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Numerical Calculation of Radiation Heating of the Hypersonic Nose in the Reentry Phase

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ABSTRACT

Keywords: *Radiation, Capsule, Gray gas, Non-gray gas, DO radiation model*

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The calculation of aerodynamic heating is one of the most important steps in designing reentry bodies. Because ignoring it can damage the thermal protection system and cut off the radar connections to the reentry capsule. Due to the high speed of the capsule, the radiation heat transfer rate is important in comparison to the convection heat transfer rate. In this paper, various parameters affecting the heat transfer rate of the nose of the reentry capsule have been investigated. To calculate the capsule nose radiation, a theoretical method is presented which is compared with the reference simulation results to confirm its correctness. In this simulation, the heat transfer rate of the Apollo4 capsule has been investigated. Due to the low optical thickness of the model, the DO radiation model is used to simulate CFD. This simulation was carried out using Fluent software version 16 and was solved with a laminar flow of gray gas and non-gray gas. The results show that the radiation heat transfer rate in non-gray gas mode has lower error rate than the gray gas state, and it is also observed that at high altitudes, the radiation transfer rate is 80% of the total heat transfer rate.

Introduction

One of the prominent features of flying objects is high speed, especially ultrasonic objects, as well as aerodynamic heating and high temperature. Calculating the rate of heat transfer is one of the most important steps in the design of high-speed flying objects, especially those returning to the atmosphere, because not taking it into account can damage the thermal protection system and cut off the radar connections of the return capsule. Since radiation is related to the fourth power of temperature and convection heat transfer is related to the power of one temperature, it is obvious that at very high temperatures, the effect of radiant heat transfer is much greater than the convection heat transfer [1].

Another distinguishing feature of radiation transmission is that there is no need for any intermediary between the two places of radiation exchange and the radiant energy completely passes through the vacuum. Therefore, not only in surface devices such as furnaces, combustion chambers, and solar energy emissions, but also in rocket nozzles and return capsule missions, radiation heat transfer plays an important role. It is important to calculate the radiation heat transfer rate in the nose of the reentry capsule, due to the high altitude and

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the change in the flow state in the shock layer and the sharp rise in temperature in these areas [2].

In 1958, examining the results of the Apollo Capsule wind tunnel, Mr. Lee stated that the total heat flux at the corners of the geometry was 80% greater than Mach 9.7 and that the angle of attack was 33 degrees higher. The real Apollo, which also carried astronauts, entered the Earth's atmosphere at an angle of attack lower than 33 degrees. Therefore, the heat flux in the real state is less than the heat flux at an angle of 33 degrees. In addition to calculating the heat flux of the Apollo capsule, Mr. Lee was also able to calculate the pressure distribution in the heat shield [3].

In 1965, the Fire 2 spacecraft was sent into space to calculate radiant heat transfer. Under these conditions, the intensity of radiation was measured at rest and in the wavelength range of 0.2 to 4 μm. In addition to this measurement, in the wavelength range of 0.3 to 0.6 μm, the intensity of radiation was measured, both of which were successful [4].

In 1969, Mr. Anderson studied the radiation heat transfer and the convection heat transfer of the Apollo 4 capsule. He observed that the heat transfer rate of radiation increases significantly with increasing flight speed [5].

In 2001, Mr. Chool Park examined the radiative heat transfer of the Apollo 4 capsule. In these calculations, the current field model and line-by-line radiation calculation method were used. This computer code receives thermodynamic properties, such as particle density, as input and calculates the amount of radiation spectrally. Finally, the results obtained from this method were compared with flight data and it was shown that this method has acceptable accuracy [6].

In 2021, Mr. Bylet et al. proposed a passive method to prevent any contamination of the optical pathway that occurs due to the radiation heat transfer to perishable matter when it enters the atmosphere and pyrolyzed materials and gases enter it so that radiation can be measured for a wide range of missions and heat shield locations [7].

Mr. Aaron et al. studied radiant heating and sacrifice in the forehead of the Galileo probe in its flight path and examined the performance of its thermal protection system. For this purpose, they solved the Navier-Stokes equations by assuming a chemical unbalanced flow field with radiation and sacrifice, and considered the deformation of the forehead due to the regression of the sacrificial material. Instead of considering the Schmidt number constant, they used Stephen-Maxwell equations to calculate the mass diffusion of the species, which resulted in a 10% increase in the calculated regression [8].

The calculation of the radiation heat transfer from flying objects is of particular importance, because it was important to calculate the radiation reentry supersonic objects at high Mach in terms of not damaging the object returning to the atmosphere. This paper investigates the heat flux, and convection heat transfer, on the reentry Apollo. In order to produce a computational network, Gambit software has been used and to study the flow, Fluent software version 16 has been used. It was observed that the information has a low error rate in comparing the obtained data with the data of the reference article.

