie Feuchte- und Wärmetransport, Eq. 2-7, 2-9, 2-10, Dissertation, Würzburg, Germany, 2004

$$\boldsymbol{\lambda_s} = \lambda_{s,0} \cdot 3{,}4 \cdot (1 - \psi)^{4/3} \cdot \left(\frac{(1 - \nu^2) \cdot p_{ext}}{E}\right)^{1/3} \qquad \text{(Eq. 5)}$$

Kaganer, M. G. (1969). Thermal insulation in cryogenic engineering, Jerusalem, ISBN 13: 9780706506075

$$\boldsymbol{\lambda_r} = \frac{16 \cdot \sigma \cdot \bar{n}^2 \cdot T_r^3}{3 \cdot \rho \cdot e_{ex,mass}} \qquad \text{(Eq. 6)}$$

Fricke, J. et al. Vacuum 82 (2008) 680–690, Eq. 7

$$\boldsymbol{\lambda_c} = (1 - \prod) \cdot \left[\frac{1 - \Gamma}{\lambda_s} + \Gamma \cdot \left(\frac{\lambda_{air}}{1 + \frac{p_{1/2,c}}{p_{air}}}\right)^{-1}\right]^{-1} \qquad \text{(Eq. 7)}$$

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, Germany, 2011

RESULTS

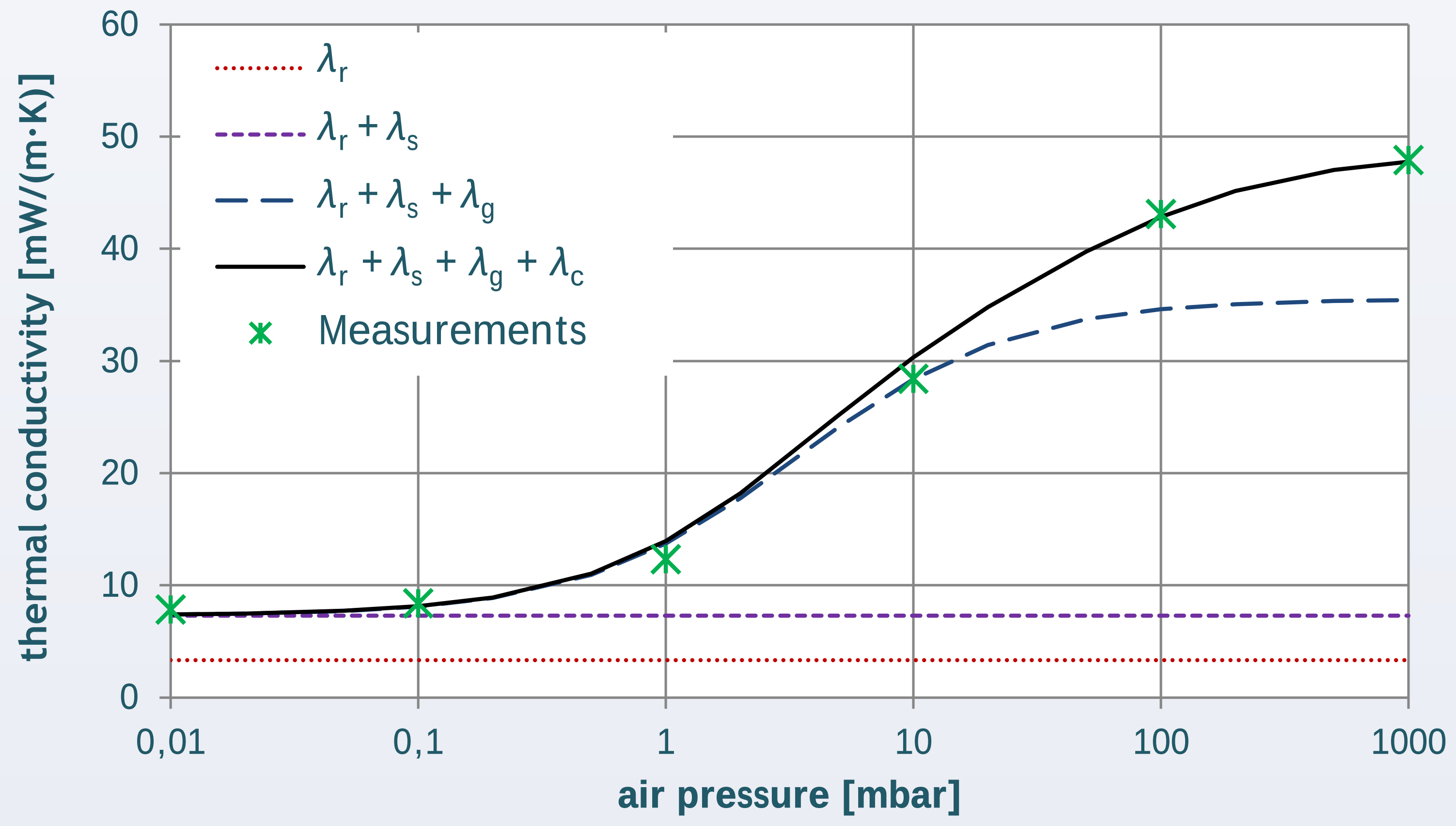

Fig. 2 *Results of measurements and calculations for cep at 50 °C. Measurements by DEMHARTER in parallel plate setup*

