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# OPTIMISATION OF MULTILAYER INSULATION - AN ENGINEERING APPROACH

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**Abstract**

A mathematical model has been developed to describe the heat flux through multilayer insulation (MLI). The total heat flux between the layers is the result of three distinct heat transfer modes: radiation, residual gas conduction and solid spacer conduction. The model describes the MLI behaviour considering a layer-to-layer approach and is based on an electrical analogy, in which the three heat transfer modes are treated as parallel thermal impedances. The values of each of the transfer mode vary from layer to layer, although the total heat flux remains constant across the whole MLI blanket. The model enables the optimisation of the insulation with regard to different MLI parameters, such as residual gas pressure, number of layers and boundary temperatures. The model has been tested with experimental measurements carried out at CERN and the results revealed to be in a good agreement, especially for insulation vacuum between $10^{-5}$ Pa and $10^{-3}$ Pa.

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**OPTIMISATION OF MULTILAYER INSULATION – AN ENGINEERING APPROACH**

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## ABSTRACT

A mathematical model has been developed to describe the heat flux through multilayer insulation (MLI). The total heat flux between the layers is the result of three distinct heat transfer modes: radiation, residual gas conduction and solid spacer conduction. The model describes the MLI behaviour considering a layer-to-layer approach and is based on an electrical analogy, in which the three heat transfer modes are treated as parallel thermal impedances. The values of each of the transfer mode vary from layer to layer, although the total heat flux remains constant across the whole MLI blanket. The model enables the optimisation of the insulation with regard to different MLI parameters, such as residual gas pressure, number of layers and boundary temperatures. The model has been tested with experimental measurements carried out at CERN and the results revealed to be in a good agreement, especially for insulation vacuum between $10^{-5}$ Pa and $10^{-3}$ Pa.

## 1. MULTILAYER INSULATION THERMAL MODEL

### 1.1. Model structure, basic equations, input and output parameters

The thermal network of multilayer insulation showing the different heat transfer modes is shown in Figure 1. Exemplary boundary temperatures are 4 K and 80 K.

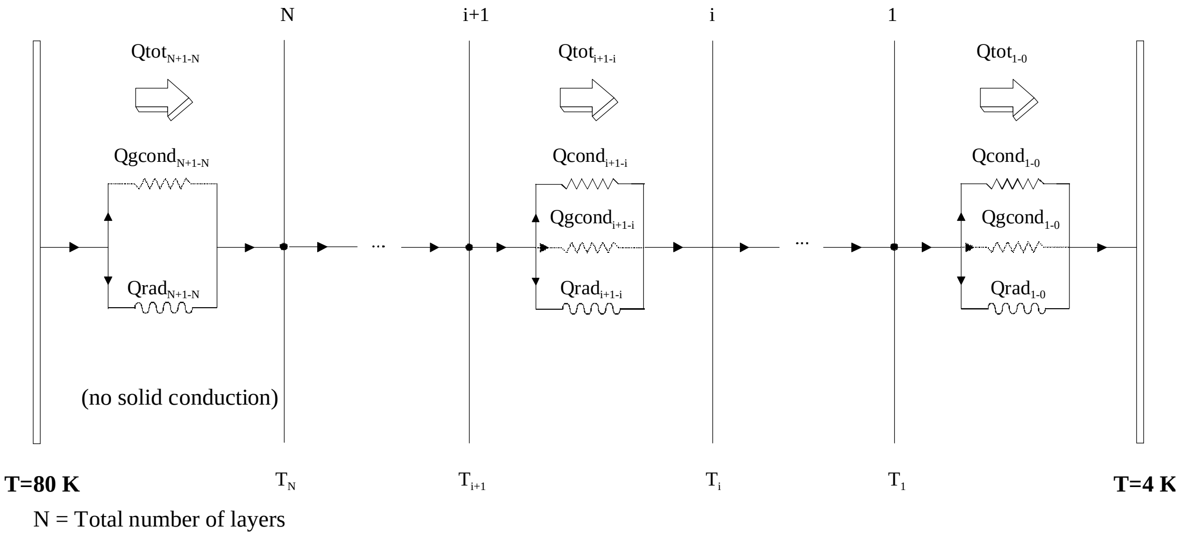



Figure 1. Thermal network of multilayer insulation.