In the present paper, the numerical solution of the heat flux of radiation of the Apollo 4 capsule in the stagnation point is investigated and the effect of different parameters on the heat transfer rate of radiation is investigated. Due to the widespread use of Ansys Fluent software in academic and industrial projects, this software has been used in this research. Despite the numerous models in this software for modeling radiation and despite the great importance of radiation, especially in the design of supersonic objects, there is almost no article in this field using this software or there is no mention of how to model. This is due to the complexity of using this software and entering the values correctly in the correct ranges, otherwise it can change the values obtained for the results up to several times. Also, in the present paper, for the first time, the difference between the two numerical models of gray gas and transparent gas on the radiant heat transfer rate has been investigated. It is a combination of the convection heat transfer due to supersonic current and the radiant heat transfer. In this paper, in addition to describing the parameters, the range of their values is also mentioned and the obtained results are examined. Due to the low optical thickness, the DO radiation model has been used to model the radiation.

Geometry

Since the purpose is to investigate radiant heat transfer and due to the high speed of Apollo 4 flight and also the availability of flight results, in this research the geometry of Apollo 4 capsule has been selected and studied. The design of the designed geometry is as shown in Figure 1.

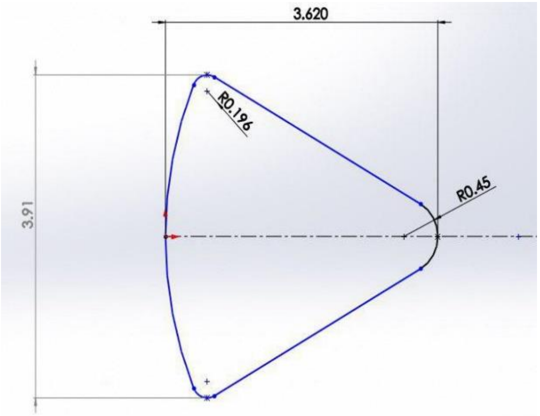

Figure 1- Geometry (nose radius of 4.5 m)

Due to the capsule axisymmetry, the axisymmetric condition is used to solve the flow. In other words, the solution field contains half of the geometry and the generated network is shown in Figure 2. As shown in Figure 2, an attempt has been made to have the aspect ratio in the shock formation range in the range of one. The minimum aspect ratio is one (in the range of shock formation which is important) and the maximum aspect ratio is 8 (near the free boundary).

The specifications of the generated network are in accordance with Table 1, which are obtained from the study of different networks and will be explained below.

Table 1 Specifications of the network produced for the Apollo 4 capsule

Number of Cells	10000
Quality of Mesh	0.0065
No. of Cells on the Wall	100
No. of Cells on the Vertical direction	100
First Cell from surface	10

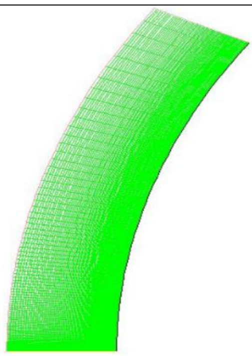

Figure 2 -A view of the generated network

Grid Study

To solve the flow field, it is necessary to produce a suitable network. The sensitivity of the results obtained from the field solution to the lattice is important and in this study the heat flux of radiation in the stationary zone has been considered to evaluate different lattices. Five networks with cell numbers 100, 900, 2500, 10000, and 19600 are produced and the amount of radiant heat flux obtained from each of these networks is shown in Figure 3. According to Figure 3, it can be seen that by increasing the number of cells, the heat flux of radiation has reached a constant value and the result obtained for the heat flux of radiation in the network with 10000 cells is not much different from the number of 19600 cells. Therefore, a network with a number of 10,000 cells has been selected as a suitable network for the field front.

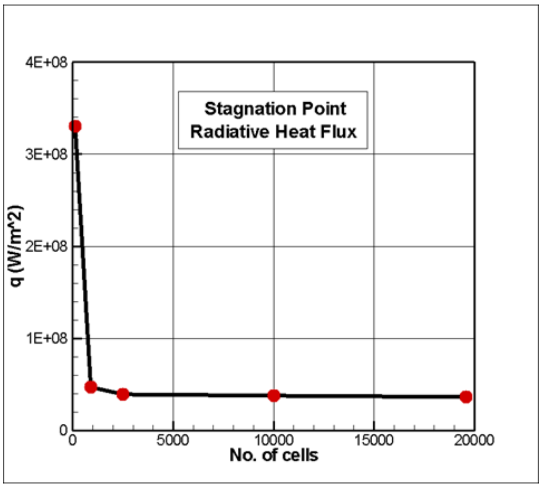

Figure 3- Grid study

Numerical method and equations

The equations used in this research are Navier-Stokes equations. The flow is considered to be compressible and stable, and the equation of continuity, momentum and energy is also solved in the flow field. To solve the flow, the base density method is used, in which the mass survival equation is used to calculate the density field, while the pressure distribution at all points is obtained using the state equation. Also stable equations, compressible flow around the return atmosphere capsule are solved.

