REDUCING HEAT TRANSFER BETWEEN TWO CONCENTRIC SEMICYLINDERS USING RADIATION SHIELDS WITH TEMPERATURE-DEPENDENT EMISSIVITY

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ABSTRACT

In this paper, a simplifying approach for calculating the radiant energy is achieved using the concept of net radiation heat transfer and provides an easy way for solving a variety of situations. This method has been applied to calculate the net radiation heat transfer between two long concentric semi-cylinders. Then this method used to calculate reduction heat transfer when radiation shields with temperature-dependent emissivity applied between these objects. Moreover, using this method the percentage reduction in heat transfer between two surfaces was calculated. The findings reveal that, one radiation shield with lower emissivity can reduce the net heat transfer even better than two radiation shields with higher emissivity. Moreover, it can be concluded that for silicon carbide radiation shield in the range of assumed temperatures, the emissivity is almost constant.

Keywords: Temperature-dependent emissivity, Radiation shield, Radiant energy, Net radiation method, Concentric semi-cylinders, Grey surface.

1. INTRODUCTION

Heat transfer by radiation is one of the basic modes of heat transfer. This model of heat transfer is not just a theoretical problem, since understanding and predicting the radiant energy becomes crucial in many practical situations. In high-performance insulating materials it is common to suppress conduction and convection heat transfer by evacuating the space between two surfaces. This leaves thermal radiation as the dominant heat loss mode even for low-temperature applications such as insulation in cryogenic storage tanks. On way of reducing radiant heat transfer between two particular surfaces is to use materials which are highly reflective. An alternative method is to use radiation shields between the heat exchange surfaces (Holman, 2009). These shields do not deliver or remove any heat from the overall system; they only place another resistance in the heat-flow path so that the overall heat transfer is retarded. Moreover use of radiation shield is recommended to and allows reproducibility of the patient positioning for daily treatments (Mantri and Bhasin, 2010; Zemnick et al., 2007; Brosky et al., 2000).

Radiation shields constructed from low emissivity (high reflectivity) materials can be used to reduce the net radiation transfer between two surfaces. Note that the emissivity associated with one side (ε<sub>1</sub>) may differ from that associated with the opposite side (ε<sub>2</sub>) of the shield (Incropera et al., 2007). Our objective consists in showing how apparently intractable problems in heat transfer by radiation can be easily solved using the concept of net radiation transfer. This method was used for all three modes of heat transfer by many researchers (Afonso and Castro, 2010; Jamalud-Din et al., 2010; Zueco and Campo, 2006; Zueco et al., 2004). Although this method is simple, but provides a useful tool for visualizing radiation exchange between plates in the enclosure and may be used as the basis for predicting this exchange. Moreover, Micco and Aldao (2003) generalized the method of net transmittance to spherical and cylindrical symmetry. But, they used only one radiation shield between two main surfaces.

We do not claim to be original since the net radiation method can be found in the literature (Howell et al., 2010). A careful assessment of the foregoing literature shows that most studies of radiation shields assume that the surfaces are gray. In reality, the surfaces are finite in extent, the shield emissivities are either functions of temperature or direction. In this work, the general formulation has been investigated to calculate net heat transfer between two gary, long concentric semi-cylinders, which is more challenging compare with our previous studies (Saedodin et al., 2010; Saedodin et al., 2010). Then, reduction heat transfer by one and two diffuse radiation shield calculated. Accordingly, by applying two radiation shields with different materials optimization was done.

2. MATHEMATICAL MODELLING

Consider two long concentric semi-cylinders as shown in Fig. 1. (a).

The space between these two semi-cylinders separated from outer space by plates A<sub>1</sub> and A<sub>2</sub>. We believe that a detailed discussion of this case brings out the thermal characteristics of the system and this case can be used as a storage tank for hot liquids or gases. For the analysis, the following simplifying assumptions were made:

1. Surfaces are diffuse and gray.
2. Space between semi-cylinders is evacuated.
3. Conduction resistance for radiation shield is negligible. Because the thickness of the shield is very small and the fact that the shield is made of highly conductive material, the temperature gradients within the shield along all its three dimensions may be assumed to be negligible. Thus it is appropriate to assume that the shield at any instant of time is at uniform temperature i.e. it behaves as a lumped capacitance system. Indeed, this assumption is commonly used in many studies on radiation heat shields (e.g. Howell et al., 2010).
4. The end effects are negligible.

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5. The temperature of the heat-transfer surfaces are maintained the same in all cases.

6. Since three surfaces $A_1, A_2$, and $A_3$ are assumed to be at the same temperature, the heat flux between surfaces $A_2$ and $A_3$, and $A_1$ and $A_4$ are assumed to be negligible.

