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THE STUDY OF THE GAS JET GENERATED BY A ROCKET ENGINE

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Abstract: *During the launch of the missile, the launching system is subject to stress both mechanically and thermally. The jet of hot gas of the missile propulsion system has a major contribution to this stress, directly influencing the strength of the various components of the launcher, its stability and oscillating motion during launch, so, implicitly, the accuracy of firing. Therefore, the knowledge of the stresses to which the launching system is subjected, due to the action of the gas jet is particularly important in the design phase, in order to be able to anticipate the necessary constructive, functional and operational measures.*

Keywords*: rocket engine, gas jet properties, thermo-gas dynamics processes*

1. Introduction

The study of the gas jet of the rocket engine on the launching system is a very complex problem, which combines thermodynamic and mechanical methods of analysis, being the subject of a vast chapter (jet theory) in a separate subject - thermo-gas dynamics. The literature offers an analytical solution to this problem only for subsonic, slightly hot jets [1]. The relations determined for such jets, however, are not confirmed in the case of jets of the type existing in rocket engines, in which, in addition to supersonic speeds and much higher temperatures (1500°C), other complex phenomena appear, such as turbulent flow, gas dissociation, etc. Therefore, the study of such a jet is mandatory on an experimental basis; the ratios given below can be used only for approximate, preliminary design calculations.

2. The study of the general properties of the gas jet of a rocket engine

This study should start from the theory of free (unrestricted by walls), isothermal (same temperature with that of the environment in which it egresses) turbulent jet, which propagates in an environment with the same properties as that of the jet gas.

The jet particles entrain particles from the undisturbed environment, and thus an exchange of particles takes place between the jet and the unperturbed environment, as a result of which the jet mass increases, its width increases, and the velocity of the jet particles decreases. By entraining the particles of the environment in the jet, they consume the energy of the jet particles. As a result, the boundary layer of the jet is formed, the thickness of which increases in the jet direction of propagation. In the initial section of the jet, the thickness of the boundary layer is zero (Figure 1), and the velocity of the particles is uniform, having its maximum value.

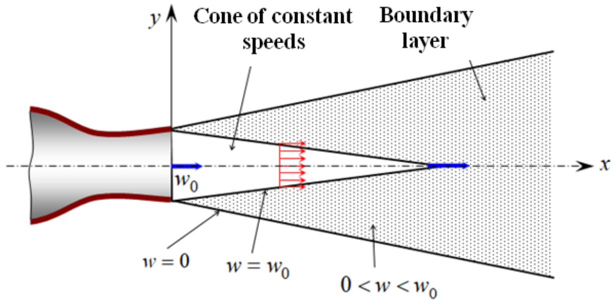

Figure 1 Isothermal free turbulent jet scheme

On the outside, the boundary layer is in contact with the unperturbed environment, the particles of which are at rest. Inside, the boundary layer is bounded by the cone of constant speeds, inside which the velocity of the particles is equal to the velocity in the initial section. As the distance to the outlet section of the rocket engine nozzle increases, the thickness of the boundary layer increases and the cone of constant speeds narrow. Downstream of the cone tip of constant speeds, all particles belong to the boundary layer, their velocity decreasing continuously until it cancels out.

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Figure 2 The gas jet generated by a 122 mm calibre unguided reactive projectile

In the case of non-isothermal jets, due to the difference between the density of the jet gas and that of the environment, there will be a deviation of the jet axis, upwards or downwards, as the jet temperature is higher or lower than that of the environment. In the studied case (a jet that presents a very large temperature difference) the deviation of the jet is significant, so the hypothesis of unidirectional flow can no longer be made, as in the case of the isothermal jet (Figure 2).

Due to the large temperature difference, Archimedes' similarity criterion, which expresses the ratio between the ascending force and the inertial force of the particles, will play a significant role in the geometry of the jet.

This non-isothermal jet has two axes and two limits, one referring to speed and the other to temperature (Figure 3). Usually, the temperature axis increases less deviated than the speed axis. In calculations, the mean of the two axes is accepted as the single axis of the jet. The dynamic divergence is slightly larger than the thermal one. Also, the jet area of action is thermally smaller than the area of dynamic action.