To solve the flow field, the implicit method is used. In the implicit method for a given variable, the unknown value in each cell is calculated using a relation that contains both existing and indeterminate values of adjacent cells. . Therefore, each unknown appears in more than one equation in the system and these equations must be solved simultaneously to reach the unknown quantities. To calculate the fluxes, AUSM method is used, which is suitable for high velocity currents, and the Courant number is considered to be 0.75. The remote pressure limit is also used for initial quantification. The problem is axially symmetric and the symmetry boundary condition is used for this purpose. The model intended to calculate radiant heat transfer is described below

Radiation model

There are various experimental and numerical methods for calculating radiant heat transfer. The methods used in Fluent software version 16 are:

1. Discrete Ordinates Radiation Model
2. Discrete Transfer Radiation Model
3. P-1Radiation Model
4. Roseland Radiation Model
5. Surface to Surface Radiation Model

Each of the above radiation models have different characteristics and applications that are used in specific situations. In this research, the radial model of Discrete Ordinates (DO) has been used [9]. The reason for not using other models in the present study is as follows [10].
The surface to surface radiation model is not used for this simulation, because the main purpose of calculating the gas radiation is in the open air, and the calculation of the radiation of the walls relative to each other has been omitted [11].
The Roseland radiation model is suitable for pressure-based simulator simulations, where a density-based solvent is used. The discrete transfer radiation model cannot be used for diffusion surfaces and mirrors. Because in the discrete Transfer model, it is assumed that all surfaces are diffusers, while in this paper both diffusers and mirrors are assumed. The P-1 radiation model is suitable for optical thicknesses greater than 1, while in this study, the optical thickness is less than 1. Therefore, the P-1 model is not suitable for the desired simulation.

The Discrete Ordinates Radiation Model is one of the five main models of radiation simulation in Fluent software that uses Equation (1) to calculate the heat transfer of radiation [12].

$$\nabla \cdot (I_\lambda(\vec{r}.\vec{s})\vec{s}) + (a + \sigma_s) I(\vec{r}.\vec{s}) = an^2 \frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi} \int_0^{4\pi} I(\vec{r}.\vec{s}')\Phi(\vec{s} \cdot \vec{s}') d\Omega' \quad (1)$$

In this relation, $\vec{r}$ position vector, $\vec{s}$ direction vector, $\vec{s}'$ scattering direction vector, s path length, a absorption coefficient, n refractive index, σ_s scattering coefficient, σ Stephan Boltzmann constant, I radiation intensity, T temperature , Ω' is the spatial angle and Φ is the phase function.
This model is used in all optical thicknesses and, unlike the Roseland model and the discrete transfer radiation model, can be used with the solvent based on density and in parallel processing. The discrete Ordinates radiation model uses the radiation transfer equation to calculate the radiation intensity. This model solves the radiation transfer equation for a limited number of spatial angles. The radiation transfer equation calculates the intensity of radiation at any position in a path with absorption, emission, or scattering.

Calculation of optical thickness

In a gaseous environment, the extinction coefficient depends on factors such as temperature, wavelength, pressure, and gas concentration, and its value is obtained from the sum of the absorption coefficient and the dispersion coefficient of the gas.

Optical thickness is a measure of the ability to dampen radiation. If radiation dampens quickly, it means that its optical thickness is high. In fact, the higher the optical thickness, the lower the penetration depth and the more opaque the environment will be. Optical thickness means a measure of the path length of a gas to attenuate radiation at the desired wavelength [13].

The relationship between optical thickness and extinction coefficient at a distance of 0 to S is defined as the following equation [14]:

$$\mathbf{K_\lambda(S)} = \int_0^{s} \mathbf{K_\lambda(s)^* \, ds} \quad (2)$$

Where $\mathbf{K_\lambda(s)}$ is the optical thickness and $\mathbf{K_\lambda(s)^*}$ the extinction coefficient. If we take the absorption coefficient as a constant in the calculations, the optical thickness is calculated from Equation (3):

$$\mathbf{K_\lambda(S) = aL} \quad (3)$$

In this Equation, **a** is the absorption coefficient and **L** is the longitudinal scale for the amplitude. In this paper, due to the high flight speed, the numerical absorption coefficient is constant. Therefore, the optical thickness is calculated from Equation (3), so for the present article, the optical thickness is equal to:

$$K_{\lambda}(S) = aL = 0.001 * 9.081 = 0.009081$$

Due to the fact that the optical thickness is less than 1, so the DO radiation model is the best choice.

Diffusion and mirror surfaces

Since radiation does not actually pass through the capsule wall, the wall type is considered opaque. Therefore, due to the choice of this type of wall, radiant radiation is reflected or absorbed to the surface. In fact, this type of wall does not transmit radiation, but either the reflected rays are absorbed or reflected. Diffuse failure in the wall section is a measure of the reflection beam from the surface. This value is actually equal to the ratio of the diffuser reflection to the sum of the diffuser reflection and the mirror. If this value is equal to 1, it means that all the reflected radiation is diffused and is actually reflected at a constant angle in all directions. But if this value is zero, it means that the reflection occurs in the form of a mirror, and if it is between zero and one, it means that both of the mentioned cases occur. Since the reflection of radiant rays in the real state can occur in both states, so this value in the present study is considered 0.5. To better understand this issue, Figure 4 is presented [1].