7. The two concentric semi-cylinders and all the shields are in radiant balance.

8. The emissivity associated with the inner and outer surfaces of the shield are the same.

The basic concepts related to heat transport by radiation are very well known. For a black surface the emitted thermal radiation leaving a surface, per unit time and unit area, is given by

$$E_b = \sigma T^4$$  \hspace{1cm} (1)

The net radiation heat transfer between inner and outer of the object can be calculated as follows

$$Q_{(net)}\text{ without shield} = \frac{E_{b1} - E_{b2}}{R_{12}} + \frac{2(E_{b1} - E_{b3})}{R_{13}}$$  \hspace{1cm} (2)

when

$$E_{b1} - E_{b2} = \sigma(T_1^4 - T_2^4)$$  \hspace{1cm} (3)

$$E_{b1} - E_{b3} = \sigma(T_1^4 - T_3^4)$$  \hspace{1cm} (4)

Using the above assumptions, the radiation heat transfer equations can be investigated by following procedures: Most real surfaces exhibit a selective emission, in the sense that the emissivity is different for different wavelengths. In general $\varepsilon$ can be a function of the wavelength $\lambda$ and the surface temperature, i.e. $\varepsilon = \varepsilon(\lambda, T)$. A special type of non-black surface, called a grey body, is defined as one for which the emissivity is independent of the wavelength (Modest, 2010). For simplicity we will restrict our study to grey bodies. In addition, we will consider that surfaces are diffuse; therefore the intensity leaving a surface is independent of direction.

Using the net radiation method the total resistance between each two surfaces can be obtained by:

$$R_{12} = \frac{1 - \varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{A_{F_{1-2}}} + \frac{1 - \varepsilon_2}{\varepsilon_2 A_2}$$  \hspace{1cm} (5)

$$R_{13} = \frac{1 - \varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{A_{F_{1-3}}} + \frac{1 - \varepsilon_3}{\varepsilon_3 A_3}$$  \hspace{1cm} (6)

Therefore, the net heat transfer between inner and outer surfaces is:

$$Q_{(net)}\text{ without shield} = \frac{E_{b1} - E_{b2}}{R_{12}} + \frac{2(E_{b1} - E_{b3})}{R_{13}}$$

where

$$E_{b1} - E_{b2} = \sigma(T_1^4 - T_2^4)$$

$$E_{b1} - E_{b3} = \sigma(T_1^4 - T_3^4)$$

By introducing $F_{2-2}$ as cited in Howell et al. (2010) and using reciprocal relations and configuration-factor algebra

$$F_{1-2} = \frac{2}{\pi} \arcsin \left( \frac{r_1}{r_2} \right)$$  \hspace{1cm} (8)

$$F_{1-3} = \frac{1}{2} - \frac{1}{\pi} \arcsin \left( \frac{r_1}{r_2} \right)$$  \hspace{1cm} (9)

the net heat transfer between inner and outer surfaces can be obtained. To have a comparison between the amount of heat transfer with and without radiation shields, it is must to find functions as the amount of heat transfer with one and two radiation shields between inner surface and outer space. As cited before, the shields do not deliver or remove heat from the system. Therefore, the net heat transfer between inner surface and outer space, using one radiation shield, can be found as follows:

$$Q_{(net)\text{ with one shield}} = 2Q_{\text{1-2 with}} + 2Q_{\text{1-1 with}} + Q_{\text{2-2 with}}$$  \hspace{1cm} (10)

When $Q_{\text{1-2 with}}$, $Q_{\text{1-1 with}}$, and $Q_{\text{2-2 with}}$ can be found same as follows:

$$Q_{\text{1-2 with}} = \frac{\sigma(T_1^4 - T_2^4)}{\varepsilon_1 A_1} + \frac{1}{A_{F_{1-2}}} + \frac{1 - \varepsilon_2}{\varepsilon_2 A_2}$$  \hspace{1cm} (11)
Using our solution, we performed sample numerical computations of reduction heat transfer between two long concentric semi-cylinders by applying one and two radiation shields as shown in Fig. 1, based on equations derived on the previous section. Note that all the calculations performed for all three materials in Fig. 2.

Example 1. Consider two concentric semi-cylinders as shown in Fig. 1. (a). As mentioned before, the space between these two semi-cylinder separated from outer space by plates $A_1$ and $A_2$. The inner semi-cylinder has temperature 873.15 K, radius 50 cm and emissivity of 0.28. The outer semi-cylinder has temperature 330 K, radius 100 cm and emissivity of 0.13. Also, plates $A_1$ and $A_2$ have temperature 330 K and emissivity of 0.13. If one shield of 75 cm radius has been applied to reduce heat transfer between inner semi-cylinder and outer space (Fig. 1. (b)), the percentage reduction in heat transfer, temperature and emissivity of the radiation shield can be calculated as follows:

\[
\frac{Q_{\text{net}} \text{ without-shield} - Q_{\text{net}} \text{ with-shield}}{Q_{\text{net}} \text{ without-shield}} \times 100 = 9500.14 - 7941.77 \times 100 = 16.40\%
\]