Radiative heat transfer (*Qrad*), solid conduction (*Qcond*) and residual gas conduction (*Qgcond*) can be calculated from equations (1 –3):

$$Qrad_{i+1\to i} = \sigma \cdot A_i \cdot F(\varepsilon_{i+1}, \varepsilon_i, A_{i+1}, A_i) \cdot \left(T_{i+1}{}^4 - T_i{}^4\right) \tag{1}$$

$$Qcond_{i+1\to i} = \frac{k_s}{t} \cdot \left(T_{i+1} - T_i\right) \tag{2}$$

$$Qgcond_{i+1\to i} = A_i \cdot \alpha \cdot \left(\frac{\gamma+1}{\gamma-1}\right) \cdot \left(\frac{\mathrm{R}}{8\cdot\pi}\right)^{0.5} \cdot \frac{P}{(\mathrm{M}\cdot T)^{0.5}} \cdot \left(T_{i+1} - T_i\right) \tag{3}$$

where: $A$ is the lateral area of the foil, $\sigma$ is the Boltzmann's constant, $F$ is the view factor and emissivity $\varepsilon$ is equal to 0.0035 $(T)^{0.5}$ , $t$ represents the spacer thickness and $k_s$ is the effective spacer thermal conductivity, $\alpha$ stands for the accomodation factor, R is the gas constant, M is the molecular weight, $T$ is the temperature and $P$ is the residual gas pressure.

In a steady-state condition the total heat transfer (*Qtot*) from layer to layer remains constant and a set of (i+1) equations can be written (compare Figure 1):

$$Qtot_{i+1\to i} = Qrad_{i+1\to i} + Qcond_{i+1\to i} + Qgcond_{i+1\to i} \tag{4}$$

The model has been written in C++ code, the input and output values are given in Table 1.

Table 1. Input and output parameters to C++ model.

| Input parameter | Output parameter |
|---|---|
| Inner shield temperature, K | Temperature of each foil layer, K |
| Outer shield temperature, K | Radiative heat flux between the adjacent layers, $mW/m^2$ |
| Inner shield diameter, m | Conductive heat flux between the adjacent layers, $mW/m^2$ |
| Outer shield diameter, m | Residual gas heat flux between the adjacent layers, $mW/m^2$ |
| Number of layers, - | Total heat flux, $mW/m^2$ |
| Foil emissivity, - | |
| Spacer conductivity, W/mK | |
| Residual gas pressure, Pa | |

### 1.2. Experimental verification of the model

A dedicated experiment has been carried out at CERN to verify the model forecasts (Chorowski *et al*. (2000)). The experimental and calculated results are presented in Figure 2, where the heat flux is given as a function of residual gas pressure. The MLI sample was composed of a 10-foil blanket of double aluminised Mylar (DAM) plus 10 spacers of the conductivity described by equation 5. The boundary temperatures were 4 and 80 K.

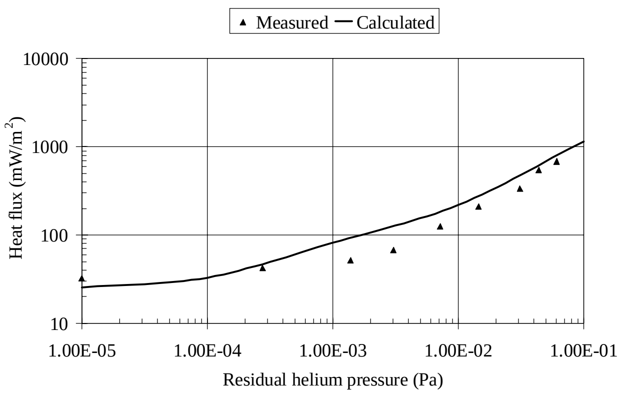
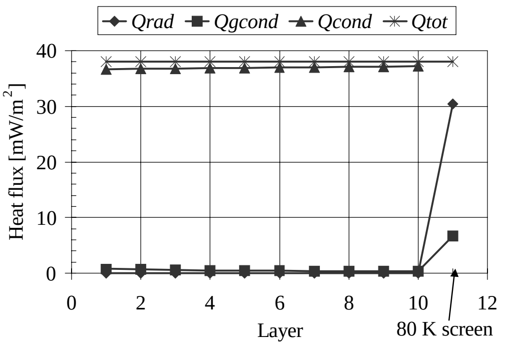


