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**SEMI-EMPIRICAL MODEL OF HEAT TRANSFER IN DRY
MINERAL FIBER INSULATIONS**

by M. Bomberg and S. Klarsfeld

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RÉSUMÉ

Un modèle semi-empirique pour calculer les transferts de chaleur dans les isolants en fibres minérales sèches prend en compte les paramètres qui caractérisent à la fois la structure du matériau en fibres et les conditions limites d'un essai normalisé en laboratoire. Ce modèle permet d'ajuster les données expérimentales en fonction des variations de densité ou d'épaisseur des échantillons, ou de température moyenne ou encore du gradient de température ; c'est-à-dire de toutes les incertitudes qui existent dans l'échantillonnage et les méthodes d'essai.

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Semi-Empirical Model of Heat Transfer in Dry Mineral Fiber Insulations

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ABSTRACT

A semi-empirical model for calculating heat transfer in dry mineral fiber insulations takes into account parameters that characterize both the structure of the fibrous material and the boundary conditions in standard laboratory testing. It permits adjustment of experimental data for changes in specimen density or thickness, mean temperature or temperature gradient, i.e., all the uncertainties involved in sampling and testing procedures.

KEYWORDS

Glass fiber, heat flow model, heat transfer, mineral fiber insulation, thermal conductivity, thermal insulation, thermal resistance, thermal testing.

INTRODUCTION

Recent advances in the manufacture of mineral fibre insulations (MFI) has increased the market for low density insulation in which a significant amount of heat is transferred by radiation. As radiative heat transfer is not linearly dependent on specimen thickness, different values of apparent thermal conductivity can be obtained for thick or thin specimens.

It is desirable to predict the value of the thermal resistance of a sample

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of any thickness from the data obtained from tests on only one or two thicknesses rather than measure R for all thicknesses of interest. This also holds for the effect of sample density and mean temperature. This paper presents a semi-empirical relation that permits such predictions for MFI.

The apparent (measured) thermal conductivity of a material is influenced by three basic heat transfer mechanisms—conduction, convection and radiation—that contribute in varying proportions, often depending on the test conditions. Figure 1 shows two photomicrographs of glass fiber insulation with various densities. The material consists of a solid phase (fibers) and a gaseous continuous phase. Although heat transfer through the gas will be defined by temperature and the state of motion, knowledge of the physical properties of the material constituting the solid matrix is not enough to permit prediction of the rate of heat transfer through it. Perhaps the first question that must be asked is how to define the structure of the material.

Experience indicates that the three main features of the solid phase are: volume ratio of the solid phase to the total volume, degree of fragmentation in the solid phase, and spatial organization of the solid phase. To characterize these aspects, the following material properties may be used [1]:

1) porosity, ϵ , dimensionless

$$\epsilon = \frac{V_g}{V} = 1 - \frac{\rho}{\rho_s}$$

where

V_g = volume of gas phase (usually air)

Figure 1. Glass fiber insulation: (a) density about 10 kg/m^3 (b) density about 140 kg/m^3 .

V = total volume of fibrous specimen

ρ_s = density of solid phase

ρ = density of fibrous specimen

2) specific area, S_v , m^2/m^3 or m^{-1} (or fineness)

$$S_v = \frac{S}{V}$$

where S is the area of the gas solid interface

3) anisotropy factor, K_v/K_H , dimensionless

where K_v , K_H = air permeability (as defined by Darcy's law) in the direction perpendicular (V) and parallel (H) to the material stratification plane. The directional thermal conductivities, λ_v and λ_H , may also be used to determine the anisotropy factor.

Figure 2 shows the dependence of thermal conductivity on porosity (or density) and the fineness index* for a given mean temperature and anisotropy factor [2]. Figure 3 illustrates the effect of fiber orientation, showing thermal conductivity, λ_v perpendicular, and λ_H parallel, to the

Figure 2. Thermal conductivity at 297 K as a function of density and fineness index (From Fournier and Klarsfeld [2]). Copyright, ASTM, 1916 Race Street, Philadelphia, PA 19103. Reprinted with permission.