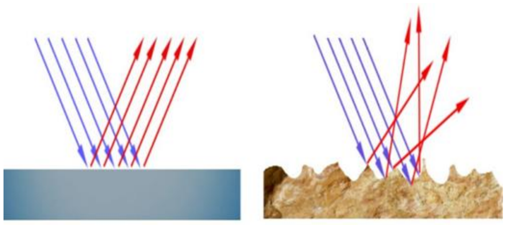

Figure 4 - Reflection from two surfaces
(a) diffuser (b) mirrors [1]

Gray gas and non-gray gas

Gray radiation for a gas is radiation emitted by gray gas. Gray gas is a gas whose absorption coefficient is independent of wavelength [12]. To model the gray gas radiation in the fluent, the number of bands is zero, and therefore, there is no need to determine the wavelength. In non-gray gas radiation, it divides the radiation spectrum into a number of wavelengths, so in Fluent software for modeling non-gray gas radiation, the number of bands is zero. When the gas is non-gray, the absorption coefficient and radiation in addition to the dependence on the characteristic length and pressure is dependent on the wavelength and temperature, and because temperature is variable, solving the radiation transfer equation is relatively complex and is associated with very large calculations and trial and error [15].

In Fluent software for modeling non-gray gas radiation, the number of opposite bands is zero. By examining the previous results and different references, two wavelengths (4-0.2) and (0.6-0.3) μm have been considered for the Apollo 4 geometry. Due to the fact that with increasing the number of bands, the cost of calculations increases, so according to the reference [5], the wavelength (4-0.2) μm is considered for the problem.

Numerical simulation

The base density method is used to solve the flow. In the base density method, the mass survival equation is used to calculate the density field, while the pressure distribution at all points is calculated using the state equation. Also stable equations, compressible flow around the return atmosphere capsule are solved. Given the assumption of flow compressibility at high velocities as well as the solution of heat transfer, the energy equation will be solved in addition to the momentum equation and mass survival. The problem is axially symmetric and the symmetry boundary condition is used.

A) Gray gas:

In the top panel, the number of bands for non-gray gas and angular discretization is determined. In the first step, we calculate the radiant heat transfer rate of the reentry capsule by considering the effects of gray gas. Gray gas is a gas whose absorption coefficient is independent of the wavelength. In modeling, there is no need to determine the wavelength by considering the gray gas. As a result, the number of bands is zero. This panel also examines angular discretization. Fluent software, for accurate measurement of these two angles, considers a measure of measurement accuracy. According to the software hypotheses, for setting ɵ and ϕ, the value of 2 is a good assumption, but it may not provide an accurate result in all situations.

But to set this value above 5, a reliable answer can be obtained to calculate the radiant heat transfer, which is due to the high number of lattices, and because by increasing this number, the solution time also increases many times over. According to the conditions of the problem, this value is considered 7. By increasing this value, there was no change in the numerical results of radiant heat transfer. A value of 7 is the best value for this problem.

B) Non-gray gas:

In the next step, assuming non-gray gas, the heat transfer rate of the radiation around the return capsule is investigated. Non-gray gas radiation divides the radiation spectrum into a number of wavelengths, so in Fluent software for modeling non-gray gas radiation the number of bands is zero. With the studies of two wavelengths (4-0.2) and (0.6-0.3) μm, it is considered for the geometry of Apollo 4 in Fluent software with increasing the number of bands, the computational cost increases, so according to the performed studies, the wavelength (4-0.2) μm is considered for the problem.

Validation

The calculated values for the radiant heat transfer rate and the convection heat transfer rate are compared with the results presented by Mr. Anderson [5] to validate the results obtained from the present study. Mr. Anderson has calculated the radiative heat transfer rate and displacement for the Apollo 4 capsule at rest. Note that the point of inertia is of particular importance for analysis due to the high temperature and maximum pressure, and the values provided in different sources for radiant heat transfer are usually provided for the area around this point. It should also be noted that the correct calculation of the thermodynamic and transfer properties of air is very important to obtain the radiant heat transfer rate. Then, the heat transfer rate of radiation in the shock layer is analyzed using the appropriate radiation model (DO) and gray gas and non-gray gas. In gray and non-gray gas, fluid particles emit or absorb radiant energy from other fluid particles produced in the shock layer. Also, the propagation of radiation from the shock layer gases to the body causes non-adiabatic flow [16]. In this way, if the temperature of the shock layer is high enough, the fluid elements in the stream will emit and absorb radiation. This makes the flow non-adiabatic.

In the present study, the radiant heat transfer rate for the desired geometry has been calculated at an altitude of 200,000 feet and at velocities of 10,000, 20,000, 30,000, 40,000, and 50,000 feet per second.

The air is assumed to consist of $\boldsymbol{O_2}$ and $\boldsymbol{N_2}$ [17] and the other species are excluded. However, due to the high velocity of objects returning to the atmosphere (here Apollo 4 capsule), the air in the shock layer decomposes and even ionizes, and due to the increase in the density of electrons $\boldsymbol{NO^+}$ $\boldsymbol{O^+}$ $\boldsymbol{N^+}$ around the body, especially in the stationary zone, disrupts radio communication in a part of the flight path where estimating the density of electrons will be of great importance [16]. The purpose of this paper is only the heat transfer rate, which is presented and compared with the assumption of gray gas and non-gray gas.

