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Technical Notes

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Thermal Analysis of Optical Windows for Spacecraft Applications

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Nomenclature

c	=	specific heat capacity, $\mathrm{J\,kg^{-1}\,K^{-1}}$
h_1, h_2	=	convective heat transfer coefficient at surfaces S_1 and S_2, respectively, $\mathrm{W\,m^{-2}\,K^{-1}}$
k	=	thermal conductivity of medium, $\mathrm{W\,m^{-1}\,K^{-1}}$
L_b	=	thickness of bth layer, m
L_t	=	total thickness of composite, $L_t = L_1 + L_2 + \cdots + L_n$, m
L_{va}	=	thickness of the vacuum layer, m
M_b	=	number of control volumes of bth layer
n	=	total number of layers of the multilayer physical model refractive index
q^c, q^r	=	thermal conductive and radiative heat fluxes, respectively, $\mathrm{W\,m^{-2}}$
q^t	=	total heat flux, $q^c + q^r$, $\mathrm{W\,m^{-2}}$
$\tilde{q}$	=	dimensionless heat flux, $q/(\sigma T_r^4)$, where q represents q^c, q^r, or q^t
$S_{-\infty}$, $S_{+\infty}$	=	left and right black surfaces representing surroundings
S^1, S^2	=	boundary surfaces
T	=	absolute temperature, K
T_{g1}, T_{g2}	=	gas temperature for convection at $x = 0$ and L_t, respectively, K
T_r	=	reference temperature, K
T_0	=	uniform initial temperature, K
t	=	physical time, s
X	=	dimensionless coordinate in direction across composite, $X = x/L_t$
x	=	coordinate in direction across composite, m
Z	=	compressibility factor of argon gas
α	=	absorption coefficient, $\mathrm{m^{-1}}$
Δt	=	time interval, s
λ	=	wave length, μm
ρ	=	density of medium, $\mathrm{kg/m^3}$

Superscripts

c	=	conduction
m	=	time step
r	=	radiation
t	=	total heat flux

Subscripts

A_r	=	relative to argon gas
b	=	layer index: $b = 1 \sim n$
gl	=	relative to glass
i	=	relative to node i
S_1, S_2	=	relative to S_1 and S_2
va	=	relative to the vacuum
$-\infty$, $+\infty$	=	relative to $S_{-\infty}$ and $S_{+\infty}$

I. Introduction

SEMITRANSPARENT media enjoy extensive applications in engineering, such as insulating techniques for the protection of aeroengines [1,2], the manufacture of glass and its application in a high-temperature environment [3–5], the ignition and flame spread through a semitransparent solid [6–8], the insulation properties of fibrous and ceramic materials [9–15], the determination of the thermal diffusivity of semitransparent minerals [16], and infrared telemetry of vegetation [17,18]. A useful method for solving problems of transient coupled radiative and conductive heat transfer in a semitransparent medium, the ray-tracing/node-analyzing method has already been used to solve the problem of coupled heat transfer in isotropically scattering [19], anisotropically scattering , and multilayer [21,22] media. However, as [19–22] show, this method has been used much more for studying the mechanism of coupled radiative and conductive heat transfer in a gray medium than for engineering application studies in a nongray medium.

Spaceborne optical windows are usually made of glass, which is typical of a semitransparent medium. The optical windows are composed of single glass or multiglass layers (usually two- or three-layer glass). For two-layer windows, the two layers are separated by a space. To balance pressure in the spacecraft cabin, the space is usually filled with argon or nitrogen gas. For three-layer windows, the three layers are separated by two spaces. Between the inner and middle layers, the space is filled with argon or nitrogen gas; between the middle and outer glass layers, the space is a vacuum. Instead of being designed to help balance pressure in the spacecraft cabin, the outer layer is just working as a heat insulation protection layer. In outer space, the temperature is almost absolute zero, which is much lower than the temperature in the spacecraft cabin. Therefore, the cabin exchanges heat energy with outer space through the optical