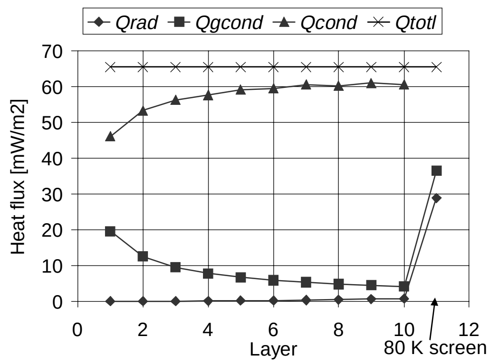

Figure 2. Exp. and calculated heat fluxes.

$$k_s = 4.5 \cdot \sqrt{T/10} \cdot 10^{-6} \tag{5}$$

## 2. OPTIMISATION OF MULTILAYER INSULATION

The influence of different parameters such as number of layers, residual gas pressure and boundary temperatures, on the heat flux through MLI, has been investigated. At low residual gas pressure (below$10^{-4}$ Pa) the heat transfer by gas conduction is negligible and a radiative heat transfer mode dominates. For a pressure above $10^{-4}$ Pa, residual gas conduction represents higher contribution and the total heat transfer through MLI increases significantly - see Figure 3.

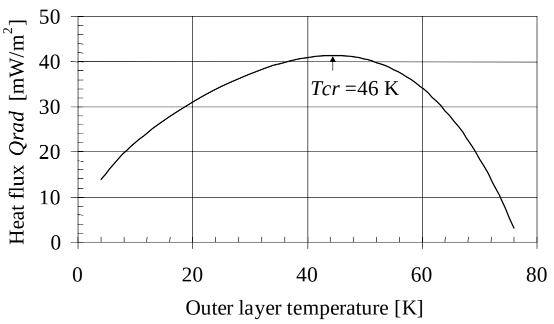


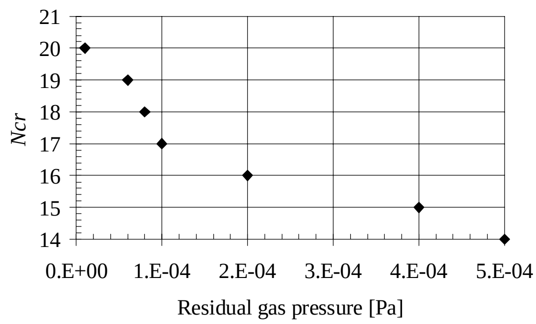




a) b)

Figure 3. Layer-to-layer heat transfer for residual gas pressure $10^{-4}$ Pa (a) and $10^{-3}$ Pa (b).

As the MLI foil emissivity changes with a square root of the temperature $T$ and the radiation from the 80 K shield to the outer MLI layer is proportional to ($80^4$-$T^4$) , the heat flux *Qrad* reaches its maximum for the outer layer temperature of $T_{cr}$ value - see figure 4a. Imposing the temperature value of $T_{cr}$ to the MLI outer layer, the corresponding critical number of layers *Ncr* as a function of residual gas pressure has been calculated - figure 4b.