A) Validation with gray gas

Reference article data [5] has been used to validate the results obtained from the present research method. Figure 5 shows the results obtained next to the reference article data. The rate of radiant heat transfer and heat transfer of the return capsule to the atmosphere with a tip radius of 4.5 m and an altitude of 60.96 km are compared and investigated in this figure. In this diagram, both radiant heat transfer rate and displacement heat transfer are shown and presented logarithmically in terms of flight speed (from 10,000 to 50,000 feet per second). In this diagram, the assumption of self-adsorbent gas and gray gas and non-coupled radiation is used in the DO radiation model, and it should be noted that in gray gas, the effect of the absorption coefficient is independent of the wavelength

The processes of absorption and propagation of radiation in the shock layer create a non-adiabatic flow field. This non-adiabatic nature affects the convection heat transfer and friction of the shell. The cooling effect of radiation reduces the enthalpy potential in the thermal boundary layer, thus reducing the surface convection heat transfer. In gray gas, the fluid elements in the boundary layer absorb and emit the radiant energy generated by other fluid particles, which is very different from the self-absorption effect in gray gas, which has an absorption coefficient independent of the wavelength. The gas is non-gray. Previous results show that the adsorbent gas has a great effect on reducing the heat transfer of radiation but its effect on the convection heat transfer is small [18]. Overall, which primarily helps to reduce the heat of radiation, which means that a large fraction of the radiant energy is trapped in the shock layer. The effect of self-absorption is first seen in the ultraviolet. In the gray gas hypothesis, the problems related to spectral details are eliminated, which causes the gas to have high absorption at one frequency to low absorption at another frequency, thus having absorption properties in terms of thin optical thickness to thick optical thickness in the same flow region.

As can be seen from the diagram in Figure 5, the results obtained are in good agreement with the results of the reference article, and the difference between the results is due to the fact that the number of bands in the gray gas is not taken into account. The results obtained by assuming non-gray gas are less different from the results of the reference article presented below.

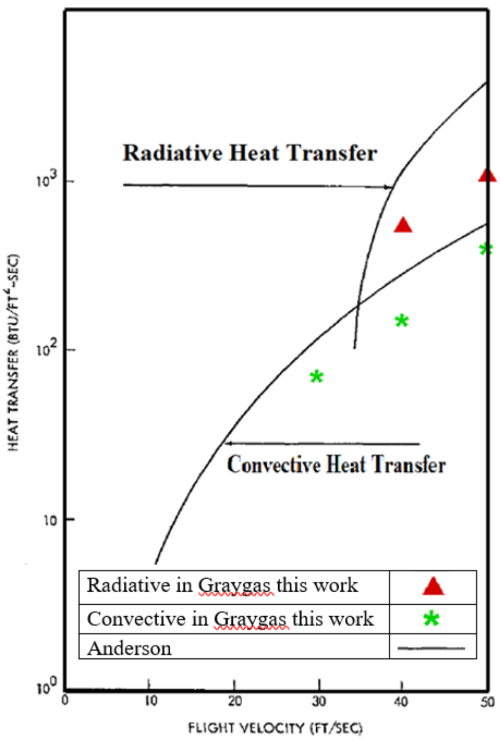

Figure 5 - Comparison of convective and radiative heat transfer rates (gray gas)

b) Validation assuming non-gray gas

The calculated values assuming non-gray gas are presented in Figure 6. According to Figure 6, it can be seen that the results are more accurate in the case of non-gray gas compared to gray gas, so then, assuming non-gray gas, the factors affecting the heat transfer of radiation are investigated.

In this case, non-gray gas radiation divides the radiation spectrum into a number of wavelengths, so in Fluent software to model non-gray gas radiation, the number of bands is zero. The radiation energy transfer of the shock layer due to non-gray self-absorbing gas is significantly reduced. More precisely, the continuous nature of the non-gray gas at high air temperatures causes it to absorb ultraviolet light while the shock layer is transparent relative to the wavelength. Non-gray self-absorbing gas reduces displacement heat transfer by 0-20% due to the effects of non-adiabatic flow of the shock layer. This reduction in stagnant heat transfer occurs at both the non-gray gas state shown in Figure 6 and the transparent gas.

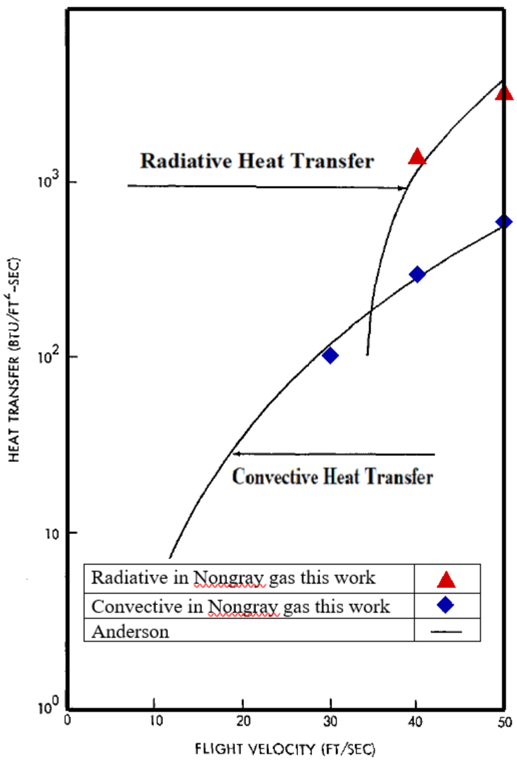

Figure 6 - Comparison of convective and radiative heat transfer rates (non-gray gas)

Results

In this section, the results of the calculations for the Apollo 4 capsule are presented. The altitude of the flight is 60.96 Km and the pressure, temperature, and current density are 17.7603 (Pa), 242.762 (K), and 0.0002537 (kg / m3), respectively. Mach number is also 48/66. In the following, the effect of different radiation parameters on the heat transfer rate of the Apollo 4 capsule is investigated.

