AEROTHERMODYNAMIC HEATING IN THE COMPRESSION SECTION OF A SCRAMJET DEMONSTRATOR UNDER BALLISTIC TRAJECTORY

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Abstract. The crescent demand for more efficient and less expensive propulsion systems for space access vehicles is characterized by the development of advanced propulsion projects in several research centers around the world. The airbreathing propulsion technology based on supersonic combustion (scramjet) is a potentially advantageous alternative in comparison the usual and already consolidated system, the rocket engines. This paper focuses on the analytical investigation of the phenomenon of aerothermodynamic heating in a scramjet vehicle flight during an ascending ballistic trajectory. In this study, the methodology to evaluate the effects of this variation on the aerothermodynamic heating in the compression section of a scramjet demonstrator vehicle along the trajectory is present. The convective heat transfer magnitude was calculated using combined empirical correlations derived from the theories of Fay-Riddell, Lees and van Driest, according to each region of interest, respectively, the point of stagnation of the flow located at the leading-edge of the vehicle, the cylindrical segment outside the stagnation point and the linear ramp surface. The trajectory is vertical and ascending with a speed corresponding to Mach number of 6.8 and altitude varies between 30 to 80 km. Several combinations were considered, varying the temperature on the wall (1000, 1400 and 1800 K) and the curvature radius of the vehicle leading-edge (1, 5 and 10 mm). The present analysis indicates, for the conditions imposed, that the heat transfer magnitude is maximum at the stagnation point and describes characteristic behavior of sinusoidal curves on the cylindrical surface, and constant under the ramps. As indicated by the results, the heat transfer decrease through an upward trajectory and increases due to the effect of increasing wall temperature and the reduction in the curvature radius.

Keywords: Scramjet, Hypersonic flow, Aerothermodynamic Heating, Ballistic Trajectory.

1. INTRODUCTION

The airbreathing propulsion system based on supersonic combustion, or scramjet, is an aeronautical engine that uses oblique or conical shock waves to compress and decelerate the atmospheric airflow at hypersonic speeds. There is no need for oxygen storage reservoirs, reducing the total mass of the vehicle and increasing availability for effective payload (Anderson, 2003). Scramjets can reach hypersonic speeds above those corresponding to Mach number 5. The scramjet engine is incapable to generate impulse from the stationary regime and need thermodynamic conditions and minimum operating speeds. This problem can be solutioned using scramjets in rocket engine couplings as secondary propulsion stages. (Bezerra, 2020; Toro *et al.*, 2018).

Hypersonic speeds cause the phenomenon of aerothermodynamic heating from the effect of shock waves on the vehicle (Anderson, 2003). The heat flux behavior in aerospace vehicles can be predicted from a combination of empirical equations applied to specific regions of the vehicle surface.

Heat flux is an important parameter required in aerospace vehicle design. In the ascending ballistic trajectory, the vehicle will experience fluctuations in atmospheric properties due to altitude variation. In this perspective, this paper focuses on developing an analysis methodology for the heat flux evaluation under the effects of atmospheric properties variation in the compression section of a scramjet engine, through the theories of Fay-Riddell (1958), Lees (1956), and Van Driest (1956). These theories present an empirical approach for the convective effects on the heat flux evaluation. Radiation effects are not considered.

