Application of Hemisphere Radiation Shields with Temperature-Dependent Emissivity for Reducing Heat Transfer Between Two Concentric Hemispheres

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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 concentric hemispheres. 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.
[Seyfolah Saedodin, M.S. Motaghedi Barforoush, Mohsen Torabi. **Application of Hemisphere Radiation Shields with Temperature-Dependent Emissivity for Reducing Heat Transfer Between Two Concentric Hemispheres.** *Rep Opinion* 2015;7(2):65-70]. (ISSN: 1553-9873). http://www.sciencepub.net/report. 10

Keywords: Temperature-dependent emissivity, radiant energy, radiation shield, net radiation method, concentric hemispheres.

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 allow 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_{shn}^{+}) may differ from that associated with the opposite side (ε_{shn}^{-}) 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. This subject is also pertinent to the design of multi-coverplate solar collectors and chimneys [Gao et al., 2007; Eisenmann et al., 2004; Bernardes et al., 2003]. 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. In addition, Afonso and Matos [2006] minimized the radiation effect of the condenser and compressor surfaces on the interior temperature of refrigerator– freezers by covering the refrigerator wall near the condenser and compressor with an aluminum foil as one radiation shield. They mentioned that putting this aluminum foil reduced the interior air temperature by 2 K.

We do not claim to be original since the net radiation method can be found in the literature [Howell et al., 2010]. In this work, the general formulation has been investigated to calculate net heat transfer between two concentric hemispheres, which is more challenging compare with our previous study [Saedodin et al., 2010a; Saedodin et al., 2010b]. This kind of geometry can be used not only in common industries, but also in space industry and military industry such as for nose cone space shuttles and ballistic missiles. Accordingly, reduction heat transfer by one and two radiation shield calculated. Moreover, by applying two radiation shields with different materials optimization was done.

2. Mathematical Modelling

Consider two concentric hemispheres as shown in Fig. 1. (a) and (b). The space between these two hemispheres separated from outer space by plate . For the analysis, the following simplifying assumptions were made:

1- Surfaces are diffuse and gray.

2- Space between hemispheres is evacuated.

3- Conduction resistance for radiation shield is negligible.

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

5- The two concentric hemispheres and all the shields are in radiant balance.

6- 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

$$E_b = \sigma T^4 \qquad (1)$$

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

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

when

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

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

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 [Modest, 2003]. 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:

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

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

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

$$(Q_{net})_{without-shield} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{A_1 F_{1-2}} + \frac{1-\varepsilon_2}{\varepsilon_2 A_2}} + \frac{\sigma(T_1^4 - T_3^4)}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{A_1 F_{1-3}} + \frac{1-\varepsilon_3}{\varepsilon_3 A_3}} \qquad (7)$$

By introducing [Chung and Naraghi, 1981]

$$F_{3-2} = \frac{1}{2\pi}\left\{ \begin{array}{l} -\left(R^2-1\right)^{0.5} + R^2 \tan^{-1}\left(\frac{1}{R^2-1}\right)^{0.5} \\ +2\tan^{-1}\left(R^2-1\right)^{0.5} - \frac{\pi}{2} \end{array} \right\} \qquad (8)$$

and using reciprocal relations and configuration-factor algebra

$$F_{1-2} = \frac{1}{R^2} \times \left\{ \frac{5}{4} - \frac{1}{2\pi}\left\{ \begin{array}{l} -\left(R^2-1\right)^{0.5} + R^2 \tan^{-1}\left(\frac{1}{R^2-1}\right)^{0.5} \\ +2\tan^{-1}\left(R^2-1\right)^{0.5} \end{array} \right\} \right\} \qquad (9)$$

$$F_{1-3} = \frac{R^2-1}{2R^2} \times -\frac{1}{2\pi R^2}\left\{ \begin{array}{l} -\left(R^2-1\right)^{0.5} + R^2 \tan^{-1}\left(\frac{1}{R^2-1}\right)^{0.5} \\ +2\tan^{-1}\left(R^2-1\right)^{0.5} - \frac{\pi}{2} \end{array} \right\} \qquad (10)$$

when

$$R = \frac{r_1}{r_2} \qquad (11)$$

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 outer surface and inner space. As cited before, the shields do not deliver or remove heat from the system. Therefore, the net heat transfer between outer and inner surface, using one radiation shield, can be found as follows:

$$(Q_{net})_{with-one-shield} = Q_{1-\frac{3}{2}out} + Q_{sh1-\frac{3}{2}in} + Q_{sh1-2} \qquad (12)$$

