DETERMINATION OF THE DEFLECTOR WALL THICKNESS AND INFLUENCE OF THE MAXIMUM ANGLE OF SHOCK WAVE ON HEAT EXCHANGE IN THE COMBUSTION GASES OF SOLID PARTICLES

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ABSTRACT

When a rocket engine is burned, it is necessary to release the combustion products away from the burning area so as not to damage the equipment and structures located on the side. This work presents a flame deflector and combustion gas design in launching platform. Such a device is intended to divert the exhaust jets and absorb a fraction of the high rate of existing heat, due to the high temperature of gases from the burning of fuel in the rocket engine. In this type of problem, the determination of the thickness of the deflector, and the material to be used in your manufacturing, are determining factors for the integrity of the launch pad. In this sense, we present in this work the temperature distribution along the deflector thickness, considering, for analysis, several materials in your construction. An analysis of the main parameters responsible for the heat exchange is carried out when a supersonic combustion jet, consisting of particles of gas and alumina, impacts the inclined surface of the deflector on a launching platform. The results show that, in relation to the location of shock wave detachment, it is possible to use the higher incidence angles when the exhaust gases contain a fraction of a solid component. This is a result that presents very important practical consequences: increased angles of incidence of jet are desirables, once they contribute to a lower launch platform and therefore less cost to the project.

KEYWORDS: *Solid fuel combustion; Launch pad; Convective flow; Shock wave; Supersonic flow; Surface thickness.*

I. INTRODUCTION

Deflector designs should be performed to protect electronic equipment and payloads housed inside space vehicles and, of utmost importance, the integrity of the launch pad Evans, R. L. [1]. Thermal shield designs shall contain information on the heat sources to which the structures to be protected shall be subject, so that material suitable for protection may be specified and the thickness meeting the limits imposed on temperature and thermal flow A. Paul et al. [2].
The outer surface of space vehicles receives thermal energy from the sun's rays, combustion gases, shockwaves caused by high jet velocities, and other heated bodies nearby, in addition to the effect of convection, called kinetic gas recirculation at high temperatures. All these effects contribute to the elevation of temperature Carvalho, T. M. B. et al. [3].
At the launch pad, the exhaust gases at high temperatures from the burning of the fuel heat up by radiation and convection both the platform and the external surface of the vehicle Jeeps, G. [4]. During the upward flight, part of the kinetic energy contained in the air flow is converted into thermal energy, which will be absorbed by the heat conduction by the vehicle structure. During the propelled flight, the external surface of the vehicle is exposed to the thermal radiation emitted by the combustion products.
Gaponov, S.A. et al. [5] realized an experimental investigation of the influence of the distributed blowing of heavy gas (sulfur hexafluoride, SF_6) into the wall layer of a supersonic boundary layer on a flat plate (at free stream Mach number M=2) on the laminar-turbulent transition. It is shown experimentally for the first time that in case of such blowing there is the boundary layer stabilization,

and the laminar-turbulent transition is removed downstream from the model leading edge. Experiments show that the heavy gas blowing stabilizes a supersonic boundary layer and increases the transition Reynolds number.

Vignesh Saravanan [6] et al. developed a comprehensive numerical study for the geometry optimization of a mobile rocket launch pad using a validated steady 2D density based. They have selected six different launch pad configurations for the parametric analytical studies. Among these, a launch pad facilitated with hemispherical shaped configuration shows relatively low noise level at both the horizontal and the vertical reference plane. They concluded that a mobile launch pad with a pragmatic mobile tunnel with hemispherical shaped inlet for the initial impingement of the rocket exhaust jet along with the water injection to the jet will be a possible option for the future launch pad designs.

Reynald Bur and Eric Garnier [7] stated that shock-wave/boundary layer interaction plays a major role in any circumstances where the flow becomes supersonic, either locally or in totality. They carried out an experimental investigation to quantify the effect of the shock-wave intensity on the boundary layer transition. Comparisons of results are performed on two configurations, one at a moderate shock intensity and the other for a strong shock intensity leading to a massive boundary layer separation.

