World Applied Sciences Journal 11 (4): 457-461, 2010
ISSN 1818-4952

Application of Net Radiation Transfer Method for Optimization and Calculation of Reduction Heat Transfer, Using Spherical Radiation Shields

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Abstract: Analytical solutions play a very important role in all modes of heat transfer. In this work a simplifying approach for calculating the radiant energy is achieved using the concept of net radiation transfer and provides an easy way for solving a variety of situations. To be more precise, the objective of this paper is to calculate the net radiation heat transfer between two concentric spheres with and without radiation shield between them. Moreover, using this method the percentage reduction in heat transfer between two surfaces was calculated and therefore optimization was done. It is 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. Moreover, it is found from these calculations that, one radiation shield with lower emissivity can reduce the net heat transfer even better than two radiation shields with higher emissivity.

Key words: Radiation shield · Net radiation method · Concentric spheres · Emissivity

INTRODUCTION

Heat transport by radiation 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 limit the effects of conductive and convective heat transfer by evacuating the space between two surfaces. This leaves thermal radiation as the dominant heat loss mode. There are many influential ways to minimize heat losses when radiation heat transfer is regnant mode. On way of reducing radiant heat transfer between two particular surfaces is to use materials which are highly reflective. Using radiation shield between the heat exchange surfaces is other possibility that is open to scientists [1]. 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. Radiation shields constructed from low emissivity materials can be used to reduce the net radiation transfer between two surfaces. Note that the emissivity associated with one side (ε^{+}_{n}) may differ from that associated with the opposite side (ε^{-}_{n}) of the shield [2]. Our goal consists in showing how apparently intractable problems in heat transport by radiation can be easily solved using the concept of net radiation transfer. Use of network representations was first suggested by Oppenheim [3]. This method provides a useful tool for visualizing radiation exchange between plates in the enclosure and may be used as the basis for predicting this exchange. This subject is also applicable to the design of multi-coverplate solar collectors. Indeed, in [4] the solar-radiation transmittance through a multi-plate planar window is calculated and a matrix-method derivation of the formulae is presented. Moreover, Micco and Aldao [5] 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 state to be original since the net radiation method can be found in the literature [6]. However, in this work, the general formulation has been investigated to calculate net heat transfer between two concentric spheres. Applying N radiation shields, aforementioned formulation will be generalized to calculate reduction heat transfer between those surfaces and accordingly some problems were solved. To the best of authors' knowledge these formulations and problems cannot found in the previous literatures.

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Analysis: For the analysis, the following simplifying assumptions are made:

- Surfaces are diffuse and gray.
- Space between spheres is evacuated.
- Conduction resistance for radiation shield is negligible.
- The temperature of the heat-transfer surfaces are maintained the same in both cases.
- The two concentric spheres and all the shields are in radiant balance.
- Radiation is one-dimensional.
- The emissivity associated with the inner and outer surfaces of the shield are the same.

Using the above assumptions, the radiation heat transfer equations can be investigated by following procedures:

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

$$E_b = \sigma T^4 \tag{1}$$

The net radiation heat transfer between any two of the concentric surfaces is then

$$Q_{io} = \frac{E_{bi} - E_{bo}}{R_{tot}} \tag{2}$$

When

$$E_{bi} - E_{bo} = \sigma(T_i^4 - T_o^4) \tag{3}$$

Most real surfaces exhibit a selective emission, in the sense that the emissivity is different for different wavelengths. In general ε can be a function of the wavelength 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 [7]. For simplicity we will restrict our study to grey bodies. In addition, we will consider that emission is diffuse, so the intensity leaving a surface is independent of direction.