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windows. This results in an inhomogeneous temperature distribution through each layer of glass, thus affecting the quality of the image because the thermal parameters of glass, such as the absorption coefficient, the thermal conductivity, and especially the refractive index, are functions of temperature. In addition, the inhomogeneous temperature distribution also causes geometrical distortion in the glass layers, and then these geometrical distortions produce forces between the glass layers and the fixed structure of the spacecraft. This further deforms the glass layer. Therefore, these disadvantages affect the quality of images seen through spacecraft windows. Related to the aforementioned problems, this paper investigates transient coupled radiative and conductive heat transfer in spacecraft windows and shows temperature distribution within the glass windows' layers. These studies are helpful in understanding the effects of temperature distribution within the glass layers on the quality of imaging.

Obviously the characteristic of spacecraft windows is that the surface of each glass layer is semitransparent and specularly reflecting, so that the reflectivity of each glass layer's surface depends on Fresnel's reflective law and Snell's refractive law. Furthermore, transient coupled radiative and conductive heat transfer in multilayer windows needs to be studied using a multilayer physical model. Nevertheless, Luo et al. [22] have already solved problems of transient coupled radiative and conductive heat transfer in a multilayer composite with specularly reflecting properties. Thus, we can use the physical model of Luo et al. [22] to study the transient temperature distribution within a multilayer glass window. Both the length and width of each layer are usually much bigger than the thickness, so heat transfer within layers can be approximated as one dimensional. Moreover, the layers do not scatter radiative energy, and so the effects of scattering on heat transfer within the layers are not considered in this paper.

The reader can find the physical model and the equations in Luo et al. [22], and, for simplicity, they are deleted here.

II. Analysis

Optical windows have the uniform initial temperature of the ground level at first, and they will be gradually cooled after the spacecraft has been launched into outer space.

The vacuum space within multilayer optical windows can be regarded as a special layer without density that cannot conduct heat and cannot attenuate radiation. Then the conductivity, optical thickness, and volume specific heat capacity of a vacuum layer can be assumed as $k_{\mathrm{va}} = 10^{-100}$, $\alpha_{\mathrm{va}} L_{\mathrm{va}} = 5 \times 10^{-8}$, $\rho_{\mathrm{va}} c_{\mathrm{va}} = 10^{-100}$, respectively, and 1 is the refractive index. The insulation gas layer has density and specific heat capacity, able to conduct heat without attenuating radiation (assume its optical thickness as $\alpha_{A_r} L_{A_r} = 5 \times 10^{-8}$), and 1 is its refractive index.

When we use the physical model of Luo et al. [22] to study this problem, some skill is required. First, assume $T_{+\infty} = 0.01$ K to simulate the temperature of outer space. Convection does not take place on outer surfaces (the facing outer space) of spacecraft windows because of the vacuum in outer space, so assume $h_2 = 0$ to simulate this condition. Then, assume $T_{-\infty} = T_{g1} = 300$ K to simulate the temperature of the environment within the cabin. $T_{-\infty}$ is the temperature of the black surrounding surface $S_{-\infty}$, but the environment of the cabin is not a black body. We will illustrate this condition as follows. Compared with the size of the spacecraft, the window can be regarded as a small hole in a spacecraft. As we know, a small hole in a large vessel can be regarded as a black body for the reason that, when rays enter the vessel through the small hole, they will be reflected and absorbed by the walls of the vessel an infinite number of times such that very few rays get out of the vessel from the small hole. It is most important to note that this black body assumption greatly simplifies the problem that we are studying. In outer space, gravity is negligible, and so there is no natural convection in the cabin. But life support systems may cause air to flow in the cabin, thus two conditions of $h_1 = 0$ and $h_1 = 20$ are considered in this study, respectively. Spacecraft windows are assumed to have an initial uniform temperature equal to that of the Earth's before the spacecraft is launched. Finally, assume $T_0 =$ 300 K (to simulate temperature of the ground) as the initial uniform temperature of the window, and the reference temperature is taken as $T_r = 1000$ K. The conductivity and volume specific heat capacity of glass are obtained from Tan et al. [23], and they are $k_{\mathrm{gl}} = 1.7\ \mathrm{W\,m^{-1}\,K^{-1}}$, $\rho_{\mathrm{gl}} c_{\mathrm{gl}} = 2.31 \times 10^6\ \mathrm{J\,m^{-3}\,K^{-1}}$, respectively. The optical properties of glass, shown in Table 1, are also obtained from Tan et al. [23].