In space vehicle design the analysis consists of identifying the main sources of external heating and, subsequently, to develop theoretical and experimental models' quantitative evaluation of the heating levels over critical regions of the vehicle. One of these heating sources consists of convective and radiative processes, due to exhaust gases at high temperatures on the launch pad. In fact, has already been demonstrated Carvalho et al. [3] that the temperature on the surface of the depends on the level of temperature of the exhaust gases encountered in the next to it. An uncontrolled flow of exhaust gases from the engine of a rocket at the time of launch of a vehicle, can cause serious damaged to the same and for the launch pad. It is necessary to implement actions to control and dissipate the large amount of energy emitted by the exhaust gases, with the objective of promoting, mainly, the integrity of the vehicle. One of the methods of protection is what uses a deflector system (Figure 01), which is a device that allows the jet to escape from exhaust gases out of the launch area.

In order to avoid damage to the jet deflector, it is essential to establish methods to predict and control the effects of exhaust jets John, N. B. [8]. One of the effects is the high heat rate in the jets, since they are at high temperatures and high speed. It is imperative to quantify this energy and at the same time divert the combustion products away from the burning area. To this end, that of deflecting the combustion products, the deflector is placed in the launching base, built with ablative material or not, depending on the type of design and whether or not it is cooled.

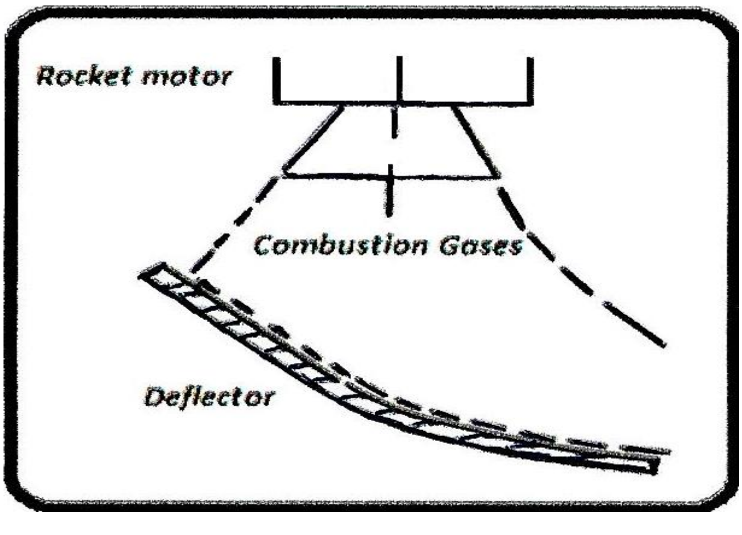

Figure 01 - Combustion jet deflector

This work presents a non-cooled flame deflector design with non-ablative material. Uncooled deflectors can be designed using two methods: ablative or non-ablative. In the non-ablative method, a material with high diffusivity is used to conduct heat through the surface in order to prevent melting of the material. This deflector does not lose material and has a long life when properly sized.

Metals are materials commonly used to design non-ablative type baffles. Any selected metal must have the ability to conduct heat along the deflecting surface at a rate that keeps the surface exposed at a temperature below its melting point. Some metals with high melting temperature and high thermal conductivity have the ability to withstand mechanical and thermal shock.

In the following sections we present the objectives, the fundamentals of kinetic heating caused by a supersonic shock wave of solid fuel coming from the engine, the calculation of the thickness of the flame deflector wall needed to withstand the heat flow during the time of the vehicle on the launch pad, and the conclusions relevant to the analyses carried out. Finally, we presented, like suggestion, section of future work that may be realized.

II. OBJECTIVE

When the exhaust gases flow under the surface of the deflector, the velocity of the jet decreases, at the same time as an increase in temperature and pressure. The angle incidence of the jet on the surface determines the decrease in speed. Few materials have physical and mechanical properties to withstand high temperatures and pressures.

Maintaining the integrity of the deflector is a serious challenge [2;8]. An analysis of the main parameters responsible for the heat exchange when a supersonic jet of gas and alumina particles collides on an inclined flat plate (Figure 02) is performed.

The main objective is to determine the wall thickness of the deflector, when subjected to the combustion gases of solid particles, at an angle of incidence of the pre-defined jet.