2. LITERATURE REVIEW

2.1 Properties of atmospheric air

The properties of the atmosphere vary with altitude. Figure 1 demonstrates the behavior of temperature, pressure and density of the atmospheric air in relation to the altitude. Pressure and density levels are highest at sea level and decay exponentially as altitude rises. Such behavior is justified due to the concentration gradient of air molecules in the atmosphere. On the other hand, Fig. 1 shows that temperature has a different and characteristic behavior for each atmospheric layer (troposphere, stratosphere, mesosphere, etc.). The constant temperature segments delimit the interface between these layers.
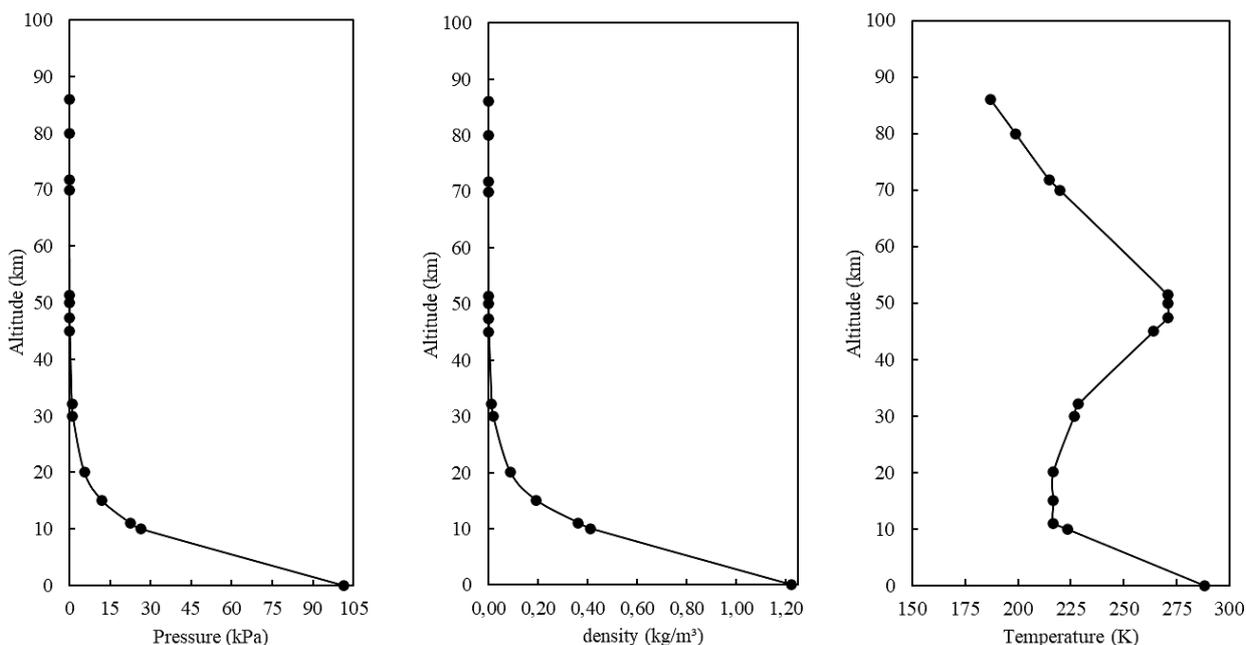
Figure 1 - Thermodynamic properties as a function of geometric altitude, U.S. Standard Atmosphere (1976).

2.2 Scramjet demonstrator

Heiser and Pratt (1994) describe terminology applied to scramjet vehicles. The vehicle is subdividing according to local physical phenomena, specifically into three main regions: the compression section (external and internal); the combustion section (isolator and combustor); and the expansion section (internal and external) (Fig. 2).
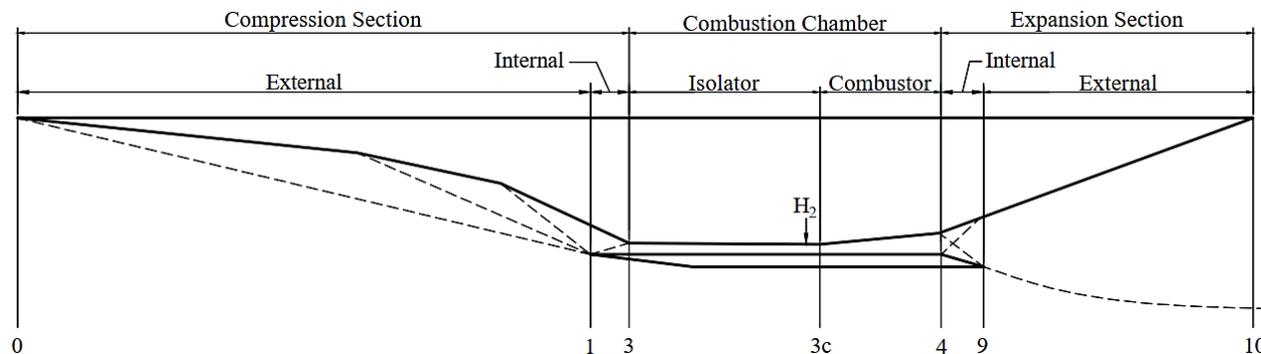
Figure 2 – Flow stations in a scramjet engine, adapted from Heiser and Pratt (1994).