Table 1 Optical properties of glass [23]

Wave length, λ	Refractive index, n_{gl}	Absorption coefficient, α_{gl}
0.40–2.65	1.45	1
2.65–2.90	1.434	1000
2.90–4.20	1.42	5
4.20–7.00	1.35	5000
7.00–20.0	1.30	5000

Table 2 Physical properties of argon gas [24]

	200 K	250 K	300 K
Compressibility factor Z	0.9972	0.9988	0.9995
Conductivity k_{A_r}	0.0124	0.0152	0.0177

Only insulating layers of argon gas and/or a vacuum are considered in this paper. The required parameters, such as density, specific heat capacity at a constant volume, and conductivity are obtained by the following methods. Compressibility factor and conductivity of argon gas are obtained from Rohsenow et al. [24], as shown in Table 2. The compressibility factor Z of argon gas is nearly unity. Thus, argon gas can be considered as an ideal gas, and its density at 1 atm of pressure can be calculated from the ideal gas equation. We assume that argon gas is injected into the space between the two glass layers of a window and sealed, and the gas volume and mass do not change after being sealed. Thus, substitute the initial temperature T_0 into the ideal gas equation to calculate its density. We obtain $\rho_{A_r} = 1.6229\ \mathrm{kg\,m^{-3}}$ [25]. Argon gas is a monatomic gas, thus its specific heat capacity at a constant volume can be calculated as $c_{A_r} = 312.1808\ \mathrm{J\,kg^{-1}\,K^{-1}}$ [25]. As shown in Table 2, the conductivity of argon gas is dependent on the temperature, yet the change is small within the temperature range of interest, that is, 200 K–300 K. Hence, we choose the value of 250 K as the value to use when making this calculation.

In this paper, a constant time step is chosen as $\Delta t = t/1000$, and the steady state is assumed to be reached if $\max |T_i^{m+1} - T_i^m| < 10^{-3}$.

III. Results and Discussion

A. One-Layer Glass Optical Window

The optical window of the American Skylab spacecraft is a one-layer glass window, which has a length of 591.8 mm, a width of 449.1 mm, and a thickness of 40.6 mm. Because the length and the width are over 10 times bigger than the thickness, this optical window can be regarded as one dimensional. Therefore, a one-layer ($n = 1$) physical model can be used to study the transient coupled heat transfer within the window. The thickness of the glass is $L_1 = 0.0406$ m, and the number of control volumes is $M_1 = 400$.

Figure 1 shows that the process from the transient state to the steady state is very slow without convection, because it will take approximately 9.36 h for the optical window to reach the steady state with convection, whereas it will require around 33.84 h without convection. We can also see from Fig. 1 that the temperature and the heat flux with convection are much greater than those without convection. The temperature difference between the inner face and the outer face of the glass layer is about 5.82 K with convection, whereas it is 3.62 K without convection. Obviously we can deduce that it is the convection that causes the temperature difference to increase, which means that the temperature distribution within the glass is more inhomogeneous than that without convection.