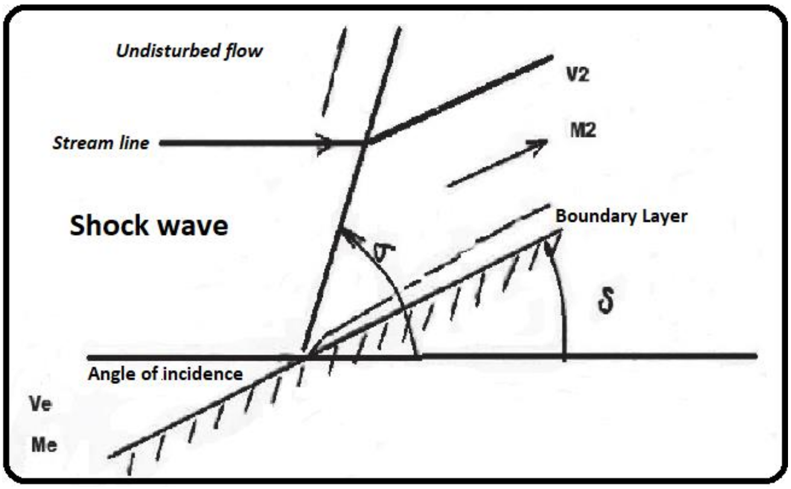

Figure 02 - Supersonic Jet colliding on Inclined Flat Plate

III. METHODOLOGY

As already mentioned, the major problem associated with to the deflector is in the high transfer of energy, in the form of heat, from the exhaust gases to the deflecting surface, and the limited ability of this surface to rapidly remove or absorb this energy, in order to prevent its physical integrity.

The solution of the problem in question involves the determination of the coefficient heat transfer of jet incident on the deflector wall. At high velocity, is influenced by the shock wave, the angle of incidence of the jet and the disturbances along the boundary layer, that form when the jet impacts on the deflecting surface.

At the point of impact of the jet on the surface (referred to as the stagnation point) the thickness of the boundary layer is negligible, and the coefficient of heat transfer is maximum. In this case Jeeps and Robson [4], the coefficient of heat transfer can be determined for very close points from the point of stagnation, to a jet without solid particles, by the equation:

$$\frac{h(x)x}{K} = 0.042 R_e(x)^{4/5} {P_r}^{1/3} \qquad (01)$$

Where,

$$R_e(x) = \frac{\rho_g V_x x}{\mu} \quad (2)$$

and

$$P_r = \frac{C_{pg}\mu}{K} \quad (03)$$

However, even for relatively distance from the point of stagnation, the coefficient of heat transfers due to the high speeds involved, is very high and, in this case, can be estimated by the expression by Evans and Sparks [1]:

$$\frac{h(x)x}{K} = 0.0296 R_e(x)^{4/5} {P_r}^{1/3} \quad (04)$$

The amount of heat transferred to the deflector surface is a function of the incidence and time of exposure to gases of exhaustion. As the exposure time increases smaller angles of incidence are required to reduce the transfer of heat. However, since smaller angles increase the height of the deflector and, logically, the height of the launch base, it is desirable to employ the highest incidence angle possible.

For geometric considerations and aerodynamics, it is demonstrated that the following expression makes it possible to determine the angle of deflection (σ) that the shock wave does with the direction of incidence of the jet Anderson, Jr. [14]:

$$\frac{1}{{M_e}^2} = sin^2\sigma - \frac{\gamma+1}{2}\frac{sin\sigma sin\delta}{\cos(\delta-\sigma)} \quad (05)$$

M_e is the Mach number associated with the angle of incidence (δ). In this case, provided the angle of incidence is known, and the velocity of impact (Ve), the pressure, the temperature and the number of Mach, after the shock wave, through the following expressions:

$$\frac{P_2}{P_e} = \frac{2\gamma}{\gamma+1}(M_e sin\sigma)^2 - \frac{\gamma-1}{\gamma+1} \quad (06)$$

$$\frac{T_2}{T_e} = \frac{(1+\frac{\gamma-1}{2}(M_e sin\sigma)^2)(\frac{2\gamma}{\gamma-1}(M_e sin\sigma)^2 - 1)}{\frac{\gamma+1}{2(\gamma-1)}(M_e sin\sigma)^2} \quad (07)$$

$${M_2}^2 = \frac{(M_e sin\sigma)^2}{\frac{2\gamma}{\gamma-1}(M_e sin\sigma)^2 - 1}(sin^2(\sigma-\delta))^{-1} \quad (08)$$

Where γ is the ratio of specific heats pressure and volume constant. The heat flux transferred from the gas to the surface is given by:

$$Q(x) = h(x)\left(T_{estag} - T_w(x,t)\right) \quad (09)$$

For points near the stagnation region, or

$$Q(x) = h(x)\left(T_r - T_w(x,t)\right) \quad (10)$$

For points distant from the stagnation region.

