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General Discussion—Session III

Measurement of the Thermal Resistance of Thick Low-Density Mineral Fiber Insulation

S. Klarsfeld[1] *and M. Hyrien*[1]

In a previous study, made using a new R-meter equipped with a bi-guarded hot plate and a large-size heat flow meter, it was shown that in the case of light fibrous and cellular insulating materials, variations of the apparent thermal conductivity related to specimen thickness have been detected.

This surprising result, which is interesting from a theoretical standpoint and because of its practical consequences, has been previously presented with this reservation:

> The results obtained here with the new instrument require additional corroborations and more precise evaluations of sources of errors.

We will attempt, in this general discussion, to analyze and survey the presently encountered difficulties regarding the accurate quantitative interpretation of the results. These difficulties motivated our initial reservations and are the reason why we feel that any immediate practical utilization of the results would be premature.

Theoretical Bases

The integration of the system of equations which describes the heat transfer by radiation in a porous medium (two-flow model or Hamaker model) limited by two infinite parallel planes

$$\frac{d\phi^+}{dx} = -(N + P)\phi^+ + N\phi^- + P\sigma T^4$$

$$-\frac{d\phi^-}{dx} = -(N + P)\phi^- + N\phi^+ + P\sigma T^4$$

[1] Saint-Gobain Industries, Rantigny, France.

where

$\phi^+(x)$, $\phi^-(x)$ = radiation flow density in the positive and negative direction of the axis of x, $W/m^2 \cdot K$,
N = scattering coefficient,
P = adsorption coefficient,
T = local temperature, K, and
σ = Stefan-Boltzmann constant.

with the boundary conditions defined by

$$x = 0; \qquad \phi^+(0) = \epsilon_0 \sigma T_0^4 + (1 - \epsilon_0)\,\phi^-(0); \qquad T = T_0$$

$$x = L; \qquad \phi^-(L) = \epsilon_L \sigma T_L^4 + (1 - \epsilon_L)\,\phi^-(L); \qquad T = T_L$$

leads to the following expression for the overall radiation flow density, assuming a number of simplifying hypotheses and also assuming that $N \gg P$ (which is the case with light materials)

$$\varphi_r = \phi^+ - \phi = \frac{\sigma(T_L^4 - T_0^4)}{1/\epsilon_0 + 1/\epsilon_L - 1 + \rho NL}$$

According to this equation, if $T_L - T_0 = \Delta T$ is not too great and assuming that $\varphi_r = -\lambda$ grad T, the thermal conductivity by radiation can be expressed as follows

$$\lambda_r = \frac{\sigma(T_L^3 + T_L^2 T_0) + T_L T_0^2 + T_0^3)}{1/L(1/\epsilon_0 + 1/\epsilon_L - 1) + \rho N} \tag{1}$$

where

T_0, T_L, $\epsilon_0(T_0)$, $\epsilon_L(T_L)$ = temperatures and emissivities of the faces at these temperatures and
L, ρ, N = thickness, bulk density, and scattering cross section (optical property of the porous medium), m^2/kg.

Discussion of the Theoretical Results

The Hamaker model (Eq 1) shows that in the case of radiation transfer ($\lambda_r \neq 0$) "apparent" thermal conductivity ($\lambda_a = \lambda_{cd} + \lambda_r$) does not solely depend on the parameters which characterize the material, but also on the experimental measurement conditions, T_0, T_L, E_0, and E_L, as well as on L, that is, specimen thickness.

It follows from the preceding that, in order to make representative laboratory measurements of the *in situ* behavior of an insulating material, simply taking the thickness factor (full thickness samples) into account is not enough; the closest and most representative boundary conditions (temperatures and emissivities) of the practical case, that is, the conditions encountered in the thermal insulation of the building sections, must be taken into account as well.

At the present time, a direct quantitative comparison of the theoretical computations with the experimental results involves difficult measurement problems. The equipment (scattering light spectrophotometer) required for the determination of the optical constants of the material is not available on the market; moreover, it is difficult to build an equipment of this kind which achieves satisfactory performance. The fact that it is not possible to make this comparison poses a problem as regards the analysis of experimental results.

Lateral Radiation Leakages

In the Hamaker model, the porous medium is considered as being limited by two infinite parallel planes. Can the plates we use really be considered as infinite planes?

In the absencc of scattering causcd by a porous medium, the cxchange by radiation occurs in accordance with the following equation

$$\varphi_r = \frac{\sigma F_{0L}(T_L{}^4 - T_0{}^4)}{1/\epsilon_0 + 1/\epsilon_L - 1} \tag{2}$$

where $F_{0L} = f(L/D)$ is the shape factor as a function of the ratio of the distance L between the two surfaces to the length D of the plates.

The shape factor, present in the expression of φ_r, simply expresses the interaction between the two planes on the one hand and the environment on the other hand; it therefore represents a lateral radiation leak. This leak is practically nil if $F_{0L} \approx 1$. Such a modified shape factor must also be taken into account in the case where semitransparent porous media are present between the two plates of the meter. It must also be ascertained that its value is close to 1 when $0 < L < L_{MAX}$. Should this not be so, $F_{0L} < 1$ and λ_r, calculated for $F_{0L} = 1$ would be overestimated in relation to the λ_r of the model.

Other Possible Sources of Error

We should be wary of factors ascribable to other causes, such as measurement errors, which might affect the measurement results (theoretically derived with the Hamaker model) in the same manner as the "thickness radiation effect."

We shall simply try to enumerate these factors and to get a feel for their magnitude based on experimental work to the extent that it can be done.

Lateral Thermal Leakages

When making λ measurements on thick insulating materials, the equipment has to operate with considerable distances between the plates; this increases the risk of lateral leakages, hence that of measurement errors. Moreover, when operating with the same temperature difference between the plates, the flow decreases by a factor of 2 or 3 as compared to the flow measured with a 50.8-mm-thick (2 in.) specimen. This further decreases measurement accuracy.

Conclusion

The interpretation of our λ (L) results raised a number of difficulties:

1. At this stage, the impossibility of comparing the theoretical computations (model) with the experimental results.

2. Identifying, more rigorously than currently undertaken using the tables in the current ASTM Tests for Steady-State Thermal Transmission Properties by Means of the Guarded Hot Plate (C 177-76) and Heat Flow Meter (C 518-76), possible measurement errors due to lateral leakages resulting from the considerable distance between the plates. To cope with this, the leakage problem requires a more thorough analysis. In the case of fibrous insulation, thermal conductivity measurements must take into account the anisotropy of the material, which provides different thermal conductivity values for different directions of heat flow ($\lambda // > \lambda \perp$).

3. If the theoretical predictions are correct, the measurement results do not derive solely from the thermal and optical characteristics of the insulating material, but are also influenced by the conditions under which the apparatus is operated. All the conditions of operation must be reexamined and standardized to insure measurement result uniformity. In particular, this applies to T_0 and T_L, which are arbitrarily chosen and are not the conditions of use of insulating materials in practice. A considerable dispersion in measurement results will be encountered if this is not done.

In conclusion, any practical utilization of the present $\lambda(L)$ curves—which, by the way, differ considerably from one laboratory to another—appears to be both difficult and premature. It is essential that we proceed with our work in this direction in order to more accurately quantify the effect of thickness on thermal conductivity, assuming this effect is confirmed.

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