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

$$R_{tot} = \frac{1-\varepsilon_i}{\varepsilon_i A_i} + \frac{1}{A_i F_{i-o}} + \frac{1-\varepsilon_o}{\varepsilon_o A_o} \tag{4}$$

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

$$(Q_{io})_{without-shield} = \frac{\sigma(T_i^4 - T_o^4)}{\frac{1-\varepsilon_i}{\varepsilon_i A_i} + \frac{1}{A_i F_{i-o}} + \frac{1-\varepsilon_o}{\varepsilon_o A_o}} \tag{5}$$

Recognizing F_{i-o}, it follows that:

$$(Q_{io})_{without-shield} = \frac{\sigma(T_i^4 - T_o^4)}{\frac{1}{\varepsilon_i A_i} + \frac{1-\varepsilon_o}{\varepsilon_o A_o}} \tag{6}$$

And finally the net heat transfer between inner and outer surfaces can be obtained by:

$$(Q_{io})_{without-shield} = \frac{\sigma A_i(T_i^4 - T_o^4)}{\frac{1}{\varepsilon_i} + \frac{1-\varepsilon_o}{\varepsilon_o}(\frac{r_1}{r_2})^2} \tag{7}$$

To have good comparison between the amount of heat transfer with and without radiation shields, it is must to find a function as the amount of heat transfer with N radiation shields between inner and outer surfaces; when N is the number of shields.

As cited before, the shields do not deliver or remove heat from the system and therefore the heat transfer between each two adjacent spheres can be obtained as follows:

$$Q_{i-s1} = Q_{s1-s2} = \ldots = Q_{sn-o} = (Q_{io})_{with-shield} \tag{8}$$

Where Q_{i-s1}, Q_{s1-s2} and Q_{sn-o} are as follows:

$$Q_{i-s1} = \frac{\sigma A_i(T_i^4 - T_{s1}^4)}{\frac{1}{\varepsilon_i} + \frac{1-\varepsilon_{s1}}{\varepsilon_{s1}}(\frac{r_i}{r_{s1}})^2} \tag{9}$$

$$Q_{s1-s2} = \frac{\sigma A_{s1}(T_{s1}^4 - T_{s2}^4)}{\frac{1}{\varepsilon_{s1}} + \frac{1-\varepsilon_{s2}}{\varepsilon_{s2}}(\frac{r_{s1}}{r_{s2}})^2} \tag{10}$$

$$Q_{sn-o} = \frac{\sigma A_{sn}(T_{sn}^4 - T_o^4)}{\frac{1}{\varepsilon_{sn}} + \frac{1-\varepsilon_o}{\varepsilon_o}(\frac{r_{sn}}{r_o})^2} \tag{11}$$

Adding all these equations, eliminates all the unknown shield temperatures and after solving for the net heat transfer, we obtain

$$(Q_{io})_{with-shield} = \frac{\sigma A_i(T_i^4 - T_o^4)}{\frac{1}{\varepsilon_i} + \frac{1-\varepsilon_o}{\varepsilon_o}(\frac{r_i}{r_o})^2 + \sum_{n=1}^{N}[(\frac{2-\varepsilon_{sn}}{\varepsilon_{sn}})(\frac{r_i}{r_{sn}})^2]} \tag{12}$$

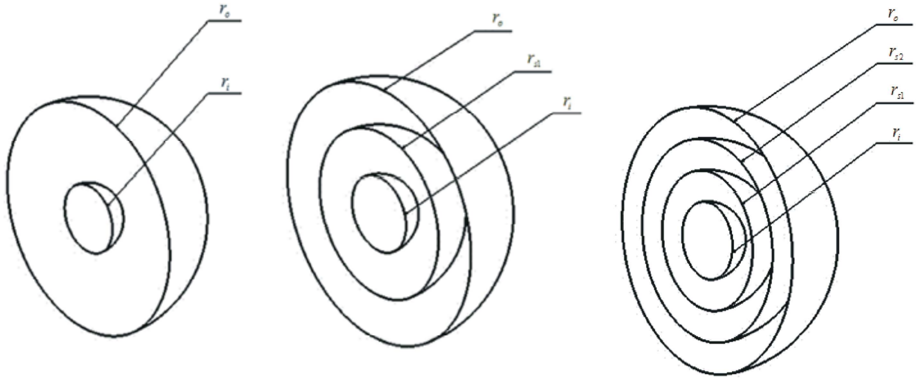

Fig. 1: Two concentric spheres (*a*) without radiation shield (*b*) with one radiation shield (*c*) with two radiation shields