*The fineness index, F , is defined by a specified air permeability measurement on a randomly compacted mineral fiber specimen with a given mass [2].

Figure 3. Thermal conductivity as a function of density and orientation, λ_H = parallel, λ_V = perpendicular, to the stratification planes. (From Klarsfeld [1]) Copyright, ASTM, 1916 Race Street, Philadelphia, PA 19103. Reprinted with permission.

planes of fiber stratification. The three characteristics describe the structure of fibrous material in a unique way, but they do not provide, by themselves, a sufficient basis for predicting the thermal conductivity of the fibrous insulation. The use of semi-empirical models that take into consideration structure and physical characteristics is a more efficient means of predicting thermal performance of mineral fiber insulations.

SEPARATION OF MECHANISMS OF HEAT TRANSFER IN MFI

As discussed in Appendix A, convective heat transfer may be neglected for most MFI materials or at near ambient temperature. If interactions among the different modes of heat transfer can be neglected or incorporated under one of the modes, the total heat flux becomes

$$q = q_g + q_s + q_r \quad (1)$$

Under these conditions, one may add the components due to conduction in gas, λ_g , and solids, λ_s , as well as that due to radiation, λ_r , to obtain the net conductivity, λ_{app} , i.e.,

$$\lambda_{app} = \lambda_g + \lambda_s + \lambda_r \quad (2)$$

Figure 4, from Bankvall [3], illustrates the use of this hypothesis for the

Figure 4. Heat transfer mechanism in a glass fiber insulation ($T = 20^{\circ}\text{C}$, $\Phi = 5 \mu\text{m}$) (From Bankvall [3]). Copyright, ASTM, 1916 Race Street, Philadelphia, PA 19103. Reprinted with permission.

analysis of contributions from radiation, and conduction through the gaseous and solid phases. In principle, the contribution of each of the mechanisms of heat transfer is similar to that shown by Verschoor and Greebler [4], except that natural convection does not appear in most cases. Bankvall [3] introduced three structural parameters, ϵ_s , ϵ_p and α , in addition to total porosity, ϵ . These structural parameters define the organization of the solid. Their relation is shown in Figure 5, which illustrates that α denotes the part of the material considered to be "parallel" to the heat flow lines and $1-\alpha$ the part considered to be "in series" with respect to heat flow. ϵ_s and ϵ_p denote volume fraction (porosity), corresponding to the series and parallel heat transfer, respectively. Total porosity can be expressed as follows:

$$\epsilon = (1-\alpha) \epsilon_s + \alpha \epsilon_p$$

The three structural parameters together with the thermal conductivity of the solid matrix, λ_s , and that of the gas, λ_g , allow Bankvall [3] to describe solid and gas contributions of thermal conductivity as follows:

$$\lambda_{app} - \lambda_r = \alpha(1-\epsilon_p)\lambda_s + \alpha\epsilon_p \cdot \lambda_g + (1-\alpha) \cdot \frac{\lambda_s \cdot \lambda_g}{\epsilon_s\lambda_s + (1-\epsilon_s)\lambda_g} \quad (3)$$

Figure 5. Structural parameters in Bankvall's model [3] shown for one unit of volume (From Bankvall [3]).

Table 1 shows the significance of each of the three components in equation 3, based on Bankvall's structural coefficients [3]. The last column relates to another model in which solid and gas fractions of thermal conductivity are described by two components only: gas conductivity and the solid plus interactive component. This model will be described by equation 6 where $A = \lambda_g$ and $B = (\lambda_s + \lambda_{sg})/\rho$. Bankvall's data (Table 1) indicate that the parameter B is approximately constant and independent of density.

In experiments on separation of heat transfer mechanisms in low-density fibrous insulation Pelanne [5] assumed that the following terms may be treated as additive components of the apparent thermal conductivity:

λ_g = gas conductivity

λ_c = contribution of gas convection

Table 1. Significance of heat transport contributions calculated from Bankvall's data [3].