The purpose of this study is to calculate the rate of radiant heat transfer using Fluent software and for this purpose the effective parameters must be modeled correctly. Unfortunately, there are not enough resources to calculate radiant heat transfer in high-speed flight, and in the few articles available on the details and values of the parameters has not been paid (we will see below that a very small change in them, changes the amount of radiant heat transfer rate several times). For this purpose, the necessary studies were performed to accurately select these parameters, which are very important and the results are presented below.

According to the criteria and assumptions of Fluent software, the default value for 1 and 2 is 2, but it may not provide an accurate result in all circumstances. By increasing this value, a reliable answer can be obtained to calculate the radiant heat transfer, but it should be noted that according to the number of networks required, increasing the value of these two angles can increase the solution time several times. The results obtained for the different values of these angles are presented in Figure 7, and according to the problem conditions and the results shown in Figure 7, the value of 7 is considered. As can be seen in Figure 7, by increasing this value, no change in the numerical results of radiant heat transfer is observed, and it can be said that the number 7 is a good value for this problem.

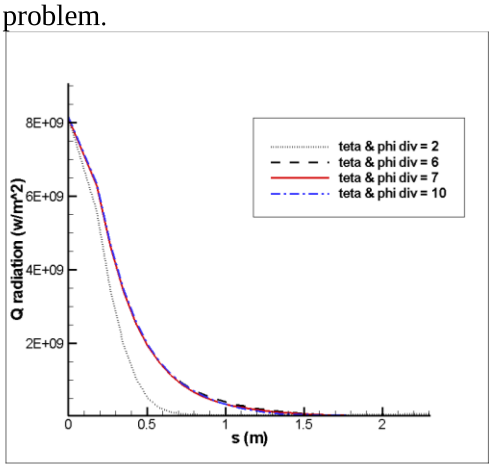

Figure 7 - Effect of angular discretization on radiation heat transfer rate

Figure 8 shows the air absorption coefficient in terms of different wavelengths for unbalanced flow. According to Figure 8, it can be seen that the amplitude of the absorption coefficient changes between the numbers 1 / m 0.1 to 1 / m 0.001. Therefore, to investigate the effect of this range of changes on the results, three different absorption coefficients were considered for gas according to Table 2. After investigating the radiant heat transfer in each of these values, the absorption coefficient was selected which had the lowest error value compared to the reference [19]. Eventually the complete gas absorption coefficient in the present paper was considered 0.001.

In Figure 9, the horizontal axis represents the distance from the capsule's stagnation point and the vertical axis represents the radiant heat transfer rate in terms of w ⁄m ^ 2, which is calculated assuming gray gas. In Figure 9, three different absorption coefficients are considered in the same flight conditions and at a speed of 50,000 feet per second. According to Figure 9, it can be seen that by decreasing air absorption coefficient, the heat transfer rate of radiation increases. Increasing the air absorption coefficient causes more radiant energy to be absorbed by the molecules in the boundary layer, which reduces the heat transfer of the radiation.

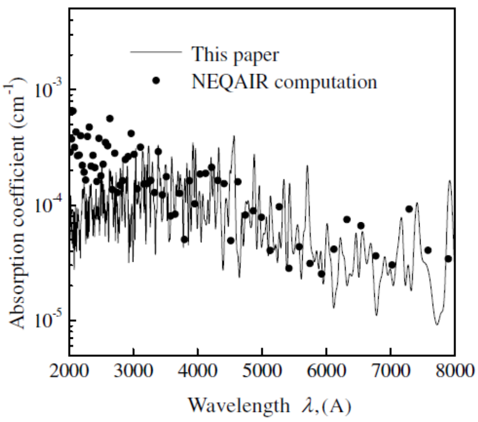

Figure 8- air absorption coefficient in terms of wavelength [19]

Table 2- Three different absorption coefficients to investigate radiant heat transfer

case	absorption coefficients
1	0.001
2	0.01
3	0.1

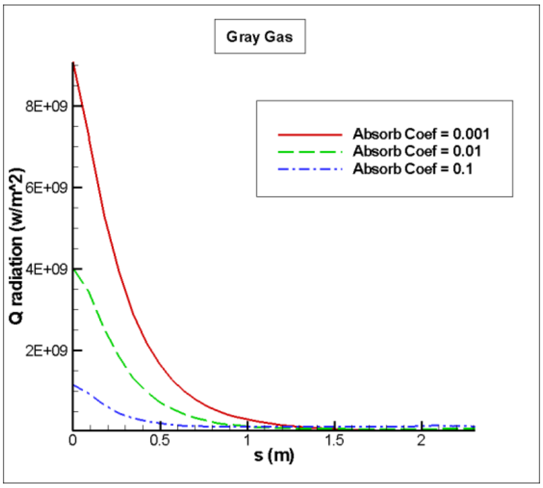

Figure 9 - Coefficient on radiant heat flux in gray gas state effect of air absorption