The external compression section is governed by the incident shock waves, while the internal compression section by the reflected shock waves. The thermodynamic properties in this section are calculated according to oblique or conical

shock wave theories. In the combustion section fuel is usually injected at sonic speed so that the combustion process occurs at supersonic speed. The air temperature must be sufficient to raise the fuel temperature to the self-ignition point. Typically, one-dimensional (Rayleigh) flow heat addition theory is used to modeling the heat provided by the fuel burn. The internal and external expansion sections, in turn, are governed by the Prandtl-Meyer expansion theory and area ratio (Heiser and Pratt, 1994).

Toro *et al*. (2018) designed the compression section of a generic scramjet engine applying the theory of one-dimensional flow, disregarding boundary layer effects and air flow modeled as a calorically perfect gas. The scramjet is designed to operate at an altitude of 30 km and a speed of 2051.6 m/s (corresponding to Mach 6.8). As can be seen in Fig. 3, the geometry has three compression ramps with relative deflection angles equal to 5.5°, 7° and 8.5°, with a leading edge in the shape of a cylindrical segment with a radius of curvature R. In the original project the dimension of the radius of curvature was not considered, however, the influence of its variation evaluated in this study.
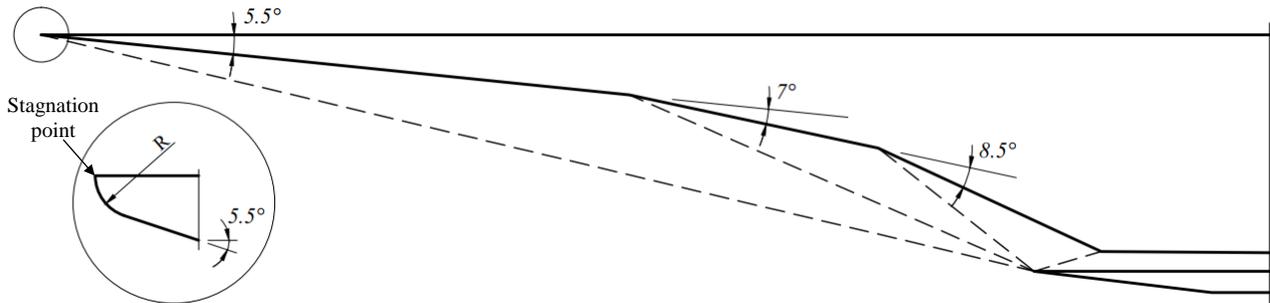

Figure 3 - Compression section of the scramjet engine, adapted from Toro *et al*. (2018).

3. METODOLOGY

In this section, the mathematical procedure of evaluation of the heat flux is presented. The heat flux across the surface of the compression section of a scramjet vehicle is analyzed differently in each specific region. Three regions of interest are classified by the stagnation point of the flow located at the vertex of the vehicle's leading edge (Fig. 3); the cylindrical segment outside the stagnation point; and the linear surface of the ramp.

For the vehicle stagnation point, the heat flux can be calculated according to the empirical correlation presented by Fay and Riddell (1958) applied to blunt planar bodies, according to Eqs. 1 and 2.

$$\dot{q}_{t,ref} = \frac{0.57}{\left(Pr_{w,t}\right)^{0.6}} (\rho_{t2}\mu_{t2})^{0.4} \left(\rho_{w,t}\mu_{w,t}\right)^{0.1} (h_{t2} - h_{wt}) \left[1 + (\text{Le}^{0.52} - 1)\frac{h_d}{h_{t2}}\right] \left[\left(\frac{du_e}{dx}\right)_{t2}\right]^{0.5} \tag{1}$$

$$\frac{du_e}{dx} = \frac{1}{R}\sqrt{\frac{2(p_{t2} - p_\infty)}{\rho_{t2}}} \tag{2}$$

where Pr is the Prandtl number, Le is the Lewis number, μ the dynamic viscosity, h the specific enthalpy, ρ is the density, p is the static pressure, R the radius of curvature, and the subscripts $_{t2}$ and $_{w,t}$ indicate, respectively, the properties at the stagnation point and the wall of the blunt body.