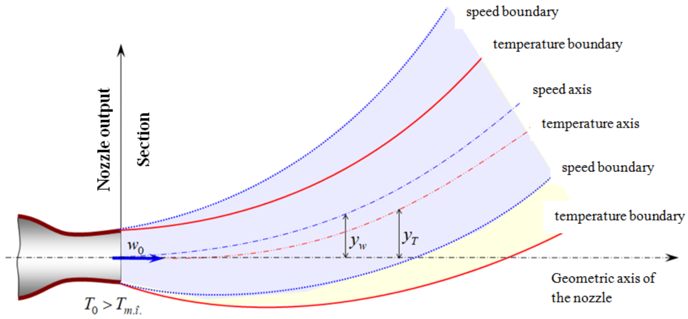

Figure 3 Non-isothermal free jet scheme

Such a jet is divided into three areas:

– *the transition zone* has a curved boundary and is characterized by a strong brightness, due to the continued combustion of fuel particles downstream of the nozzle outlet section. The evolution of the gases in this zone is determined by the ratio between the pressure in the nozzle outlet section p_e and atmospheric pressure p_a; they suffer a relaxation, if $p_e > p_a$, or a compression, if $p_e < p_a$. The transition zone is comprised between the nozzle outlet section and the initial jet section (for which the static pressure in the jet is equal to the atmospheric pressure);

– *the initial zone* of the jet is comprised between the initial section and the passage section, being determined by the length of the cone of constant speeds;

- *the main zone* of the jet, is located downstream of the passage section.

Within the jet three cones can be distinguished, which are based in the initial section: the cone of constant speeds, the cone of constant temperatures and the cone of supersonic speeds.

The high-temperature supersonic jet of a rocket engine differs from the subsonic turbulent jets, a little warm, by a series of peculiarities, of which the most important are:

- continuation of combustion outside the nozzle, a phenomenon that determines the existence of the transition zone;
- supersonic flow velocities determine the change of the jet shape:

– the length of the initial zone, x_0 increases;

– the limits of the jet are narrowing;

– the decrease of the axial speed and the axial braking temperature, as it moves away from the nozzle outlet section, is less pronounced, therefore the dynamic action distance of the jet will be greater;

- due to the high jet temperatures, the heat exchange with the environment is more intense and, as a result, the law of jet propagation as well as the value of the braking temperature change; for the same flow speeds, the higher the jet temperature, the smaller the length of the initial zone x_0, the deformation of the jet boundary is stronger, and the decrease of the axial speed and of the braking temperature is more accentuated as it departs from the nozzle.

3. Jet parameters in the initial section

Static gas *pressure* in the initial section of the jet, S'_e, is equal to atmospheric pressure (at ground level $p'_e = p_a \cong 1 \text{ daN/cm}^2$). Between the outlet section of the nozzle and the initial section of the jet considered, conventionally, where the static pressure becomes equal to the atmospheric one, a series of very complex phenomena take place. Thus, in this area, called the transition zone, the expansion phenomena of a supersonic jet overlap at the outlet of a Laval nozzle, determined by the ratio between the pressure in the nozzle outlet section and the atmospheric pressure, with the post-combustion phenomenon behind the nozzle. Therefore, for the calculation of the other parameters of the jet in this area, simplified models will be presented below, specifying that a study of fineness of this area requires a much more complex approach [2].

Gas velocity in section S'_e is determined starting from the energy conservation equation, written for the nozzle output section, $e-e$, and the initial section of the jet, $e'-e'$, for an adiabatic-isentropic evolution:

$$\frac{i_e}{A} + \frac{w_{ee}^2}{2g} = \frac{i'_e}{A} + \frac{w_e'^2}{2g} \quad \textbf{(1)}$$

where

i – specific enthalpy of gases;

w – gas velocity;

A – the mechanical equivalent of the calorie;

g – gravitational acceleration;

Whereas

$$i = c_p T \; ; \; c_p = \frac{k}{k-1} AR \, , \qquad \textbf{(2)}$$

where

c_p – the specific heat of the gases at constant pressure;

T – gas temperature;