Figure 10 shows the effect of three different absorption coefficients on radiant heat transfer assuming a non-gray gas. As before, the effect of these three different absorption coefficients on the same flight conditions at 50,000 feet per second has been investigated. Comparing the results of Figure 10, which is taken in the case of non-gray gas, with the results of Figure 9, which is calculated with the assumption of gray gas, it can be seen that in both cases, the heat transfer rate decreases with increasing absorption coefficient. Radiation heat is further reduced. This behavior for non-gray gas is due to the non-isothermal (non-isothermal) structure of the shock layer.

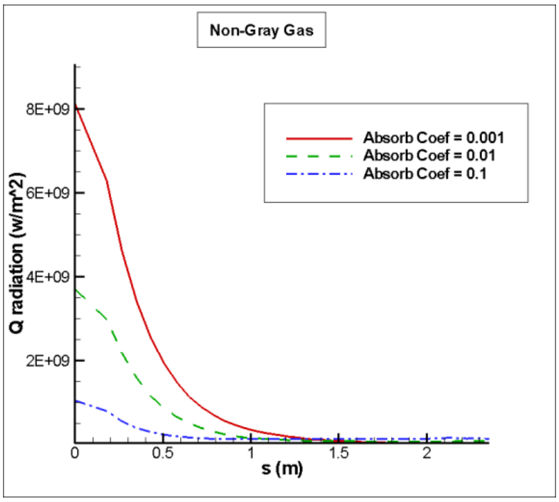

Figure 10- Effect of air absorption coefficient on radiant heat flux in non-gray gas state

The effect of air scattering coefficient on radiation heat transfer rate

Figure 11 shows the air scattering coefficient in terms of wavelength, which is clean for the air in different conditions and has dust, etc. This diagram is taken from experimental meteorological data. According to the problem conditions, three different scattering coefficients were examined according to Table 3, which are based on the studies performed and according to the values presented in the reference [20], the scattering coefficient value 0.0001 was selected.

According to Figure 12, it can be seen that the scattering coefficient changes do not have much effect on the radiation heat transfer rate. Because according to the radiation heat transfer relationship in the discrete classification (DO) model (Equation 1), the intensity of radiation decreases with increasing gas dispersion, which is a reduction term, but because the fourth term of this relationship absorption effect it receives from the scattering of the environment and increases with the scattering of this term, thus neutralizing the effect of reducing the intensity of radiation due to the increase of scattering of gas and the temperature changes remain almost constant.

According to the above diagrams, the sensitivity of radiant heat transfer to the scattering coefficient is very small, but the sensitivity of radiant heat transfer to the absorption coefficient is very high. The scattering coefficient selected for this paper is 0.0001, because the results in this value have the least difference with the reference paper.

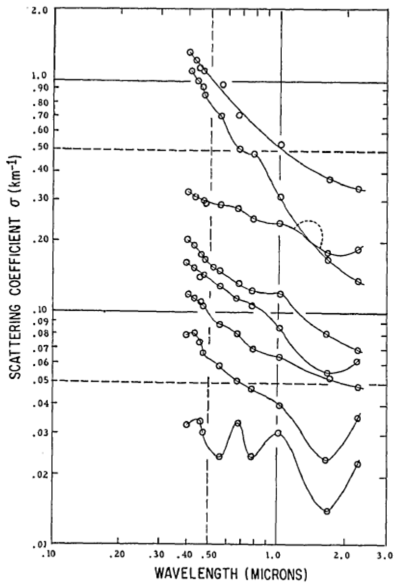

Figure 11 - Air scattering coefficient in terms of wavelength [20]

Table 3 - Three different scattering coefficients to investigate radiant heat transfer

case	scattering coefficients
1	0.0001
2	0.001
3	0.1

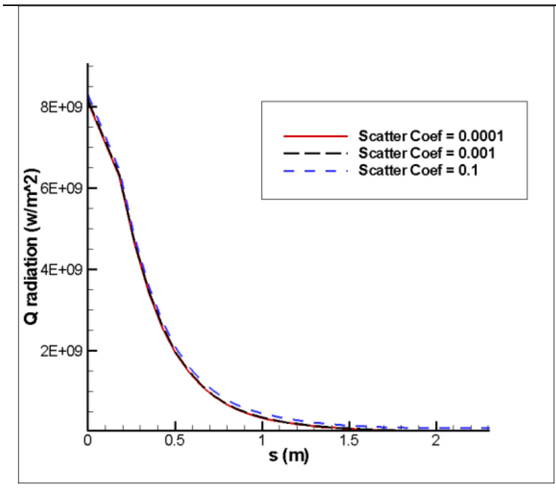

Figure 12- Effect of scattering coefficient on radiation heat transfer rate

Figure 13 shows a comparison of the heat transfer rate of radiation in two modes of gray gas and non-gray gas. In Figure 13, the horizontal axis is the distance from the stationary point and the vertical axis is the radiant heat transfer rate in terms of w ⁄m ^ 2. These results are calculated in the same flight conditions.