Where,

$$T_{estag} = T_e + \frac{{V_e}^2}{2C_{pg}} \quad (11)$$

$$T_r = T_2\left(1 + R\left(\frac{\gamma-1}{2}\right){M_2}^2\right) \quad (12)$$

Where R is the recovery factor.

The effect of variation of properties can be included Eckert, E. R. G. [10] in the above heat transfer ratios if these are evaluated at the recovery temperature Tr.

For understanding of the approximation made for biphasic flow, we synthesize the adopted steps:

Step 1 - Determination of deflection angle (δ);

Step 2 - Determination of P_2, T_2 and M_2;

Step 3 - Determination of the stagnation temperature (T_{estag}) and recovery (T_r);

Step 4 - Determination of the heat flow, with properties determined through T_r and P_2.

It is assumed that the mixture behaves as a pseudo-gas Wallis, G. B. [8], and the properties are determined through relations:

$$\bar{R}_e == \frac{\bar{R}}{1+\lambda} \quad (13)$$

$$C_e = \frac{C_{pg} + \lambda C_s}{1 + \lambda} \tag{14}$$

$$\gamma_e = \frac{1 + \lambda \frac{C_s}{C_{pg}}}{\frac{1}{\gamma} + \lambda \frac{C_s}{C_{pg}}} \tag{15}$$

Where $\bar{R}$ is the gas constant, C_s it is the specific heat of the solid and the λ it is the mass fraction of particles of alumina. We note that the solid medium is strongly dependent on temperature and, in in this case, we use the expression provided by Pessoa Filho and Cotta [12], Machado, H. M. [13]:

$$C_s = 41.063(22.08 + 0.008971T - 522500T^2) \tag{16}$$

The viscosity of the pseudo-gas is determined through Einstein's equation Wallis, G. B. [11]:

$$\mu_e = \mu_g(1 + 2.5\alpha) \tag{17}$$

Where,

$$\alpha = \frac{\alpha \rho_e}{(1 + \lambda)\rho_s} \tag{18}$$

In any type of deflector the greatest damage occurs at the point of impact of the jet, where the downstream flow direction is changed and where the stagnation front is formed. To reduce the effects of the boundary layer the deflector should be designed as flat plate in the collision area and a surface with a large radius of curvature in the area of direction change of the flow. The entire surface of the deflector shall be smooth and free of any protuberance in order to reduce the formation of stagnation points and prevent local heating.

The temperature of the wall is obtained through conduction heat transfer analysis, considering one-dimensional heat transfer (Flat Plate) in a transient regime, without ablation. The temperature profile, in this case, is given by T = T (r, t). Then,

$$\frac{\delta}{\delta r}\left[k \frac{\delta T}{\delta r}\right] = \rho C_p \frac{\delta T}{\delta t} \tag{19}$$

Where, r is the coordinate along the thickness of the material, k, ρ, Cp are, respectively, the thermal conductivity, the specific mass and the specific heat of the wall material.

The initial condition is given by:

$$T(r,t) = T_i \tag{20}$$

The boundary conditions are given by:

$$-k_1 \frac{\delta T(o,t)}{\delta r} = -h(0)[T(0,t) - Tr] + \epsilon q_{rad} - \epsilon \sigma T^4(0,t) \tag{21}$$

and

$$-k_2 \frac{\delta T(L,t)}{\delta r} = 0 \tag{22}$$

ε and σ are, respectively, the emissivity of the material and the Stefan-Boltzmann constant. L is the thickness of the deflector and Tr is the reference temperature.

The combustion products are hot gases and solid particles of high temperature alumina. The conditions of the combustion chamber, upstream and downstream of the shock wave are shown in Table 01.