Similarly for silicon carbide shield:

\[
\frac{Q_{\text{net}} \text{ without-shield} - Q_{\text{net}} \text{ with-shield}}{Q_{\text{net}} \text{ without-shield}} \times 100 = 9500.14 - 8235.30 \times 100 = 13.31\%
\]

Finally for tungsten shield:

\[
\frac{Q_{\text{net}} \text{ without-shield} - Q_{\text{net}} \text{ with-shield}}{Q_{\text{net}} \text{ without-shield}} \times 100 = 9500.14 - 4436.89 \times 100 = 53.29\%
\]

Example 2. Consider the two concentric semi-cylinder of Example 1. If two shields with same materials have been applied at radius 66.67 and 83.33 cm to reduce heat transfer between inner semi-cylinder and outer space (Fig. 1. (c)), the percentage reduction in heat transfer, temperatures and emissivities of the radiation shields can be calculated as follows:

\[
\frac{Q_{\text{net}} \text{ without-shield} - (Q_{\text{net}} \text{ without-shield})}{Q_{\text{net}} \text{ without-shield}} \times 100 = 9500.14 - 6554.31 \times 100 = 31.00\%
\]

Similarly for silicon carbide shield:

\[
\frac{Q_{\text{net}} \text{ without-shield} - (Q_{\text{net}} \text{ without-shield})}{Q_{\text{net}} \text{ without-shield}} \times 100 = 9500.14 - 2971.50 \times 100 = 26.11\%
\]

Finally for tungsten shield:

\[
\frac{Q_{\text{net}} \text{ without-shield} - (Q_{\text{net}} \text{ without-shield})}{Q_{\text{net}} \text{ without-shield}} \times 100 = 9500.14 - 2971.50 \times 100 = 68.72\%
\]

Example 3. Consider the two concentric semi-cylinder of Example 1. If two shields with different materials have been applied at radius 66.67 and 83.33 cm to reduce heat transfer between inner semi-cylinder and outer space (Fig. 1. (c)), the percentage reduction in heat transfer, temperature and emissivity of the radiation shields can be calculated with same procedures as Example 2. The temperatures, emissivities, net heat transfer and percentage reduction in heat transfer in all six possible models are shown in Table 1.

As it can be perceived from Table 1., model No. 5 is the best model for reducing heat transfer between two concentric hemispheres, if we want to use two radiation shields with different materials, it is better to use the shield with lower emissivity closer to the surface with higher temperature.
Table 1. the percentage reduction in heat transfer, temperatures and emissivities of two radiation shields with different materials

<table>
<thead>
<tr>
<th>Model</th>
<th>Shield at radius 66.67 cm</th>
<th>Shield at radius 83.33 cm</th>
<th>Percentage reduction in heat transfer %</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 1.</td>
<td>Aluminum oxide</td>
<td>737.68</td>
<td>0.64</td>
</tr>
<tr>
<td>No. 2.</td>
<td>Aluminum oxide</td>
<td>809.02</td>
<td>0.62</td>
</tr>
<tr>
<td>No. 3.</td>
<td>Silicon carbide</td>
<td>744.55</td>
<td>0.88</td>
</tr>
<tr>
<td>No. 4.</td>
<td>Silicon carbide</td>
<td>812.02</td>
<td>0.88</td>
</tr>
<tr>
<td>No. 5.</td>
<td>Tungsten</td>
<td>710.59</td>
<td>0.06</td>
</tr>
<tr>
<td>No. 6.</td>
<td>Tungsten</td>
<td>709.51</td>
<td>0.06</td>
</tr>
</tbody>
</table>

3. CONCLUSIONS

In this paper an equation for calculating heat transfer between two concentric semi-cylinder was investigated. Thanks to net radiation method the percentage reduction in heat transfer, temperature and emissivity of the radiation shield were calculated, unlike the previous literature (Micco and Aldao, 2003). It is found that, when two shields with same materials applied for reducing heat transfer, the one with lower emissivity better reduced net heat transfer. Also it was concluded that when two radiation shields with different materials have been applied to reduce heat transfer, the shield with lower emissivity should be closer to the surface with higher temperature to increase reduction in heat transfer.

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NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>A</td>
<td>Surface area (m²)</td>
</tr>
<tr>
<td>$E_b$</td>
<td>Blackbody emissive power (W/m³)</td>
</tr>
<tr>
<td>F</td>
<td>Shape factor</td>
</tr>
<tr>
<td>Q</td>
<td>Net heat transfer (W)</td>
</tr>
<tr>
<td>r</td>
<td>Radius of hemisphere (m)</td>
</tr>
<tr>
<td>T</td>
<td>Absolute temperature (K)</td>
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</table>

Greek Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon$</td>
<td>Emissivity</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Wavelength</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Stefan-Boltzmann constant (W/m²K⁴)</td>
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</table>

Superscripts

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>-</td>
<td>Outer surface</td>
</tr>
<tr>
<td>+</td>
<td>Inner surface</td>
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</table>

REFERENCES


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