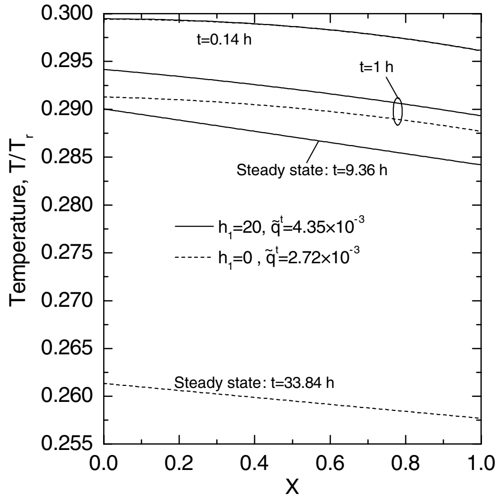
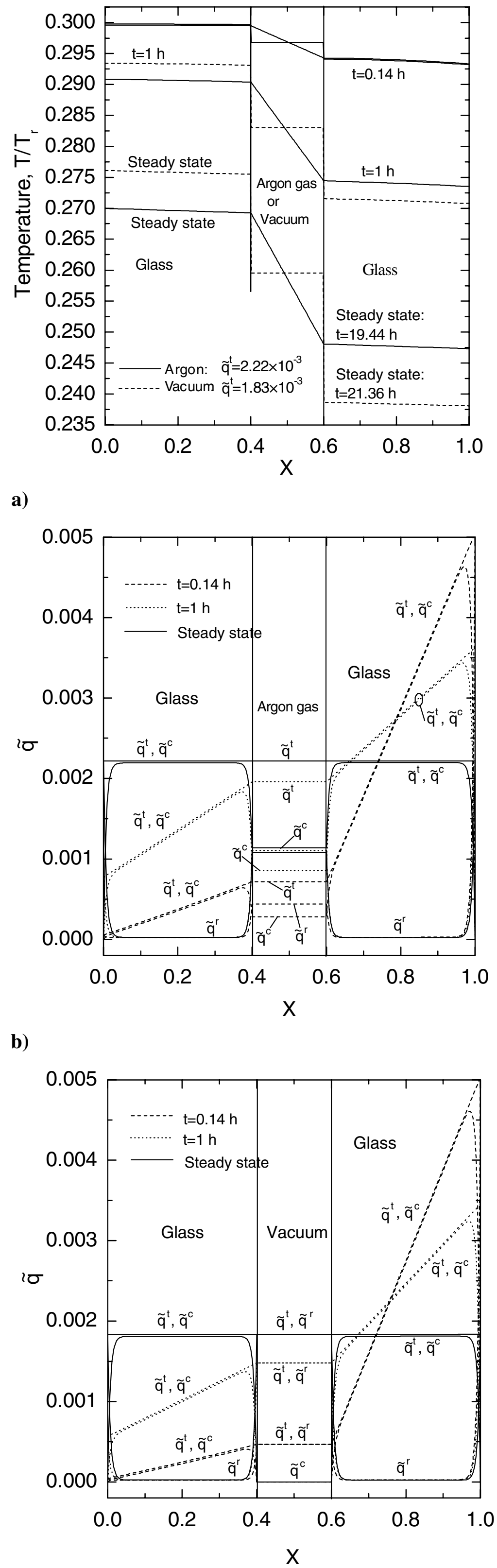


Fig. 1 Transient coupled heat transfer in a one-layer optical window.

B. Two-Layer Glass Optical Window

In a two-layer window, the gap between the layers can be considered as a special layer having different characteristics, thus a three-layer ($n = 3$) physical model can be used to study transient coupled heat transfer of a two-layer window. The gap may be a vacuum or be filled with an argon gas. In the first case, we consider that $h_1 = 0$, and the inner and outer layers are made of the same material. The thickness of the inner layer (L_1) is identical to that of the outer layer (L_3) and is equal to 0.01 m, and the special layer has a thickness (L_2) of 0.005 m. The number of control volumes of the inner layer M_1 and of the outer layer M_3 are both equal to 200, and that of the special layer M_2 is equal to 100. The result obtained in Fig. 2 shows that the cooling process of a two-layer window is very slow. When the spacecraft is launched into space, the temperature outside the spacecraft is lower than inside. This causes the temperature of the outer layer to be lower than that of the inner layer, having a direct effect on the temperature change between the outer layer and the inner layer, which becomes higher. Therefore, the deformation encountered by the outer layer will be more intense.