Considering that the gas is in chemical equilibrium close to the wall and the temperature in the wall is lower in relation to the temperature outside the viscous boundary layer, the Lewis number assumes a value equal to 1, the equation of Fay and Riddell (1958) can be reduced to Eq. 3. Although radiation effects are important at high altitudes, these equations only address convective effects on heat flux.

$$\dot{q}_{t,ref} = \frac{0.57}{\left(Pr_{w,t}\right)^{0.6}} (\rho_{t2}\mu_{t2})^{0.4} \left(\rho_{w,t}\mu_{w,t}\right)^{0.1} (h_{t2} - h_{wt}) \left[\left(\frac{du_e}{dx}\right)_{t2}\right]^{0.5} \tag{3}$$

The density can be calculated from the perfect gas equation and the dynamic viscosity according to the Sutherland relations described below (Eq. 4).

$$\frac{\mu}{\mu_r} = \left(\frac{T}{T_r}\right)^{3/2} \left(\frac{T_r + S}{T + S}\right) \tag{4}$$

where $\mu_r = 1.789 \times 10^{-5}$ Pa.s is the reference viscosity evaluated at the temperature of $T_r = 288$ K and S is the Sutherland constant or effective temperature, with S value = 110 K.

For calorically perfect gases the specific enthalpy is a function of the state temperature according to Eq. 5 (Anderson, 2003).

$$h = c_p T \tag{5}$$

The second region of interest is the cylindrical segment outside the stagnation point. The relations of Lees (1956) applied to bodies can be used to solve the heat flux methodology (Eqs. 6 and 7). The theory relates the heat flux ratio relative to points on the cylindrical surface according to angular positioning and heat flux at the stagnation point. Angular positioning varies in the range between the angle corresponding to the stagnation point and the angle of intersection of the curvature with the linear region of the ramp.

$$\dot{q}_w = (\dot{q}_w)_0 \frac{2\theta \sin\left\{\left[1 - \frac{1}{\gamma M_\infty^2}\right]\cos^2\theta + \frac{1}{\gamma M_\infty^2}\right\}}{\sqrt{D(\theta)}} \tag{6}$$

$$D(\theta) = \left(1 - \frac{1}{\gamma M_\infty^2}\right)\left(\theta^2 - \frac{\theta \sin 4\theta}{2} + \frac{1 - \cos 4\theta}{8}\right) + \frac{4}{\gamma M_\infty^2}\left(\theta^2 - \theta \sin 2\theta + \frac{1 - \cos 2\theta}{2}\right) \tag{7}$$

where M_∞ is the freestream Mach number and γ is the specific heat ratio.

The upper limit corresponding to the intersection angle between the curvature and the linear segment of the ramp θ_r is quantified according to the deflection angle of the first compression ramp $\theta_{1,n}$ according to Eq. 8.

$$\theta_r = \frac{\pi}{2} - \theta_{1,n} \tag{8}$$

Finally, the last region of interest is the linear surface of the compression ramps. van Driest's (1956) theory for the heat flux applied to flat plates can be used in this region as follows, according to Eqs. 9, 10 and 11.

$$\dot{q}_w = St^* \rho^* u^* c_p \left[T^*\left(1 + r\frac{\gamma - 1}{2}M_\infty^2\right) - T_{w,t}\right] \tag{9}$$

$$St^* = \frac{0.332}{Pr^{2/3} Re^{*1/2}} \tag{10}$$

$$Re^* = \frac{\rho^* u^* x}{\mu^*} \tag{11}$$

where the term x is the length of the ramp, St^* is the Stanton number, Re^* is the Reynolds number, r is a correction factor of the reference temperature T^* ρ^* is the density, u^* is the velocity and μ^* is the dynamic viscosity. Properties referenced with an asterisk are calculated as a function of the reference temperature.

The van Driest's theory (1956) describes that the heat flux along the linear segment of the slopes is constant and depends on the flow properties in the boundary layer region. The r factor is equal to 0.85 for laminar flows.

4. RESULTS AND DISCUSSIONS

First, atmospheric properties data were collected from the US Standard Atmosphere (1976) in the range between 30 and 80 km of altitude. The thermodynamic properties of the atmosphere for all altitude points, the thermodynamic property ratios from the theory of shock waves, the thermodynamic properties in the wall, and finally, the heat flux for all atmosphere situations along the three previously mentioned regions of interest, were calculated. All equations were applied following the described process flow. As a result, graphs were constructed that correlate heat flux with atmospheric properties.