ρ Density kg/m ³	λ_s Solid Phase	λ_g Gas Phase	λ_{sg} Serial Solid/gas	Contributions, percent
				$B' = \frac{\lambda_s + \lambda_{sg}}{\lambda_g \rho}$ % m ³ /kg
16.4	0	96	4	24
31.4	0	94	6	19
40.2	0.3	91.4	8.3	21
78.6	6.4	82.4	11.2	22

λ_s = solid gas conduction

λ_{rc} = radiation absorption and re-emission of the fibers

λ_r = radiation transmission (i.e., radiation transmitted by scattering)

λ_i = interaction of different mechanisms

Using plates with different emittances ($\epsilon = 0.95$ and $\epsilon = 0.08$) in a vacuum and in air, Pelanne [5] separated the contributions of radiation, solid, and air. Other than λ_s , the term λ_r is the most significant at densities lower than 30 kg/m^3 , whereas λ_{rc} and λ_s appear to be almost constant and of a magnitude comparable to that of λ_i .

This research by Pelanne [5], as well as previous work, was carried out on one specimen thickness and did not permit extrapolation to other thicknesses. Hollingsworth [6], however, undertook an experimental determination of the thickness effect using a specially constructed large-scale apparatus. The experimental data were examined by Bhattacharyya [7], who used the following equation for the radiative part of thermal conductivity:

$$\lambda_r = \frac{4 \sigma T_M (T_M^2 + T_D^2)}{\rho N' + \left(\frac{1}{\epsilon_H} + \frac{1}{\epsilon_C} - 1 \right) \frac{1}{L}} \quad (4)$$

where

$$T_M = \frac{1}{2} (T_H + T_C)$$

$$T_D = \frac{1}{2} (T_H - T_C)$$

ϵ_H, ϵ_C = hot and cold plate emissivity

N' = specific scattering coefficient, m^2/kg

σ = Stefan-Boltzmann constant, $5.67 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$

L = specimen thickness, m

ρ = material density, kg/m^3

$N = \rho N'$, called a scattering coefficient, m^2/m^3 .

Equation 4 is based on the two-flux model introduced by Schuster and developed by Hamaker (see Timmermans et.al. [8]). This equation was also used by Larkin [9] and Churchill [10] in studies of radiation through fibrous and foamed insulating materials. The model takes into consideration two optical parameters of the material: scattering, N , and absorption, P , coefficients. Equation 4, based on complete scattering, $P = 0$, shows that when radiation plays a significant role in heat transfer, apparent (measured) thermal conductivity depends not only on material parameters but also on the conditions of the test, T_H , T_C , ϵ_H , ϵ_C , and specimen thickness, L .

Studies by Poltz [11], Jones [12], Lao and Skochdopole [13], Rennex [14], and Shirliffe [15], Fine et.al. [16] discussed thermal resistance at a given mean temperature as a linear function of specimen thickness

$$R = A + B \cdot L \quad (5)$$

The intercept, A , often called R_0 , and the slope, B , sometimes called R_∞ , are also related to the radiative characteristics of the material. References 14 to 16 provide detailed discussion of these characteristic properties.

SEMI-EMPIRICAL MODEL OF HEAT TRANSFER IN MFI

The results of linear regressions for three MFI materials with different surface areas or fineness indices are shown in Figure 6. The regression analysis was performed by Klarsfeld [17] using the following equation:

$$\lambda = A + B\rho + \frac{C}{\rho} \quad (6)$$

The first term represents gas (air) conductivity, $A = \lambda_g$, the second, solid phase conductivity and interaction with gas, and the third, radiative heat transfer conductivity, $\lambda_r = C/\rho$, as given by equation 4.

Figure 6. Linear regression model for TEL glass fiber products ($T = 24^\circ\text{C}$) (From Klarsfeld [17]).

Equation 4 is based on complete scattering, $P = 0$. Such an assumption may overestimate the reduction of thermal conductivity for small thicknesses, i.e., 10 to 25 mm. Another approach, postulated by Fine, et.al. [16], could be more suitable for thin layers of materials with a significant fraction of absorption ($P \neq 0$).