Table 01: Shockwave properties

Combustion chamber: Temperature - 3200 K		
	Pressure: 5.65 MPa	
Shockwave properties	Upstream	Downstream
Velocity (m/s)	2490	
Temperature (K)	1430	2053
Pressure (N/m²)	10000	59000
Mach Number	3.3	2.1

IV. Results and Discussion

Through Figure 03, below, we analyze the effects of the angle of incidence and the fraction mass in the heat transfer coefficient average [$h_m(x)$], at a close distance the point of impact, where,

$$h_m(x) = \frac{1}{x}\int_0^x h(x)dx \qquad (23)$$

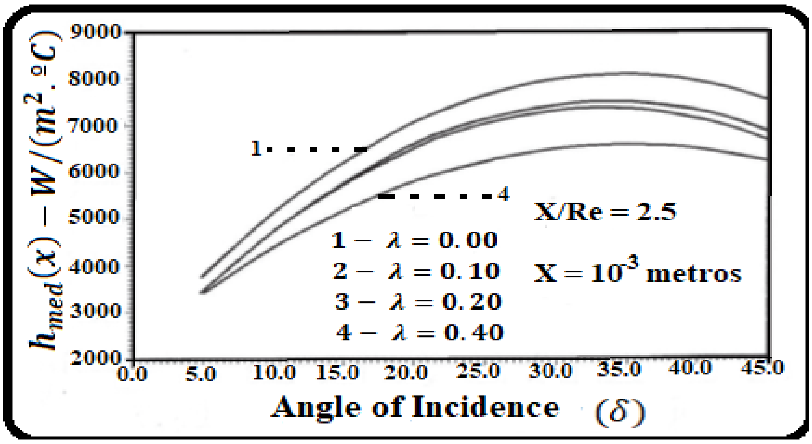

Figure 03 - Average heat transfer coefficient, at a distance of 1 mm from the point of impact of the jet, located at a distance equal to 2.5 times the radius of the divergent.

The coefficient of heat transfer average [$h_m(x)$] increases as the angle of incidence increases, up to around 35 °, for all mass fractions analyzed. From this limit, for all the situations, the transfer coefficient of decreases. It is observed that the transfer coefficient decreases for a given angle of incidence, when increasing the mass fraction of the solid medium.

Figure 04 shows that the coefficient of heat transfer is extremely high in regions close to the point of impact and decreases rapidly to relatively low values as it distances from this point increases.This demonstrates that, according to Evansand Sparks [1] and Jeeps and Robinson [4], preserving the integrity of the deflector material is, in fact, a serious challenge. It is observed that the coefficient of heat transfer is significantly lower in the region close to point of impact, when considering thesolid of 40% (λ = 0.40) of mass fraction,in relation to gas flow (= 0.00).

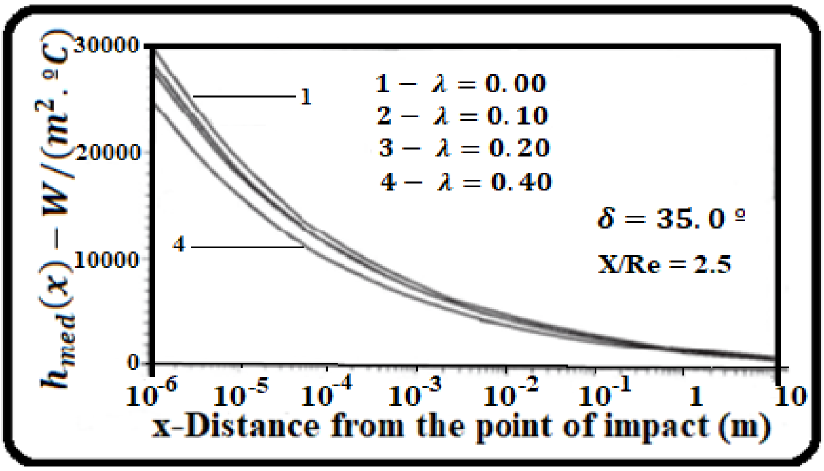

Figure 04 - Average heat transfer coefficient, function of the distance of the impact point, to the angle of incidence where the maximum heat transfer rate occurs.

The results presented in Figure 05 show that, with respect to the shock wave detachment point, it is possible to use more pronounced incidence angles when the exhaust gases contain a fraction of solid medium.