The temperature gradient is higher within the argon gas insulation layer due to the small conductivity of argon gas. Compared with the vacuum insulation layer, the argon gas insulation layer intensifies heat transfer through the window. As a result, the temperature decreases in the inner layer while it increases in the outer layer. Meanwhile, the average temperature difference between the two layers decreases, and the heat flux at the steady state increases. Thus, the difference between the deformation index of the inner layer and the outer layer will become smaller. This has an advantage of improving the image quality for the two-layer window. However, Table 3 reveals that the temperatures of the inner and outer faces of each layer are different. This difference is higher when the space between the two layers is filled with argon gas. In this case the temperature distribution within each layer becomes more inhomogeneous, and this has a negative impact on the image quality. On the other hand, the temperature distribution (represented by the parallel dashed lines) within the vacuum layer has no influence on the overall transient heat transfer process. Figures 2b and 2c show that after 0.14 h, the transient heat flux distribution (represented by the dashed lines) near the outer face of the outer glass layer has a very high radiative heat flux within the very thin glass media, which releases high radiative energy to outer space. At the same time, we also note that there is almost no heat flux on the interface of the inner layer facing the cabin. Therefore, we can conclude that the radiative emission of the outer layer dominates the overall heat transfer process in outer space. With time, the temperature of the inner glass layer decreases, as is shown in Fig. 2a, and then the cabin begins to exchange radiative energy with the inner layer. As a result, the total heat flux on the surface of the inner layer increases. Therefore, radiative energy from the cabin does not exchange directly with outer space because of the shielding by the glass layers. In the center of each glass layer, the total heat flux is almost equal to the conductive heat flux because the radiative heat flux is nearly equal to zero, which means that conduction dominates the heat transfer process therein. But in very thin glass media, near the two faces bounding the gap of each glass layer, the radiative heat flux is obvious. Conductive heat



a)

b)

c)

Fig. 2 Transient coupled heat transfer in a two-layer optical window ($h_1 = 0$): a) temperature distribution, b) heat flux distribution for the argon gas layer, and c) heat flux distribution for a vacuum layer.

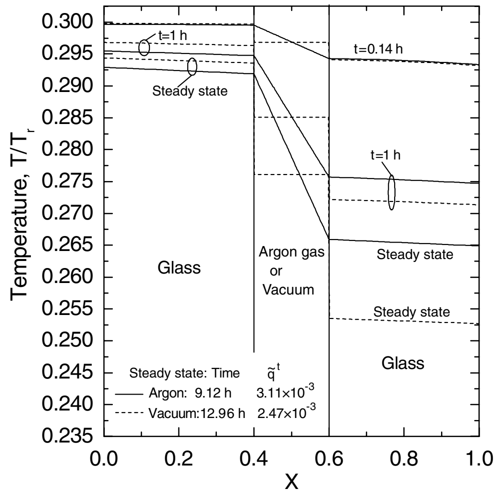


Fig. 3 Transient coupled heat transfer in a two-layer optical window ($h_1 = 20$).

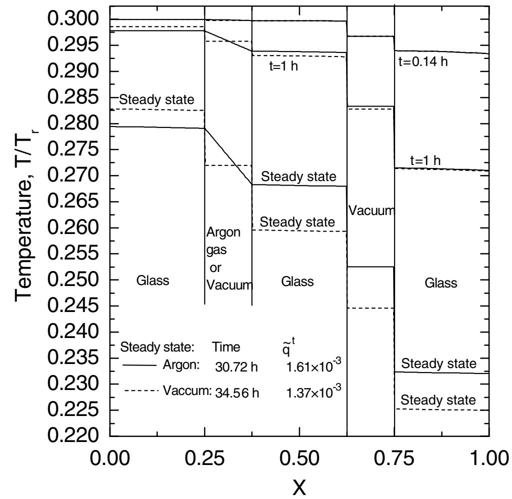
flux does not exist in the vacuum layer, but the conductive and radiative heat fluxes coexist in the argon gas layer.

When $h_1 = 20$, a comparison of Fig. 3 with Fig. 2a shows that the convection causes the temperature to rise in the two layers. Thus, the difference in the degree of deformation between the two layers decreases and, specifically, the temperatures remain almost unchanged in the inner layer from the ground level values before the spacecraft was launched. As seen in Table 3, as compared with the case of $h_1 = 0$, convection ($h_1 = 20$) causes the temperature difference between the two faces of each layer to increase. This phenomenon indicates that the temperature distribution within each layer is more inhomogeneous than when the convection does not take place.