The Mach number was considered constant for each altitude state to evaluate the heat flux. The atmosphere temperature influences the speed of sound and consequently the Mach number, so, assuming that the vehicle performs ascending ballistic flight, the effect of atmospheric temperature must be compensated by modifying the vehicle flight speed. Figure 4 demonstrates the relationship between vehicle speed and geometric altitude.
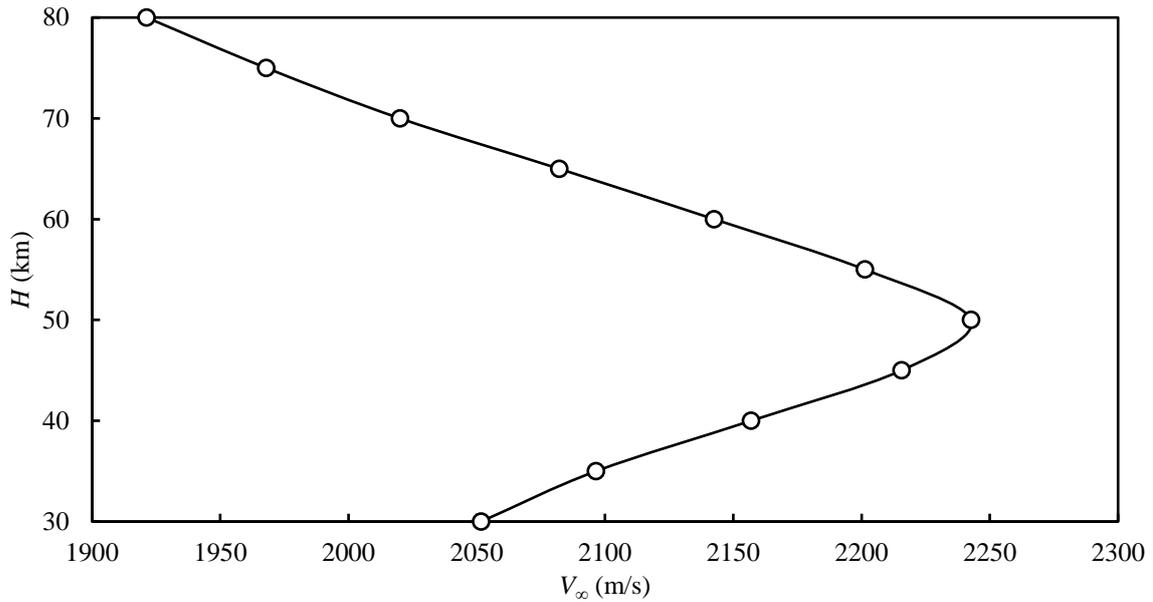
Figure 4 – Flight trajectory of the scramjet vehicle.

In the region of the boundary layer, a constant wall temperature $T_{w,t}$ was assumed and wall pressure equal to the pressure at the stagnation point of the scramjet $p_{2t} = p_{w,t}$ for three configurations of the radius of curvature of 1, 5 and 10 mm at the leading edge of the scramjet vehicle, with $T_{w,t} = 1000$ K (Fig. 5). In a second moment, to evaluate the influence of the wall temperature on the process, considering the configuration of the scramjet with a radius of curvature of 1 mm, the calculations were performed for, specifically, 1000, 1400 and 1800 K of wall temperature (Fig. 6).
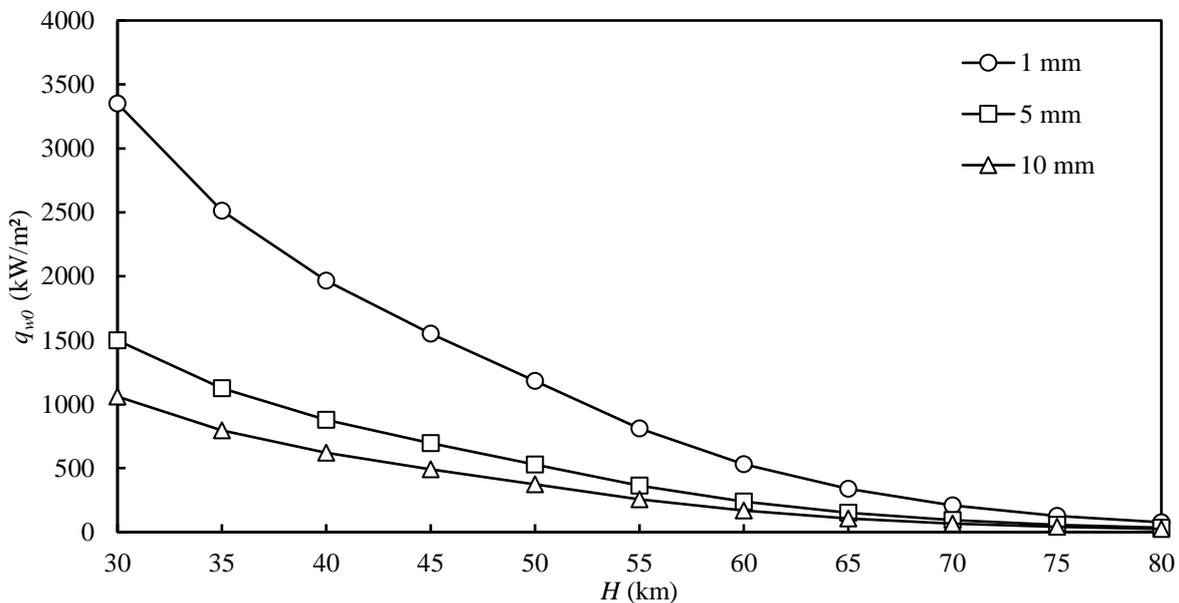
Figure 5 - Effect of the curvature radius on heat flux at the flow stagnation point ($T_{w,t} = 1000$ K).