Following this so-called three-region estimate, one may introduce an additional term into equation 4 (compare [18]). The model becomes:

$$\lambda_{app} = \lambda_g + Bq + \frac{\alpha(T_H^2 + T_C^2)(T_H + T_C)}{L_o \left(\frac{1}{\epsilon_H} + \frac{1}{\epsilon_C} - 1 \right) + qN'} + \frac{\alpha(T_H^2 + T_C^2)(T_H + T_C)}{-\frac{1}{L} \left(\frac{1}{\epsilon_H} + \frac{1}{\epsilon_C} - 1 \right) + qN'} \quad (7)$$

B , N' , L_o = parameters determined from thermal conductivity measurements. L_o is defined from the third term of equation 7, a term supplemental to the fourth term that describes only the scattering model.

Figure 6 shows that the B coefficient is practically independent of the fineness index, so that for practical use in low-density glass fiber (LDGF) insulations one may use a constant coefficient $B = 4.0 \times 10^{-5}$. In the temperature range of 250–350 K air conductivity may be assumed to be [19] (see Figure 7):

$$\lambda_g = 0.0240 + 0.000078 (T - 273) \quad (8)$$

Figure 7. Thermal conductivity of air as a function of temperature (NBS [19]) (From Bankvall [3]). Copyright, ASTM, 1916 Race Street, Philadelphia, PA 19103. Reprinted with permission.

Parameters N' and L_0 must be determined from a curve fit of $\lambda = \lambda(L)$ for a given set of boundary conditions.

EXPERIMENTAL VERIFICATION OF MODEL

Pelanne [20] introduced the experimental use of paper septa between layers of low-density glass fibers to separate the effects of thickness and systematic equipment errors in thermal transmission measurements. Placing a radiation barrier n times in a material thickness, L , will modify equation 7. Thickness, L , will now represent the distance between septa, and the number of septa, n , must be introduced in the third term of equation 7. Equation 7 then becomes:

$$\lambda_{app} = \lambda_g + Bq + \frac{\sigma(T_H^2 + T_C^2)(T_H + T_C)}{\left(\frac{1}{\epsilon_H} + \frac{1}{\epsilon_C} - 1\right) \frac{1}{L_0} \sum_{n=1}^n \left(\frac{1}{n+1}\right) + qN'} + \frac{\sigma(T_H^2 + T_C^2)(T_H + T_C)}{\frac{1}{L} \left(\frac{1}{\epsilon_H} + \frac{1}{\epsilon_C} - 1\right) + qN'} \quad (9)$$

where

$\sum_{n=1}^n \frac{1}{n+1}$ = a term assumed to describe the decreasing significance of each added absorptive septum on the total amount of absorption caused by all the septa placed in the specimen.

n = number of septa

L = distance between septa, or in their absence, distance between hot and cold plates.

Table 2 gives the calculated values of λ based on equation 9, with $\epsilon_H = \epsilon_C = 0.95$ and measurements on 8 kg/m^3 LDGF. Although the density of the specimens varied from 7.9 to 8.8 kg/m^3 , some reduction of the effects caused by material variability was achieved by averaging the test results obtained for different specimens. Two tests on three specimens and three tests on two specimens were averaged.

Table 3 compares results measured by Pelanne [20] and calculations obtained with equation 9, where parameters N' and L_0 were experimentally determined. Although calculations shown in Tables 2 and 3 agree relatively well and describe the effects of changes in mean temperature, thickness of the specimen, and density of the specimen Table 4 shows that the thermal conductivity calculated from equation 9 falls far below

Table 2. Thermal conductivity of specimen or stack of specimens, measured and predicted using equation 9. Tests performed at NRC on LDGF specimens with density 7.9 to 8.8 kg/m³ (8.34 mean).