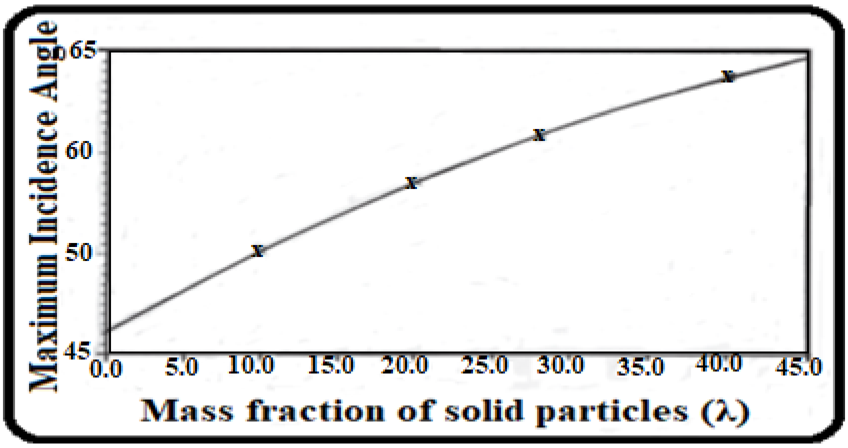

Figure 05 - Maximum Incident Angle, above which the shock wave separates from the surface, allowing exhaust gases to return.

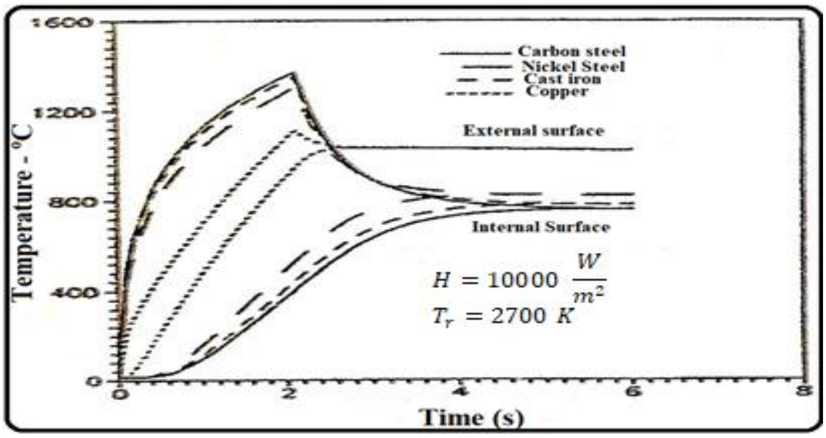

Figure 06 - Temperature distribution according to the materials under analysis

Although the particle radius does not appear explicitly in the analysis, the transfer coefficient is dependent on this parameter, since the velocity, temperature and pressure at the point of impact depend on it.

Table 02 - Materials used in the analysis of temperature variation on deflector surfaces.

MATERIALS	k (W/mK)	C_p (J/kg K)	ρ (kg/m3)	$T_{fusão}$ (K)
Carbon steel	54	465	7833	1482
Nickel steel	73	452	7897	1505
Cast iron	59	460	7849	1537
Copper	386	383.1	8954	1083