It is possible to observe that as the vehicle moves in the atmosphere in ascending ballistic flight, there is a decrease in the heat flow along its trajectory. The highest levels of heat flux are calculated at lower altitudes. The effect is justifiable due to the higher levels of pressure and density. Atmospheric temperature acts by causing small fluctuations that are more evidently noted in vehicles with a larger curvature radius at the leading edge. Furthermore, the curvature radius showed a significant reduction in heat flux, about 68.37% relative reduction observed between the 1 mm and 10 mm curves, at all points of altitude. At the same time, lower wall temperature levels have greater heat fluxes. The temperature gradient between the hot viscous boundary layer and the cold wall surface is responsible for the effect. In other words, greater temperature gradients imply greater heat fluxes. However, very high temperature levels under wall surfaces are

undesirable due to the ablation phenomenon. This phenomenon is characterized by the loss of material caused by the melting or vaporization of the materials of the wall surfaces.

The curvature radius R are inversely proportional to the velocity gradient du_e/dx.. This fact explains why there is a significant reduction in heat flux with the increase in the curvature radius. However, very large curvature radius can impair the functioning of the scramjet by displacing the oblique shock wave in a different direction than the projected one. The airflow may do not get thermodynamic properties necessary for combustion to occur in the scramjet combustion chamber.
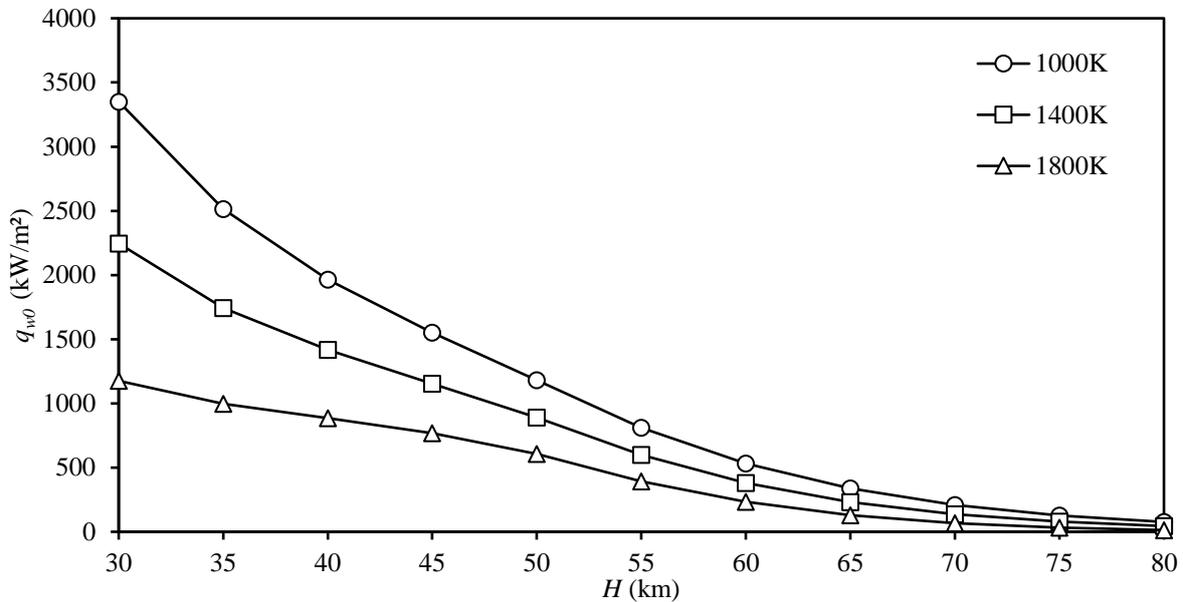
Figure 6 - Effect of wall temperature on heat flux at the stagnation point of flux (R = 1 mm).