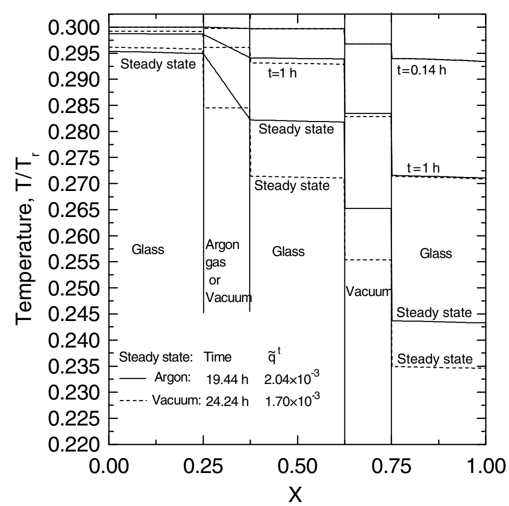
C. Three-Layer Glass Optical Window

Considering any space between two glass layers as a special layer, a three-layer window has two special layers. Therefore, we can use a five-layer ($n = 5$) physical model to study its transient coupled heat transfer, and the results obtained are shown in Fig. 4. In this case, both sides of the outer layer are a vacuum, which works as a heat insulator to make the temperature distribution of all the glass layers more uniform. The outer layer does not have to be hermetically sealed. Because the space between the inner and the middle layers is filled with argon gas, these two layers must be hermetically sealed. Thus, the force generated by the deformation between these two layers and the frame in which they are fixed on the spacecraft must be more intense than that between the outer layer and its frame. Therefore, to reduce the intensity of this deformation, the temperature distributions within the inner and the middle glass layers should be as homogeneous as possible.

Looking from the cabin to outer space, the first, third, and fifth layers are made of glass, having a thickness of 0.01 m each; the second and fourth layers are special layers that are each 0.005 m thick. The second layer may be a vacuum or filled with argon gas, whereas the fourth layer should be a vacuum. The numbers of the control volumes of the first, third, and fifth layers are M_1, M_3, and M_5, respectively, and they are given a value of 100 each. Those of the



a)



b)

Fig. 4 Transient coupled heat transfer in a three-layer optical window: a) $h_1 = 20$, b) $h_1 = 20$.

second and fourth layers are M_2 and M_4, respectively, and they are given a value of 50 each. Comparing Fig. 4a with Fig. 2a on one the hand, and Fig. 4b with Fig. 3 on the other hand, it appears that the temperature distribution within the three-layer optical window behaves as that within the two-layer optical window for which a special layer and a glass layer are added.

Comparing Fig. 4a with Fig. 2a, we can see that the temperatures of the inner and middle glass layers rise due to insulation by the outer layer. At the same time, the deformations caused by temperature variation are attenuated in these two layers. Meanwhile, the average temperature difference decreases between the inner and middle layers, so that the difference in the degree of deformation between these two layers also decreases. All of these factors contribute to improving the image quality seen through the three-layer window. A comparison of Table 4 and Table 3 reveals that the temperature

Table 3 Steady-state temperature difference between both surfaces of each glass layer of a two-layer window

		Inner glass layer, K			Outer glass layer, K		
		Left surface	Right surface	Temperature difference	Left surface	Right surface	Temperature difference
$h_1 = 0$	Vacuum layer	276.07	275.49	0.58	238.65	238.07	0.58
	Argon gas layer	269.96	269.25	0.71	248.05	247.34	0.71
$h_1 = 20$	Vacuum layer	294.39	293.60	0.79	253.52	252.73	0.79
	Argon gas layer	292.92	291.91	1.01	265.91	264.91	1.00

Table 4 Steady-state temperature difference between both surfaces of each glass layer of a three-layer window