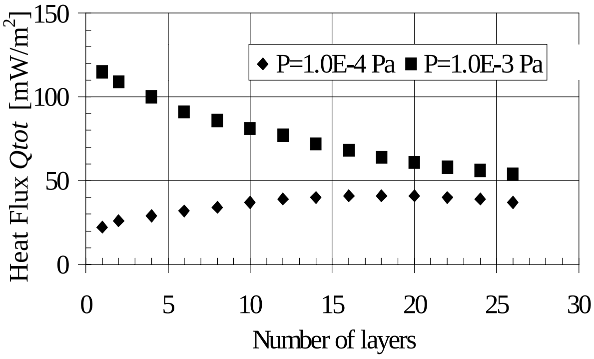


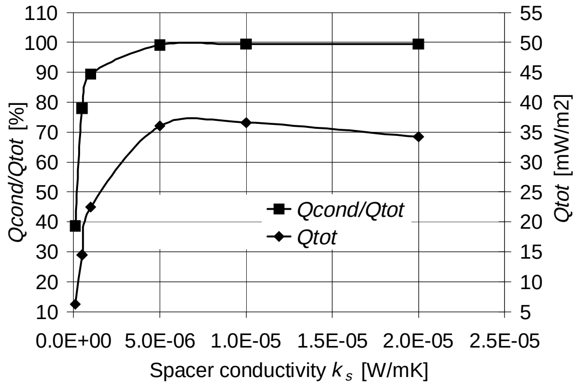




a) b)

Figure 4. Radiative heat transfer versus outer layer temperature (a) and influence of residual gas pressure on critical number of layers (b), boundary temperatures 4 K and 80 K.

Heat transfer variation as a function of a number of layers is shown in figure 5. For a residual gas pressure of $10^{-4}$ Pa, total heat flux reaches its maximum for a number of layers equal to 17, when the outer layer radiates the maximal *Qrad* – see figure 4a . For a residual gas pressure of $10^{-3}$ Pa, the relation is monotonous and an increase in a number of layers is always accompanied by the reduction of a total heat flux. Figure 6 shows the dependence of *Qtot* on the spacer conductivity. When the conductivity is of about 5♥$10^{-6}$ [W/mK], *Qcond* dominates and is practically equal to *Qtot*. Further increase of the conductivity leads to a decrease of *Qtot*, what can be explained by the fact that a temperature of the outer layer exceeds then the critical value $T_{cr}$ –compare figure 4a.




N=10, P=$10^{-4}$ Pa

Figure 5. Influence of number of layers on the total heat transfer *Qtot*.

Figure 6. Influence of spacer conductivity on the total heat transfer *Qtot*.

**2.1. Optimisation procedure**

The MLI optimisation enables to define a proper number of layers to minimise the total heat flux for a nominal residual gas pressure and to maintain a restricted heat flux in case of insulation vacuum degradation.

First it is necessary to specify the boundary temperatures for MLI. Then a nominal residual gas pressure level and spacer effective conductivity should be determined. For standard spacer materials, the value of effective heat conductivity varies from $1 \cdot 10^{-8}$ to $1 \cdot 10^{-3}$ W/m·K and it is a function of temperature – see eq. 5.

Further a temperature of an outer layer corresponding to maximum radiative heat flux *Qrad* should be calculated and the critical number of layers determined.

Now two strategies are possible. If the probability of insulation vacuum degradation is very low, a number of layers should be decreased by the factor of about 2. If the vacuum degradation is probable, a number of layers should be increased, to keep the heat flux low also for the increased residual gas pressure – compare figure 5.

## CONCLUSIONS

A layer-to-layer model has been developed and revealed to be in a good agreement with experimental results obtained with a dedicated test facility built at CERN. The model enables to vary different parameters and investigate their influence on the MLI thermal performance. For residual gas pressures below $5 \cdot 10^{-4}$ Pa, it is possible to define a number of layers which gives the highest value of radiation between the 80 K shield and the MLI outer layer. The optimal number of layers can be determined, taking into account the probability of the insulation vacuum degradation.

## REFERENCES


1. Chorowski M., Grzegory P., Parente C., Riddone G., Experimental and Mathematical Analysis of Multilayer Insulation below 80 K, paper presented at 18. ICEC (2000), Bombay, India.