Heat flux in the cylindrical segment outside the stagnation point relates to relative heat flux according to an angular position, in the form of a function dependent on the angle θ, as shown in Fig. 7. According to Eq. 8 and knowing that the deflection angle of the first ramp is 5.5°, the upper limit of the angular position is 84.5°. A sinusoidal decay of the flux is observed of heat with the addition of the bending angle independent of the bending radius or the wall temperature.
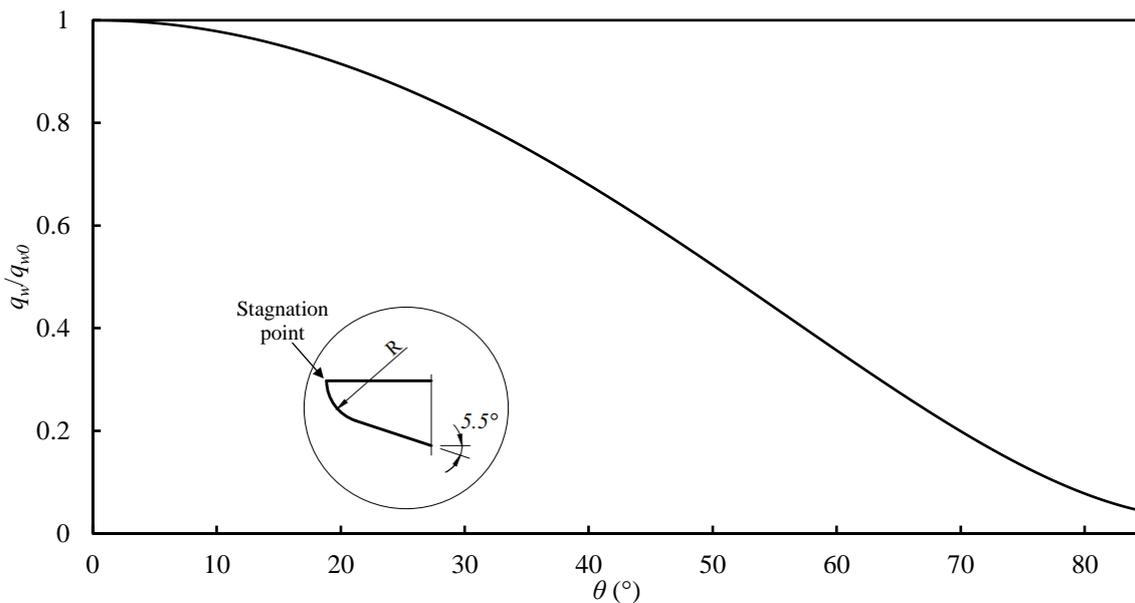

Figure 7 - Heat flux as a function of the angular position of the cylindrical segment of the leading edge.

The heat flux is constant over every flat surface and decreases with increasing altitude, as shown in Fig. 8. The behavior is similar to the situations already presented. There is a gradual reduction of the flow with the increase, presenting