		Inner glass layer, K			Middle glass layer, K			Outer glass layer, K		
		Left surface	Right surface	Temp. difference	Left surface	Right surface	Temp. difference	Left surface	Right surface	Temp. difference
$h_1 = 0$	Vacuum layer	282.80	282.53	0.27	259.57	259.30	0.27	225.26	224.99	0.27
	Argon gas layer	279.43	279.11	0.32	268.28	267.96	0.32	232.36	232.04	0.32
$h_1 = 20$	Vacuum layer	296.16	295.82	0.34	271.40	271.06	0.34	234.91	234.57	0.34
	Argon gas layer	295.37	294.96	0.41	282.20	281.79	0.41	243.70	243.29	0.41

differences decrease significantly between the two sides of the inner and middle layers due to insulation by the outer layer. Considering the case where $h_1 = 0$, Table 4 shows that, when the second layer is filled with argon gas, the sum of all temperature differences is 0.96 K. This sum becomes 0.81 K when the second layer is a vacuum. On the other hand, Table 3 reveals that those sums are 1.42 and 1.16 K, respectively, for the two-layer window that does not have the insulation provided by the third glass layer. This shows a decrease of nearly 32% in the temperature difference when the second layer is filled with argon gas and 30% when this layer is a vacuum. Based on this result, we can conclude that, although the total thickness of the three glass layers in the three-layer window is increased when one glass layer and one vacuum space are added to the outer layer of the two-layer optical window, the total temperature difference decreases significantly. This is due to the fact that the insulation provided by the outer layer, which exists in the case of the three-layer optical window and does not in the case of two-layer optical window, renders the temperature distribution more homogeneous. As we know, the refractive index of glass is a function of temperature, and the homogeneity of the refractive index distribution depends on the homogeneity of the temperature distribution. Because the temperature distribution in the three-layer window is more homogeneous, the refractive index distribution will also be more homogeneous. These facts are advantageous in improving the image quality. The same conclusion also can be drawn by comparing Table 4 with Table 3 for $h_1 = 20$.

A comparison of Fig. 4b and Fig. 4a shows that convection causes each glass layer's temperature to increase. At the same time, the average temperature difference between the inner and middle layers will decrease, leading to a decrease in the deformation forces between the two glass layers. Also, according to Table 4, the temperature difference between the two sides of each glass layer increases due to convection, whereas a comparison of Fig. 4b with Fig. 3 reveals that, at the steady state, the heat flux for the three-layer window is less than that of the two-layer window due to insulation by the outer layer.

In this paper, although we considered the refractive indices of the glass layers to be constant instead of being a function of the temperature, the results of our research may provide an indication of what the temperature distribution will be if the exact expression for the refractive index as a function of the temperature is used.

IV. Conclusions

Using the multilayer transient coupled radiative and conductive heat transfer physical model of Luo et al. [22], the phenomenon of transient coupled heat transfer in single-, two-, and three-layer optical windows has been investigated. According to our analysis, the following conclusions can be drawn:

1) The cooling process of windows in outer space is very slow, and radiation plays an important role in the cooling process.

2) Convection in the cabin intensifies the heat transfer within the window, thus causing the average temperature difference to decrease between two neighboring glass layers. At the same time, convection also causes the temperature difference to increase between the two sides of each glass layer. Therefore, the temperature distribution in each layer becomes more inhomogeneous than when there is no convection. Convection also causes the heat flux at the steady state to increase and reduces the time to reach the steady state.

3) Argon gas between glass layers intensifies the heat transfer within the window and reduces the average temperature difference between two neighboring glass layers. Meanwhile, the temperature difference increases between the two sides of each layer, which means that the temperature distribution within the layers is more inhomogeneous than when the argon gas is replaced with a vacuum.

4) The insulating effect of the outer glass layer of a three-layer window causes the temperatures of the inner and the middle glass layers to increase; on the contrary, this leads to the decrease not only of the average temperature difference between the inner and the middle glass layers, but also of the temperature difference between both sides of each glass layer. As a result, the temperature distributions within the three glass layers are more homogeneous as compared with those of the two-layer optical window. All of these factors contribute to improving the image quality seen through the three-layer window. Thus, in this respect, the three-layer optical window is better than the two-layer optical window.

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