Specimen Numbers (Test Code 364-129)	No. of Septa	Average Thickness m	Temperature T _H and T _C °C	Measured λ_{app} W/mk	Calculated λ_{cal} W/mk
1,2,3,4,5,6	0	0.15246	34.94, 12.91	0.0510	used for N' and L _o determination
1,2,3,4,5,6	5	0.15298	38.90, 13.30	0.0497	
1,2,3 and 4,5,6	0	0.07596	34.80, 13.01	0.0504	
1,2,3,4,5,6	5	0.15298	51.50, 29.90	0.0545	0.0551
1,2 and 3,4, and 5,6	0	0.05008	34.83, 13.37	0.0491	0.0497
1 and 2	0	0.02503	34.85, 13.43	0.0478	0.0479

N' = 28.28 m²/kg
L_o = 0.07 mm

the measured values for surfaces with low emittance. Such an effect may be expected since L_o factors calculated in Tables 2 and 3 were a few times smaller than expected from a knowledge of the extinction length for the materials tested. Thus equation 9 is limited to use for emittance close to that of a black body. It is not clear whether the N'-value determined from the regression models or the least squares estimate of equation 9 relates to both absorbed and re-emitted radiation, or whether absorption was really negligible for the MFI tested.

CONCLUSION

Although equation 9 cannot be used to distinguish between the two components of the radiative heat transport, it appears to be a useful means of predicting thermal conductivity, taking into consideration parameters characterizing the fibrous material and boundary conditions

Table 3. Thermal conductivity for specimen stack with and without paper septa, measured by Pelanne [20] and predicted by equation 9, (T_H = 37.8°C, T_C = 10.0°C, $\epsilon_H = \epsilon_C = 0.95$).

Specimen Density Kg/m ³	Thickness m	Number of Paper Septa	Measured λ_{app} W/mK	Calculated λ_{cal} W/mK
3.6	0.0508	0	0.0698	N' = 33.50 m ² /kg L _o = 0.034 mm
3.6	0.0508	1	0.0620	
3.6	0.0754	0	0.0613	
4.8	0.0508	0	0.0589	0.0590
4.8	0.0508	1	0.0554	0.0556
4.8	0.0254	0	0.0547	0.0555

Table 4. Thermal conductivity, W/mK, measured with golden or black GHP surfaces and calculated by means of equation 9. MF Insulation A from Pelanne [5], ($L = 25.4$ mm, $T_m = 23.9^\circ\text{C}$).

Density kg/m ³	$\epsilon = 0.95$		$\epsilon = 0.08$	
	Measured	Calculated	Measured	Calculated
16.8	0.0392	0.0390	0.0379	0.0308
24.7	0.0355	0.0356	0.0352	0.0306
45.5	0.0324	0.0327	0.0322	0.0304

$N = 27.19$ m²/kg
 $L_0 = 0.08$ mm

in standard guarded hot plate or heat flow meter test methods. It permits one to adjust the experimental data to obtain values that would be appropriate for selected conditions of specimen density or thickness as well as for various mean temperatures, i.e., all the uncertainties involved in sampling and testing procedures.

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APPENDIX A. NATURAL CONVECTION

Heat transfer from a solid body through an adjacent layer of fluid can be increased if the fluid moves with respect to the solid material. The phenomenon is usually called heat convection. Figure A-1, a and b, from Cambarnous and Bories [21], shows characteristic structures of convective movements in horizontal and inclined layers of fibrous and porous materials. Heat transfer by convective fluid movement can be predicted with the help of relations utilizing dimensionless numbers. These numbers contain the physical parameters that describe the phenomenon in various stages of evolution.

Dimensionless numbers associated with heat convection in fibrous media are as follows:

1) Rayleigh filtration number, Ra^* :

$$Ra^* = g \frac{\beta(\varrho c)_f}{\nu} \cdot \frac{4K_v K_H}{[(\lambda_H * K_v)^{1/2} + (\lambda_v * K_H)^{1/2}]^2} \cdot \Delta T \cdot d$$

where

$g \frac{\beta(\varrho c)_f}{\nu} = f(T_m)$, are the properties of the interstitial fluid at a given temperature, namely,

g = acceleration due to gravity, m/s^2 ,

β = volumetric expansion coefficient of fluid, K^{-1} ,

ν = kinematic viscosity of fluid, m^2/s ,

$(\varrho c)_f$ = heat capacity of fluid, $J/m^3 K$,

$\frac{4K_v K_H}{[(\lambda_H * K_v)^{1/2} + (\lambda_v * K_H)^{1/2}]^2}$ ratio characterizing the fibrous medium, anisotropic in thermal conductivity and permeability.