small fluctuations, mainly due to the oscillating characteristic of the atmospheric temperature. The superposition of the curves occurs due to the deceleration of the flow due to the effect of the oblique shock waves.
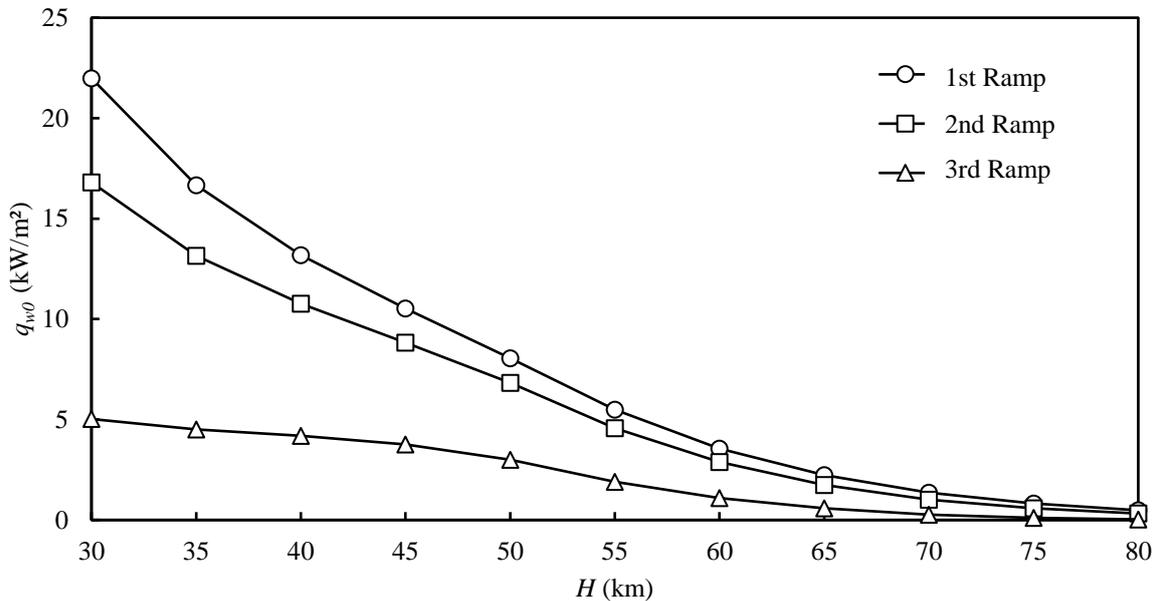

Figure 8 - Heat flux on compression ramps ($T_{w,t}$ = 1000 K).

5. CONCLUSIONS

This paper focuses in present analyses of the effect of the atmospheric thermodynamic properties in the heat flux in a scramjet generic vehicle moving in an ascending ballistic trajectory. The heat flux behavior was evaluated observing the variation of geometric characteristics, atmospheric and wall surfaces conditions.

Through the results it is concluded that the vehicle speed at altitudes between 30 and 80 km must vary between 1921 m/s to 2243 m/s so that the Mach number remains constant. This imposition allows that the intensity of the shock wave doesn't vary, consequently, the ratios of air thermodynamic properties will remain constant during the entire displacement of the vehicle. Therefore, only the atmospheric properties have a direct influence on the temperature, pressure and density after the shock wave and on the viscous boundary layer formed on the vehicle surfaces.

The heat flux is maximum at the stagnation point, decreases on the adjacent surfaces and rises with decreasing altitude. The increase in the curvature radius due to a significantly reduction of the heat flux, in the order of 68.37% of relative reduction between the curves of 1 mm to 10 mm. Furthermore, the effect of the temperature gradient between the hot viscous boundary layer and the cold wall surface showed an inversely proportional relationship between heat flux and wall temperature. High temperatures on wall surfaces are undesirable from a structural point of view, what needs to be better investigated is the phenomenon of determining forms of temperature control, including using cooling systems. On the cylindrical surface adjacent to the stagnation point, a characteristic sinusoidal curve behavior is observed with the addition of the curvature angle. An interface between the cylindrical segment and the flat surface occurs at 84.5° relative to the stagnation point. From this point on, the heat flux and from this model is constant along the surface and smaller as the flow is subjected to a new compression resulting from a shock wave.

In a worldwide scenario, the point of greatest interest in scramjet projects, as far as aerothermodynamic heating is concerned, should be the vehicle's leading edge. This necessarily requires more investigations in the optimal determination of the curvature radius, such that it reconciles the reduction of the heat flux without compromising the vehicle's efficiency. In addition, more investigations of the atmospheric influence on the combustion process, as well as prospecting for new advanced materials that efficiently resist the heat flux levels estimated here are necessary.

6. ACKNOWLEDGEMENTS

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8. RESPONSIBILITY NOTICE