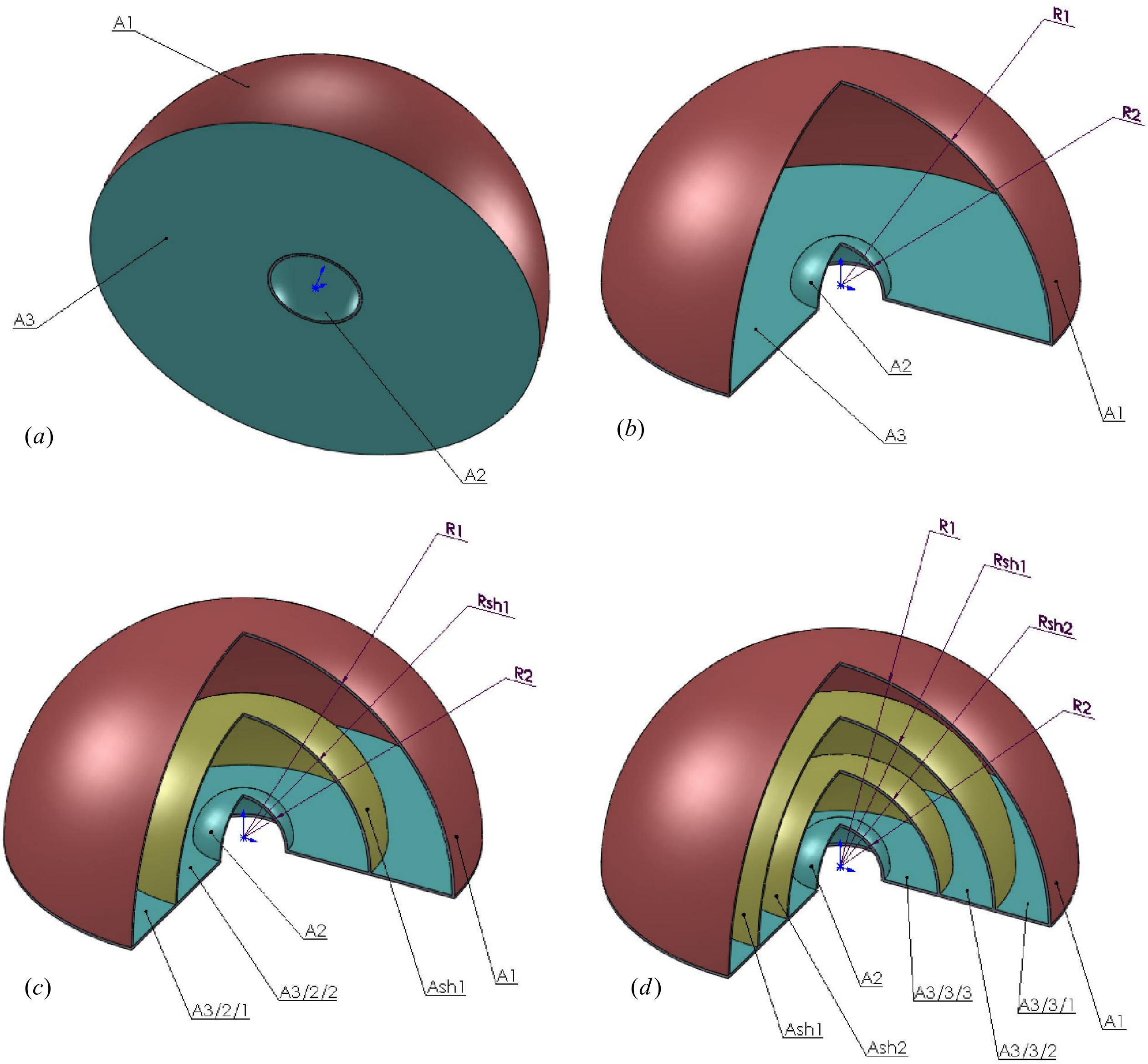

Figure. 1. Two concentric hemispheres (a) isometric view (b) without radiation shield (c) with one radiation shield (d) with two radiation shields

when $Q_{1-\frac{3}{2}out}$, $Q_{sh1-\frac{3}{2}in}$ and Q_{sh1-2} can be found same as follows:

$$Q_{1-\frac{3}{2}out} = \frac{\sigma\left(T_1^4 - T_3^4\right)}{\dfrac{1-\varepsilon_1}{\varepsilon_1 A_1} + \dfrac{1}{A_1 F_{1-\frac{3}{2}out}} + \dfrac{1-\varepsilon_3}{\varepsilon_3 A_{\frac{3}{2}out}}} \tag{13}$$

$$Q_{sh1-\frac{3}{2}in} = \frac{\sigma\left(T_{sh1}^4 - T_3^4\right)}{\dfrac{1-\varepsilon_{sh1}}{\varepsilon_{sh1} A_{sh1}} + \dfrac{1}{A_{sh1} F_{sh1-\frac{3}{2}in}} + \dfrac{1-\varepsilon_3}{\varepsilon_3 A_{\frac{3}{2}in}}} \tag{14}$$

$$Q_{sh1-2} = \frac{\sigma\left(T_{sh1}^4 - T_2^4\right)}{\dfrac{1-\varepsilon_{sh1}}{\varepsilon_{sh1} A_{sh1}} + \dfrac{1}{A_{sh1} F_{sh1-2}} + \dfrac{1-\varepsilon_2}{\varepsilon_2 A_2}} \tag{15}$$

while T_{sh1} and ε_{sh1} should be found from the following equation:

$$Q_{1-sh1} = Q_{sh1-\frac{3}{2}in} + Q_{sh1-2} \tag{16}$$

As mentioned before the emissivity is a function of temperature; Because of the fact that emissivity and temperature of each shield are unknown, Fig. 2. has been employed for solving Eq. (16) at the same time. By following the same procedures as for one radiation shield, the net heat transfer can be found when two radiation shields applied between two main surfaces as follows:

$$(Q_{net})_{with-two-shield} = Q_{1-\frac{3}{3}out} + Q_{sh1-\frac{3}{3}mid} + Q_{sh2-\frac{3}{3}in} + Q_{sh2-2} \quad (17)$$

It is obvious that, for calculating T_{sh1}, T_{sh2}, ε_{sh1} and ε_{sh2}, Fig. (2) should be employed at the same time with two following equations:

$$Q_{1-sh1} = Q_{sh1-\frac{3}{3}mid} + Q_{sh1-sh2} \quad (18)$$

$$Q_{sh1-sh2} = Q_{sh2-\frac{3}{3}in} + Q_{sh2-2} \quad (19)$$

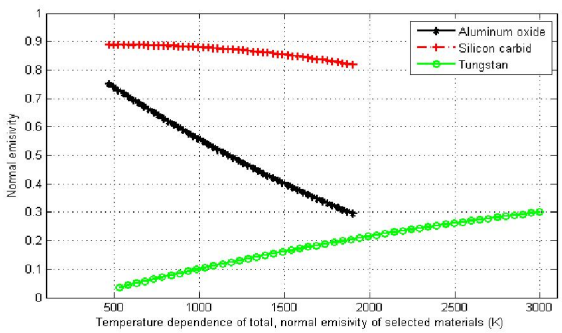

Figure 2. Normal emissivity as a function of temperature [Incropera et al., 2007]

3. Application

Using our solution, we performed sample numerical computations of reduction heat transfer between two concentric hemispheres 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 hemispheres as shown in Fig. 1. (a) and (b). As mentioned before, the space between these two hemispheres separated from outer space by plate A_3. The outer hemisphere has temperature 873.15 ^oK, radius 100 cm and emissivity of 0.28. The inner hemisphere has temperature 330 ^oK, radius 50 cm and emissivity of 0.13. Also, plate A_3 has temperature 330 ^oK and emissivity of 0.13. If one shield of 75 cm radius has been applied to reduce heat transfer between outer space and inner hemisphere (Fig. 1. (c)), the percentage reduction in heat transfer, temperature and emissivity of the radiation shield can be calculated as follows:

$(Q_{net})_{without-shield} = 14649.6466 \;\; W$

For aluminum oxide shield:

$(Q_{net})_{with-one-shield} = 13177.3929 \;\; W$

$T_{sh1} = 821.7554\ ^oK, \;\; \varepsilon_{sh1} = 0.6180$

And the percentage reduction in heat transfer is:

$$\frac{(Q_{net})_{without-shield} - (Q_{net})_{with-one-shield}}{(Q_{net})_{without-shield}} \times 100$$

$$= \frac{14649.6466 - 13177.3929}{14649.6466} \times 100 = 10.0497\%$$

Similarly for silicon carbide shield:

$(Q_{net})_{with-one-shield} = 13614.0120 \;\; W$

$T_{sh1} = 827.8050\ ^oK, \;\; \varepsilon_{sh1} = 0.8846$

And the percentage reduction in heat transfer is:

$$\frac{14649.6466 - 13614.0120}{14649.6466} \times 100 = 7.0693\%$$

Finally for tungsten shield:

$(Q_{net})_{with-one-shield} = 8512.8369 \;\; W$

$T_{sh1} = 745.8773\ ^oK, \;\; \varepsilon_{sh1} = 0.0668$

And the percentage reduction in heat transfer is:

$$\frac{14649.6466 - 8512.8369}{14649.6466} \times 100 = 41.8904\%$$

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

$(Q_{net})_{without-shield} = 14649.6466 \;\; W$

For aluminum oxide shield:

Using Fig. 2. and solving Eqs. (15), (16) and (17) together:

$(Q_{net})_{with-one-shield} = 11943.0966 \;\; W$

$T_{sh1} = 825.9366\ ^oK, \;\; \varepsilon_{sh1} = 0.6165$

$T_{sh2} = 790.3873\ ^oK, \;\; \varepsilon_{sh2} = 0.6292$

And the percentage reduction in heat transfer is:

$$\frac{(Q_{net})_{without-shield} - (Q_{net})_{with-tow-shields}}{(Q_{net})_{without-shield}} \times 100$$

$$= \frac{14649.6466 - 11943.0966}{14649.6466} \times 100 = 18.4751\%$$

Similarly for silicon carbide shield:

$(Q_{net})_{with-one-shield} = 12655.7126 \;\; W$

$T_{sh1} = 829.3988\ ^oK, \;\; \varepsilon_{sh1} = 0.8846$

$T_{sh2} = 805.5816\ ^oK, \;\; \varepsilon_{sh2} = 0.8851$

And the percentage reduction in heat transfer is:

$$\frac{14649.6466 - 12655.7126}{14649.6466} \times 100 = 13.6107\%$$

Finally for tungsten shield:

$(Q_{net})_{with-one-shield} = 6634.3749 \;\; W$

$T_{sh1} = 793.2673\ ^oK, \;\; \varepsilon_{sh1} = 0.0732$

$T_{sh2} = 647.0081\ ^oK, \;\; \varepsilon_{sh2} = 0.0530$

And the percentage reduction in heat transfer is:

$$\frac{14649.6466-6634.3749}{14649.6466}\times 100=54.7130\%$$

Example 3.

Consider the two concentric hemispheres 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 outer space and inner hemisphere (Fig. 1. (d)), 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 interesting that, although the radiation shields' temperature in model No. 6 is less than model No. 5, but the net radiation heat transfer and percentage reduction in heat transfer are smaller than model No. 5. This behavior is in the wake of higher emissivity in second radiation shield in model No. 6. 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.

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

Model	Shield at radius 66.67 cm			Shield at radius 83.33 cm			$(Q_{net})_{with-two-shields}$ W	Percentage reduction in heat transfer %
	Material	Temperature ^oK	Emissivity	Material	Temperature ^oK	Emissivity		
No. 1.	Aluminum oxide	824.1668	0.6171	Silicon carbide	795.2574	0.8852	12230.8590	16.5108
No. 2.	Aluminum oxide	845.2122	0.6097	Tungsten	725.2736	0.0639	8707.0776	40.5645
No. 3.	Silicon carbide	831.0985	0.8846	Aluminum oxide	800.1369	0.6257	12332.1286	15.8196
No. 4.	Silicon carbide	848.6930	0.8842	Tungsten	730.3288	0.0646	8864.7199	39.4885
No. 5.	Tungsten	757.2165	0.0683	Aluminum oxide	642.6961	0.6836	7467.4224	49.0266
No. 6.	Tungsten	755.7042	0.0681	Silicon carbide	642.2522	0.8870	7496.4208	48.8286

4. Conclusions

In this paper an equation for calculating heat transfer between two concentric hemispheres 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.

Acknowledgement

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

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