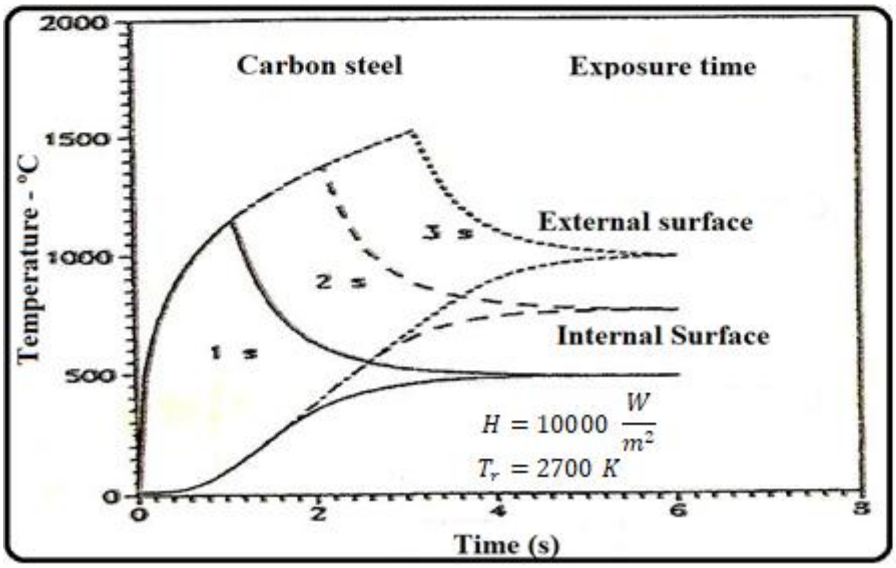

Figure 07 - Temperature distribution as a function of exposure time

Figures 06 and 07 shows the temperature distribution, along the thickness and as a function of time. It is considered that the vehicle remains in the launching base for 2 seconds and that it is submitted to the maximum thermal flow. After 2 seconds the vehicle is already in ascending flight and the thermal flow is practically zero.

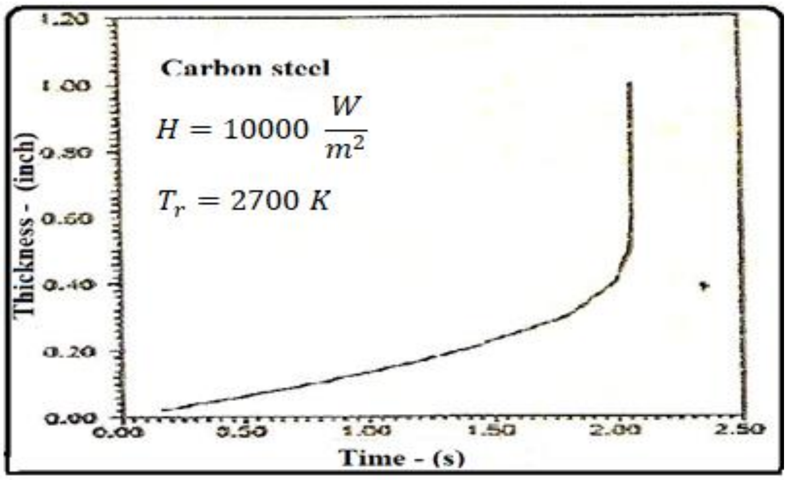

Figure 08 - Thickness required for the Deflector as a function of the exposure time

Figure 07 shows the temperature distribution of the Deflector, considering Carbon Steel, in three different exposure times. The less time the vehicle remains in the launch base, the shorter the time the Deflector will be exposed to a high heat transfer rate.

Figure 08 shows the required thickness of the Deflector as a function of the exposure time, without the constituent material, Carbon Steel, melting. As expected, the longer the exposure time, the greater the thickness required. However, for longer than 2 seconds, regardless of the thickness of the Deflector, the outer surface will melt.

V. CONCLUSIONS

Copper, because of its high thermal conductivity, very quickly conducts the heat from the external surface to the internal surface. After 2 seconds the copper is completely melted. Nickel steel has the lowest external surface temperature after 2 seconds of exposure on the platform. The cast iron has intermediate behavior among the steel types considered. Three materials can be used in the Deflector, since none of them reached the melting temperature after 2 seconds.

From the analysis carried out, it is verified that Carbon Steel has good performance, besides the advantages of low cost, easy acquisition and good malleability for conformation. Copper, Nickel Steel are noble materials of high cost. Cast iron, despite the low cost, is difficult to machine.

The coefficient of convective heat transfer on the surface of the Jet Deflector,when subjected to a two-phase gas flow is less than the heat flux obtained for a jet composed only of gases.

The maximum incidence angle, for which reflux of the exhaust gases occurs, is greater for the two-phase flow jet. The results obtained clearly demonstrate that, for exhaust gas from solid fuel, the launching platform may have a lower height than that of the platform used for combustion gases absent from solid particles, reflecting the final cost of the project.

VI. FUTURE WORK

As a suggestion for future work we highlight detailed thermal analysis of the base region of the vehicle during the first two seconds during the start.

Since the open literature for the analyzed problem is non-existent, it is suggested, for the complete validation of the results obtained through the present analysis, that experimental tests be carried out to estimate the coefficient of heat transfer.

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