K_v, K_H = vertical and horizontal permeability of the medium, m^2

λ_v^*, λ_H^* = vertical and horizontal thermal conductivity with unmovable interstitial fluid, $W/m.K$

Figure A-1a. Structure of convective movements in layers of horizontal porous materials (From Combarnous and Bories [21]).

Figure A-1b. Structure of convective movements in inclined layers of porous materials (From Combarnous and Bories [21]).

ΔT , T_m = temperature difference, mean temperature, K
 d = characteristic distance, e.g., distance between hot and cold plates of the thermal conductivity test apparatus, m

2) Aspect ratio:

$$A = l/d$$

where l = height, d = width of vertical cells,

3) Nusselt filtration number, Nu^* :

$$Nu^* = \frac{\phi}{\phi^*} \text{ or } \frac{\lambda}{\lambda^*}$$

where

ϕ = heat flow rate, including heat transfer caused by convection (ϕ^* = the same but without contribution of convection).

λ , λ^* = thermal conductivity with and without interstitial fluid movement, respectively.

When the Nusselt number is equal to one, heat transfer does not contain any contribution from convection. In the presence of convective movement, ϕ is greater than ϕ^* and the Nusselt number becomes greater than one.

Heat transfers with natural convection in horizontal, vertical, or inclined layers by a general equation of the following type:

$$Nu^* = f(Ra^*, A, \cos \alpha)$$

The relation between Nusselt number and flow conditions is either entirely experimental or semi-empirical. The remarkable fact is, however, that a transition from one type of flow to another always occurs at the same values of dimensionless numbers, independent of the porous medium in which convection takes place. These numbers are called critical numbers. They depend on geometrical configuration, temperature differences, and assumptions made regarding the interstitial gas properties. For example, in a horizontal layer with heat flow upwards, convection will not occur ($Nu = 1$) if

Ra^* is smaller than 40 for small ΔT , or

Ra^* is smaller than $40 - 6 \frac{\Delta T}{T_m}$ for large ΔT (Combarous [22])

Figure A-2. Nusselt number (Nu^*) as a function of Rayleigh number for filtration (Ra^*) in a plane horizontal layer immersed in water. Three types of glass fiber insulations are shown (From Klarsfeld [1]).

In plane, horizontal layers the convective movement starts suddenly at a given threshold level, as shown in Fig. A-2. In other geometrical configurations (vertical, inclined layers) convective movement grows gradually with temperature difference [23] (as shown in Fig. A-3). At first the movement is slow and the heat transfer is pseudo-convective. Later,

Figure A-3. Thermal field associated with convective movements in a vertical cell filled with glass fiber (From Klarsfeld [23]), a: asymptotic conditions; b, c: intermediate conditions; d: separate limit layer conditions.

movement accelerates as a function of mean temperature and temperature difference up to the point at which a change of regime occurs, as described by the transition criteria.

Users of fibrous insulation must determine to what extent the material may exhibit convection in a particular set of use conditions (thermal and geometrical). It is necessary to know the parameters describing the porous medium (solid matrix and interstitial fluid). The following means may be used by a manufacturer to ensure that Ra^* value will not exceed the critical value:

- 1) Material permeability may be reduced by either changes in porosity (density) and/or volumetric surface (fineness).
- 2) Thickness of the layer may be reduced by use of impermeable screens.
- 3) A combination of points 1) and 2) may be achieved when using layered products.

For building applications, both computations and experimental data show that for all currently used types of mineral fiber insulations there is either no convection or an asymptotic or pseudo-convective regime if 1) the insulation fills the space completely and 2) it is enclosed by two air-impermeable surfaces.

Natural convection becomes important in cryogenic applications (low mean temperatures) and for larger temperature differences. It can also be amplified by forced convection if the wall system does not provide proper measures for controlling air movement. These problems are, however, beyond the scope of material manufacturers and must be dealt with at the building design stage (see discussion by Schuyler and Solvason [24]).

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