Figure 14 shows a comparison of the heat transfer rate of radiation and the heat transfer rate of convection in the static region of the capsule and in the same flight conditions. Figure 14 is calculated in the non-gray gas state. According to the figure, the heat transfer rate of radiation in the stationary zone is approximately 8 times the rate of heat convection of displacement, which shows the importance of the heat flux of radiation in the stationary zone.

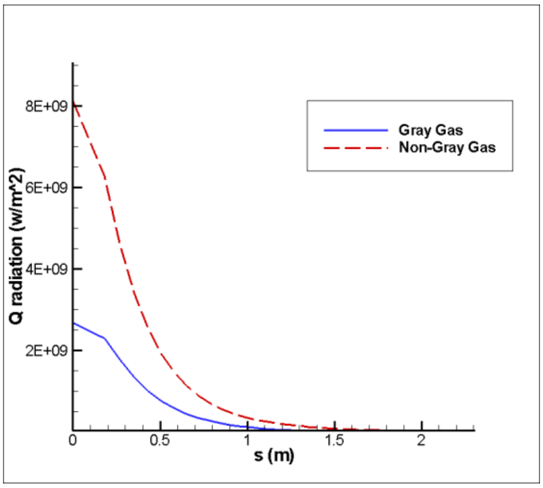

Figure 13- Radiation temperature in two states of gray gas and non-gray gas

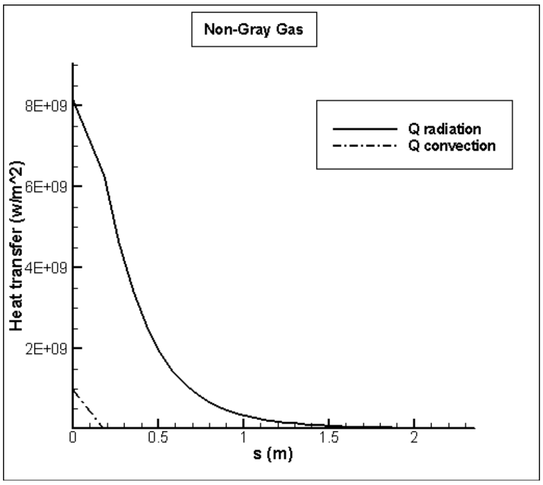

Figure 14- Radiation heat flux and convection heat transfer in the non-gray gas state

The calculated results for the total heat transfer in two modes of gray gas and non-gray gas in the same flight conditions and at a speed of 50,000 feet per second are presented in Figure 15. The combined effect of radiation loss and self-absorption in the shock layer of the capsule inertia region reduces radiant heat. But it has little effect on heat transfer. The effect of the adsorbent and the loss of radiation both tend to reduce the radiant heat of the capsule surface, in other words, the loss of radiation tends to reduce the heat of convection, while the adsorbent itself has a compensatory effect and tends to increase heat mobility. The net effect of self-absorption by all gas particles in the shock layer significantly reduces the total heat transfer, which primarily contributes to the reduction in radiant heat. This indicates that a large fraction of the radiant energy is trapped in the gas shock layer.

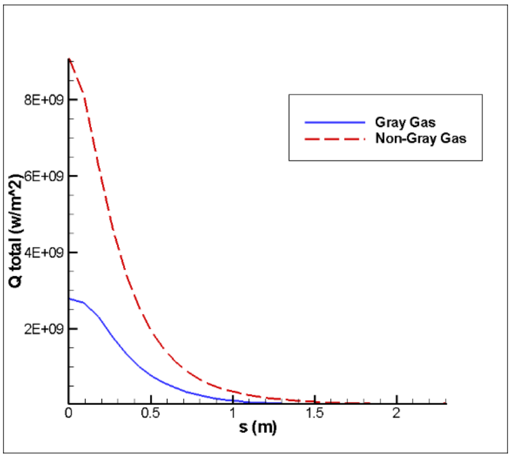

Figure 15- Comparison of total heat transfer in two modes of gray gas and non-gray gas

Conclusion

In the present paper, using Fluent commercial software version 16, radiative heat transfer has been simulated using a discrete classification radiative model with different assumptions of gray gas and non-gray gas. The reason for choosing this radiation model is that it is used for problems with all optical thickness ranges and can also be used in cases where heat transfer between the body wall and the environment is important. The results of this article can be summarized as follows:

The results of the present article have been compared with the available results, which shows the acceptable agreement of this data, in other words, it indicates the correct simulation of the problem and the correct selection of the required values.

In the case of non-gray gas, the heat transfer rate of radiation is higher than in the case of gray gas. These results are more accurate because the radiation spectrum is divided along the desired wavelength.

It was observed that by decreasing the heat flux absorption coefficient, radiation increases.

The results show that the heat transfer rate is very sensitive to the air absorption coefficient, but 1000-fold changes in the air distribution coefficient do not have much effect on the results.

Comparing the convection heat transfer rate and the radiation heat transfer rate, it was observed that the radiant heat flux is much higher than the convection heat transfer rate, so that it constitutes 80% of the total heat transfer rate.

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