R – gas state constant,

the result is

$$\frac{i}{A} = \frac{k}{k-1} RT \qquad \textbf{(3)}$$

Length of transition area, x_t, is determined by considering that this is greater than the divergence $\left(D_e - D_e'\right)/2$ by a number of times equal to the mean Mach number of the area

$$x_t = \frac{M_e + M_e'}{2} \frac{D_e - D_e'}{2} \qquad \textbf{(4)}$$

4. Jet parameters after the initial section

The study is done in the following hypotheses:

- the jet parameters (speed, temperature, pressure, density) in the initial section are constant and equal to their average values in this section;
- the jet can be considered as a sum of concentric jets, with identical parameters in the initial section S_e';
- the static pressure inside the jet is constant and equal to the pressure of the unperturbed environment; as a result, the density enjoys the same property;
- the jet propagates in an unperturbed gaseous environment with constant temperature and density;
- density jumps (shock waves) and pulsations in the supersonic area of the jet are neglected;
- the momentum (amount of motion) of the gas masses is preserved (it has the same value in any cross section of the jet).

Based on the last hypothesis, it results:

$$I = \int_0^m w_{xr} \mathrm{d}m = \int_A \rho w_{xr}{}^2 \mathrm{d}A = \mathrm{ct.} \qquad \textbf{(5)}$$

where it was taken into account that:

$\mathrm{d}m = \rho w_{xr} \mathrm{d}A$, mass of the gas element;

ρ – gas density;

w_{xr} – gas velocity in the considered section;

$\mathrm{d}A$ – the elementary area in that section; for an axial-symmetrical jet (circular section), $\mathrm{d}A = 2\pi r \mathrm{d}r$.

The average gas velocity in any section of the jet is:

$$w_{x\text{med}} = \frac{\dot{V}_x}{A_x} = \frac{\dot{V}_x}{\pi R_{grx}{}^2} \quad \textbf{(6)}$$

where A_x is the area of that section.

Dimensionless average speed for any section at a distance x from the initial section, of radius R_x, will be:

$$\frac{w_{x\text{med}}}{w_e'} = \frac{\dot{V}_x}{\dot{V}_e'}\frac{A_e'}{A_x} = \frac{\dot{V}_x}{\dot{V}_e'}\left(\frac{R_e'}{R_x}\right)^2 \quad \textbf{(7)}$$

The lengths of the three characteristic zones of the jet are of particular importance, given that the range of the jet is a very important measure, which characterizes its area of action[3]. For the length of the main zone, however, only a dependency relation can be established with respect to the value of the velocity in the jet axis, in the sense that the section in which the value of the velocity in the jet axis is equal to, for example, $0,2\,\text{m}/s$ is accepted as a final section of the jet. So, the length of the main jet zone results from the calculation of the axial velocity $w_{xr=0}$. The variation of the temperature in the boundary layer of the jet takes place due to the mixing of the jet gases with the gas absorbed from the environment, which, in the case of non-isothermal jets, have different temperatures. Obviously, there is also a heat exchange with the environment which is untrained by the jet, but its share as to the jet-driven heat exchange with the environment is negligible.

5. Conclusions

Following the determination of the thermo-gas dynamic parameters in the jet points, the mechanical and thermal action of the jet on the different parts of the launching installation, arranged in the respective points of the jet, can be determined.

When the jet of exhaust gases through the engine-rocket nozzle encounters an obstacle, its energy is partially transmitted to the obstacle and partially dispersed by the gases flowing around the obstacle. Due to the obstacle, the direction and speed of the jet change. Energy transfer from jet to obstacle depends on the type of obstacle and the gas flow regime.

References

[1] M. J. Chiaverini and K. K. Kuo, Fundaments of Hybrid Rocket Combustion and Propulsion, AIAA Progress in Astronautics and Aeronautics, Arlington, Texas, 2007

[2] P.Somoiag, C.E. Moldoveanu, S.Buono, Mathematical Model for Computing the Unguided Rocket Trajectories, The International Scientific Conference - Defense Technology Forum 2015, Shumen, Bulgaria

[3] P.Somoiag, C.E. Moldoveanu, S.Buono, Researches Concerning the Aerodynamic and Ballistic Performances of an Unguided Missile, The 2nd Edition of The New Challenges in Aerospace Sciences International Conference, NCAS 2015