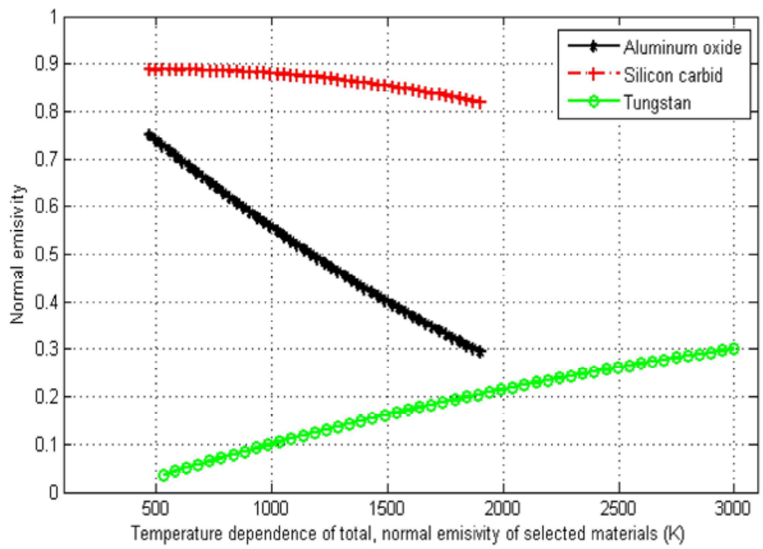

Fig. 2: Normal emissivity as a function of temperature [2]

Equation (12) not found in previous literatures and represents the net heat transfer between two concentric spheres when *N* shields have been applied to reduce the amount of heat loss.

Application: As mentioned before the emissivity is a function of temperature. Because emissivity and temperature of each shield is unknown, Fig. 2. has been employed for solving Eqs. (9)-(12) at the same time. Note that all the calculations have been performed for all three materials in Fig. 2.

Example 1: Consider two concentric spheres as shown in Fig. 1. (a). The inner sphere has temperature 873.15 ^oK, radius 50 *cm* and emissivity of 0.28. The outer sphere has temperature 330 ^oK, radius 100 *cm* and emissivity of 0.13. If one shield has been applied at radius 75 *cm* to reduce heat transfer between inner and outer spheres (Fig. 1. (b)), the percentage reduction in heat transfer, temperature and emissivity of the radiation shield can be calculated as follows:

$(Q_{io})_{with-shield} = 19329.0063\ w$

For Aluminum Oxide Shield:
Using Fig. 2. and solving Eqs. (9) and (12) together:

$(Q_{io})_{with-shield} = 16509.9582\ w$

$T_{s1} = 691.8374\ ^oK,\ \varepsilon_{s1} = 0.6653$

And the percentage reduction in heat transfer is:

$$\frac{(Q_{io})_{without-shield} - (Q_{io})_{with-shield}}{(Q_{io})_{without-shield}} \times 100 = \frac{19329.0063 - 16509.9582}{19329.0063} \times 100 = 14.5845\%$$

Similarly for silicon carbide shield:

$(Q_{io})_{with-shield}$ = 17470.2026 w

T_{s1} = 688.8900 ^oK, ε_{s1} = 0.8867

And the percentage reduction in heat transfer is:

$$\frac{19329.0063 - 17470.2026}{19329.0063} \times 100 = 9.6166\%$$

Finally for tungsten shield:

$(Q_{io})_{with-shield}$ = 5411.5204 w

T_{s1} = 723.8032 ^oK, ε_{s1} = 0.0638

And the percentage reduction in heat transfer is:

$$\frac{19329.0063 - 5411.5204}{19329.0063} \times 100 = 72.0031\%$$

Example 2: Consider the two concentric spheres 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 and outer spheres (Fig. 1. (c)), the percentage reduction in heat transfer, temperature and emissivity of the radiation shields can be calculated as follows:

$(Q_{io})_{with-shield}$ = 19329.0063 w

For aluminum oxide shield:
Using Fig. 2. and solving Eqs. (9), (10) and (12) together:

$(Q_{io})_{with-shield}$ = 14276.5794 w

T_{s1} = 721.1234 ^oK, ε_{s1} = 0.06545

T_{s2} = 658.8736 ^oK, ε_{s2} =0.6776

And the percentage reduction in heat transfer is:

$$\frac{(Q_{io})_{without-shield} - (Q_{io})_{with-shield}}{(Q_{io})_{without-shield}} \times 100 = \frac{19329.0063 - 14276.5794}{19329.0063} \times 100 = 26.1391\%$$