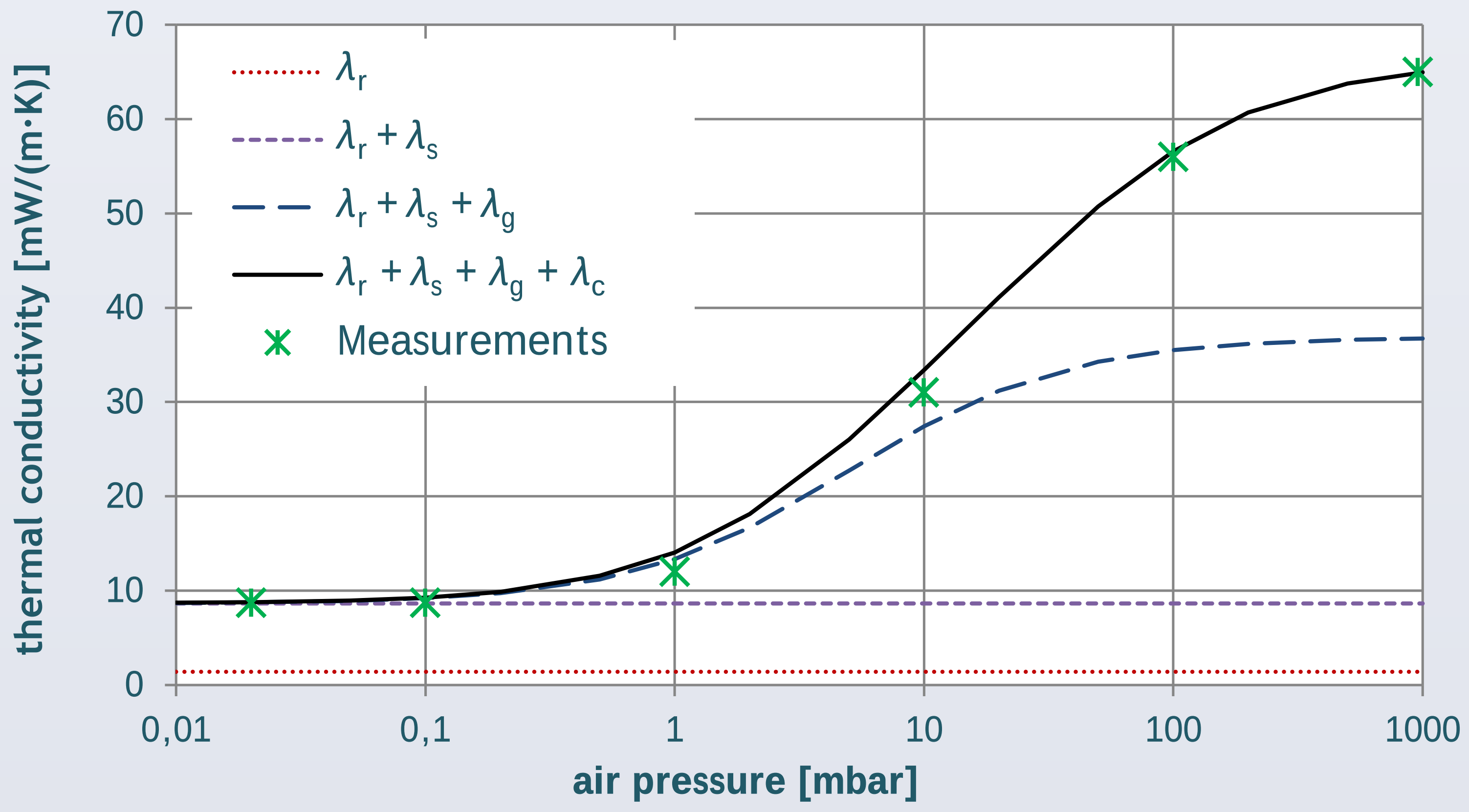

Fig. 3 *Results of measurements and calculations for fep at 48 °C. Measurements by the corresponding author in a guarded cylinder apparatus.*

CONCLUSIONS

The selected models suitably quantify the heat transfer mechanisms in free-flowing vacuum thermal insulation materials (see Figures 2 and 3). 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.

SYMBOLS

Symbol	Description
d	Mean pore diameter [m]
E	Modulus of elasticity [Pa]
$e_{ex,mass}$	Mass-specific extinction coefficient [m²/kg]
k_B	Boltzmann constant [J/K]
$\bar{n}$	Refractive Index [-]
$p_{1/2,air}$	Half-value pressure of the thermal conductivity of air in pores [Pa]
$p_{1/2,c}$	Half-value pressure of the coupling effect [Pa]
p_{air}	Absolute air pressure [Pa]
p_{ext}	External pressure [Pa]
T	Temperature [K]
T_r	Reduced Temperature [K]

Symbol	Description
α_k	Accomodation coefficient [-]
β	Gas-dependent factor [-]
Γ	Weighting factor for the contributions of the coupling effect [-]
κ	Adiabatic exponent [-]
λ_{air}	Thermal conductivity of still air [W/(m·K)]
$\lambda_{s,0}$	Thermal conductivity of the solid [W/(m·K)]
ν	Poisson's ratio [-]
$\prod$	Modified porosity which only includes pores [-]
ρ	Densitiy [kg/m³]
σ	Stefan-Boltzmann constant [W/(m²·K⁴)]
σ_0	Collision cross section [m²]
ψ	Porosity [-]

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