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Effect of spacers on the thermal performance of an annular multi-layer insulation

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HIGHLIGHTS

- The multi-layer insulation of cylinder consists of foils separated by particles.
- The particles are widely spaced in gaps.
- Particles heat transfer rate is almost half of the total in vacuum.
- At higher pressures the particles contribution is negligible.
- The predicted thermal performance agrees with experimental results.

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ABSTRACT

The current study presents a model and is experimentally conducted in a system of 40 stainless steel coaxial foils, of nitrogen gas, entrapped between the foils, and of spacers, which are zirconia, spherical, 50 μm in size particles, widely dispersed in the gaps between the foils. The model, experimentally verified, relates to radiation between the foils, unobstructed by particles, to conduction in the nitrogen gas, and to conduction across the particles. The study was, in particular, aimed to measure the effective thermal conductivity of the particles and to assess its effect upon the array. At vacuum of 0.092 Pa, the effective thermal conductivity of the particles was 2.13×10^{-4} W/m K, while the effective thermal conductivity of the array was 4.74×10^{-4} W/m K. Thus, the low contribution of the particles conduction at vacuum conditions improves the insulation. It reaches 45% of the heat transfer rate. At atmospheric pressure, the effective thermal conductivity of the array reaches 4.5×10^{-2} W/m K. There, the spacers contribution is negligible.

1. Introduction and modeling

The application of multi-layer insulation is found in industries of cryogenics, aircraft, spacecraft, electronics, and in the last decade in nano-technologies. Multi-layer insulation (MLI) has been known as a very effective, compact technique, demonstrating an effective thermal conductivity of about 5×10^{-4} W/m K in vacuum of 0.1 Pa. That related to a gradient of hundreds of degrees, achieved in an insulation of a few millimeters.

The present physical model is aimed to predict the thermal performance of that type of insulation array for an annular geometry, over the entire range of Knudsen regimes. The physical model is based on conduction across spherical particles, conduction in the entrapped gas and radiation between the foils. It assumes that heat is transferred only radially, at steady state. The particles in a gap are widely dispersed volumetrically. All the surfaces have the same emissivity. The foils are coaxial having uniform gaps between them. The gap between adjacent foils is wider than the minimal wave length, inhibiting radiation tunneling. Convective heat transfer is negligible at Rayleigh numbers below 1700. In our study Ra $\sim 5 \times 10^{-5}$.

Gas conduction between two adjacent parallel surfaces has been formulated [1,2] as:

$$q'' = \frac{k_0(T_h - T_c)}{L_c + g_h + g_c} \quad (1)$$

For a small temperature difference between the two surfaces it is assumed that $g = g_c = g_h$, where the temperature jump, g, is defined as:

$$g = \left(\frac{2}{\gamma+1}\frac{\gamma}{Pr}\frac{2-\alpha}{\alpha}\right)\lambda = \beta\lambda \quad (2)$$

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where λ, is the mean free path, of the gas molecules [2] and α is the accommodation coefficient [3]. The Knudsen number is expressed by the ratio $Kn = \lambda/L_c$. It determines the regime in the gap.

Presenting Eq. (1) as a function of Knudsen number yields,

$$q'' = \frac{k_0(T_h - T_c)}{L_c(1 + 2\beta Kn)} \tag{3}$$

Similarly in a coaxial system:

$$q' = \frac{2\pi k_0(T_h - T_c)}{\ln\left(\frac{r_{out}}{r_{in}}\right) + \frac{g_h}{r_{out}} + \frac{g_c}{r_{in}}} \tag{4}$$

By substituting the temperature jump coefficient, g, [1,2] leads to,

$$q'_{g,j} = \frac{q_{g,j}}{L} = \frac{2\pi k_0(T_{2j-2} - T_{2j-1})}{\ln\left(\frac{r_{2j-1}}{r_{2j-2}}\right) + \beta\lambda\left(\frac{1}{r_{2j-1}} + \frac{1}{r_{2j-2}}\right)}, \quad j = 1, 2 \ldots n+1 \tag{5}$$

where j is an index for the surfaces and gaps. For adjacent radiation shields where $r_{2j-1}/r_{2j-2} \approx 1$, as in our case, Eq. (5) converges to:

$$q'_{g,j} = \frac{2\pi k_0(T_{2j-2} - T_{2j-1})}{\ln\left(\frac{r_{2j-1}}{r_{2j-2}}\right)(1 + 2\beta Kn)}, \quad j = 1, 2 \ldots n+1 \tag{6}$$

For $Kn << 1$ this equation converges to the radial form of Fourier equation.