Similarly for silicon carbide shield:

$(Q_{io})_{with-shield}$ = 15840.2946 w

T_{s1} = 711.7174 ^oK, ε_{s1} = 0.8865

T_{s2} = 665.8673 ^oK, ε_{s2} = 0.8869

And the percentage reduction in heat transfer is:

$$\frac{19329.0063 - 15840.2946}{19329.0063} \times 100 = 18.0911\%$$

Finally for tungsten shield:
$(Q_{io})_{with-shield}$ = 3007.1435 w

T_{s1} = 796.6888 ^oK, ε_{s1} = 0.0736

T_{s2} = 631.8779 ^oK, ε_{s2} = 0.0509

And the percentage reduction in heat transfer is:

$$\frac{19329.0063 - 3007.1435}{19329.0063} \times 100 = 84.4503\%$$

It can be easily seen that, one radiation shield with lower emissivity (shield with tungsten material in example 1.) can reduce the net heat transfer even better than two radiation shields with higher emissivity (shields with aluminum oxide and silicon carbide materials in example 2.).

Example 3: Consider the two concentric spheres 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 and outer spheres (Fig. 1. (c)), the percentage reduction in heat transfer, temperature and emissivity of the radiation shields can be calculated by following the same procedures as Example 2.

Table 1. presents the temperatures, emissivities, net heat transfer and percentage reduction in heat transfer in all six possible models.

As it can be perceived from Table 1. model No. 5 is the best model for reducing heat transfer between two concentric spheres, if we want to use two radiation shields with different materials. It is interesting that, although the radiation shields' temperature in model No. 6 is less than model No. 5, but in the wake of higher emissivity in second radiation shield in model No. 6, the net radiation heat transfer and percentage reduction in

Table 1: The percentage reduction in heat transfer, temperature and emissivity of two radiation shields with different materials

	Shield at radius 66.67 *cm*			Shield at radius 83.33 *cm*				
Model	Material	Temperature ^oK	Emissivity	Material	Temperature ^oK	Emissivity	$(Q_{io})_{with-shield}$ w	Percentage reduction in heat transfer %
No. 1.	Aluminum oxide	731.5921	0.6573	Silicon carbide	655.6398	0.8834	14842.6201	23.2106
No. 2.	Aluminum oxide	821.0189	0.6183	Tungsten	708.0786	0.0623	5770.6988	70.1449
No. 3.	Silicon carbide	725.8787	0.8863	Aluminum oxide	771.2806	0.5708	14838.8679	23.2300
No. 4.	Silicon carbide	822.8935	0.8847	Tungsten	713.2072	0.0626	5993.1473	68.9940
No. 5.	Tungsten	732.5698	0.0650	Aluminum oxide	509.0278	0.6944	4508.5007	76.6749
No. 6.	Tungsten	730.7122	0.0647	Silicon carbide	504.2897	0.8892	4537.5995	76.5244

Nomenclature		Greek symbols	
A	Surface area	ε	Emissivity
E_b	Blackbody emissive power	λ	Wavelength
F	Shape factor	σ	The Stefan–Boltzmann constant, 5.67×10^{-8}
N	Number of shields	Subscripts	
Q	Net heat transfer	i	Inner sphere
r	Radius of sphere	o	Outer sphere
R_{tot}	Total resistance	sn	nth radiation shield
T	Absolute temperature	Superscripts	
		-	Outer surface
		+	Inner surface

heat transfer are smaller than model No. 5. It can be deduced from this Table that, if we want to choose the best combination of two radiation shields with different materials, it is better to use the shield with lower emissivity closer to the surface with higher temperature.

CONCLUSIONS

In this work an equation for calculating heat transfer between two spheres was investigated. Thanks to net radiation method the percentage reduction in heat transfer, temperature and emissivity of the radiation shield were calculated. It is found that, when two shields with same materials applied for reducing heat transfer, the one with lower emissivity better reduces 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.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the support of the talented office of Semnan University for funding the current research grant.

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