The contact thermal conductivity for a single particle, k_{cell}, is obtained by Hertz formula [4,5] as,

$$k_{cell} = \frac{G_F k_p (1 - \upsilon^2)^{1/3} P_p^{1/3}}{E^{1/3}} \tag{7}$$

The above formulation leads to the effective thermal conductivity of the particles, and their conduction rate per unit length of the array, between any two adjacent shields,

$$q'_{p,j} = \frac{2\pi k_{p,e,j}(T_{2j-2} - T_{2j-1})}{\ln\left(\frac{r_{2j-1}}{r_{2j-2}}\right)}, \quad j = 1, 2 \ldots n+1 \tag{8}$$

Eqs. (7) and (8) have been used in the literature to assess the particles conductivity. However, the mechanical pressure, which may be measured at the enveloping stage, is much smaller after the relaxation stage. Also, G_F, which relates to the contact area, may change at the relaxation stage. Some researchers considered the contribution of particles to be negligible. In the current case a new procedure has been used: the measured, thermal conductivity of the particles was introduced into the model, instead of the computed value. Such procedure, although never used before, improves the model reliability.

The particles and the entrapped gas have no effect on the radiation in the analyzed system [6]. That is certainly not the case with fibrous spacers or densely packed particles. In such cases the entire path of radiation is obstructed. The modeling in those works has used the “two-flux model” [7].

Thus, in our system the radiation rate between shields per unit length is expressed as,

$$q'_{r,j} = \frac{2\pi r_{2j-2}\varepsilon\sigma\left(T_{2j-2}^4 - T_{2j-1}^4\right)}{2 - \varepsilon}, \quad j = 1, 2 \ldots n+1 \tag{9}$$

Radial conduction of heat across any shield layer is calculated for its cylindrical shape as,

$$q'_{sh} = \frac{2\pi k_{sh,m}(T_{2j-1} - T_{2j})}{\ln\left(\frac{r_{2j}}{r_{2j-1}}\right)}, \quad j = 1, 2 \ldots n+1 \tag{10}$$

It equals the sum of the three other mechanisms, Eqs. (6), (8) and (9),

$$q' = q'_{sh,j} = q'_j = q'_{p,j} + q'_{g,j} + q'_{r,j} \tag{11}$$

All the above equations, including the experimental value of the effective thermal conductivity of the particles, yield the heat transfer rate, which if introduced into Eq. (12), leads to the effective thermal conductivity of the array. Eq. (12) is also later used in the measurements calculations.

$$k_e = \frac{q' \ln\left(\frac{r_o}{r_i}\right)}{2\pi(T_{in} - T_{out})} \tag{12}$$

2. Experimental system

The experimental apparatus consisted of a test section, a vacuum system, and sensors for measurements and control as shown in Fig. 1. The outer diameter of the array was 20.3 mm, the inner diameter was 15 mm, the length of the test section was 67 mm, and the overall length, including the thermal guards was 102 mm. A multi-foil array was constructed of stainless steel foils, 0.012 mm thick, spirally wrapped in 40 turns. An external tube, 0.12 mm thick, served as an envelope of the array. Zirconium oxide particles were sprayed on one side of the foil, to serve for separation (50 μm) and mechanical support of the radiation shields. To outgas the adhesive and to reduce the mechanical stress, a thermal treatment at 700 °C was applied.

The upper and lower heaters (Fig. 1) were operated as “thermal guards”. Due to the strict control, the axial gradient was practically eliminated, imposing radial transfer across the array. To reduce errors in temperature measurements, Cr–Al pins were used at the connectors of the test section for the thermocouples wires. The thermocouples were of K type, ungrounded, 304ss cover, and 0.5 mm in external diameter. Eight thermocouples were installed inside the heaters, as shown in Fig. 1. The measured temperature differences between the thermocouples were recorded with a resolution of 0.1 °C. The uncertainty in pressure measurements was up to 10%. The uncertainty in the supplied power was 3%. The emissivity of the shields, measured by a Raytek infra-red thermometer, was $\varepsilon = 0.2$ with an uncertainty of 3%. All those uncertainties were introduced into the model, yielding the uncertainty in the effective thermal conductivity of the array, as tabulated in Table 1.

3. Results and discussion

15 experiments were conducted in nitrogen, at gas pressures from 9.2×10^{-2} Pa up to 1.01×10^{5} Pa as presented in Table 1.

The experiments were performed at steady state with nitrogen as the interstitial gas in the array. All the measurements are summarized in Table 1. The presented overall uncertainty includes also the uncertainty in axial heat transfer rate, which is thermally guarded.

The “shield to shield” numeric code was developed by using the Engineering Equation Solver (EES software) with all the built-in material physical properties. The inputs were type of gas, in-and-out temperatures, pressure, number of foils, width of gap between foils, surface emissivity, and geometrical parameters. The