PERFORMANCE OF A RAMJET USING POLYBUTADIENE AS SOLID FUEL

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Abstract. *The aim of this work is to simulate in test bench the performance of a solid fuel ramjet (SFR), using hydroxyl terminated polybutadiene (HTPB) as fuel. The oxidant needed to burn this fuel is the oxygen contained in an air stream previously heated and compressed by means of a device called "vitiated air generator", which emulates real flight air conditions. In parallel with the propulsion uses, ramjet is also a well suited means for studying polymers combustion properties, like temperature, regression rate, pyrolysis characteristics, etc. The results obtained are well in accordance with previous ones obtained in similar configurations using several polymers as fuels.*

Keywords: *ramjet, hydroxyl terminated polybutadiene, vitiated air generator, fuel regression rate.*

1. INTRODUCTION

Solid fuel ramjets (SFR´s) constitute an important subject in the current stage of propulsion research. These systems can incorporate the high performance achieved by conventional liquid fuel ramjets to the simplicity of solid fuel motors, leading to significant advantages related to fabrication and operation costs.

A ramjet is an air-breathing propulsion device. As it flies at a certain speed and altitude, the air captured from the atmosphere is heated and compressed as it passes through the shock wave established in the air intake entrance section. Air pressure is additionally increased as it traverses the diffusion zone of the engine and, in the combustion section, this hot, high-pressure air stream is put in contact with some fuel, that can be liquid or solid. The resulting combustion gases are then expanded in a nozzle to produce thrust.

The extreme simplicity and ease of operation of solid ramjets is fundamentally based in the fact that they need no movable part to perform properly. On the other hand, they do not have starting capability: they have to be led up to an initial speed, at which the incoming air reaches the expected values of pressure and temperature downstream the shock wave.

Figure 1 shows a schematic view of a typical solid fuel ramjet.

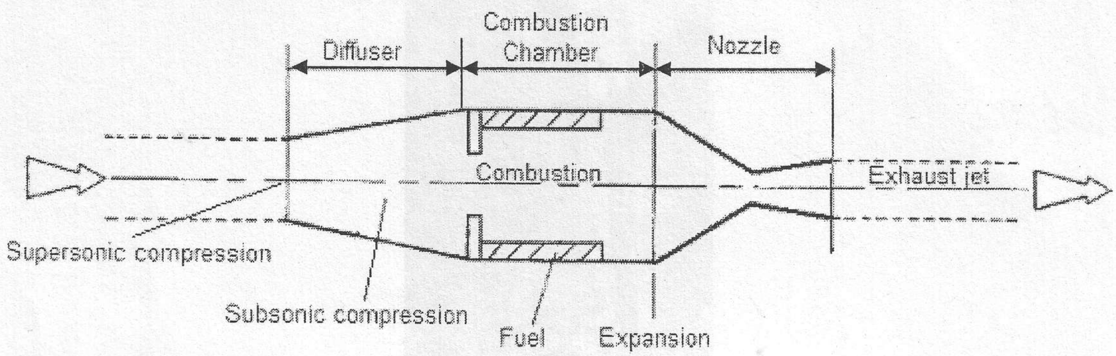

Figure 1. Schematic diagram of a solid fuel ramjet engine.

In Brazil, research on this subject is intended to provide understanding of the main features that control the performance of the propulsion system. Migueis (1986) designed, built and ran a static test stand that simulates SFR´s flight conditions. Ronzani (1989) established simplified theoretical models of the characteristic processes that occur in a SFR, mainly in the combustion chamber. Veras (1991) used the work of Ronzani as the basis for an experimental research with a SFR operating with polyethylene as the solid fuel. Silva (1995) continued Veras´ work improving knowledge over polyethylene burning phenomenon.

In this work, the following problems, usually associated with the study of this propulsion device, were considered:

1. The design and building of a convenient experimental set to simulate real flight conditions;
2. The selection of a fuel material;
3. The determination of fuel regression rate as a function of flight speed and altitude;
4. The fulfillment of flame holding requirements;
5. The definition of mixing, heating and reaction sections in order to take maximum profit of diffusion controlled by combustion processes.

2. SELECTION OF FUEL MATERIAL

Some desirable characteristics for a material to be chosen as a fuel in a ramjet are the gravimetric or volumetric heat release, the combustion properties (ease of ignition, stability, etc), the ease of processing, the cost and the availability.

Hydroxyl terminated polybutadiene is the fuel used in this research. It is the most commonly used binder for composite propellants and it fulfils the requirements above. Its combustion properties are a matter of great interest in propulsion field. The ramjet combustion conditions allow the study of these properties, providing a means to evaluate its linear regression rate, a procedure which is otherwise hard to perform.

3. THE EXPERIMENTAL SET

A critical problem in SFR development is the fact that, in the static test of these systems, it is necessary to bring a relativity great amount of air to the pressure and temperature found in real flight conditions. In this study these conditions are reached by the use of the so-called vitiated air generator. In such device, a stream of air is forced through a chamber where an exothermic reaction takes place. A stoichiometric reaction between oxygen and hydrogen was chosen, mainly because it produces a very clean reaction product: water vapor. With this procedure, air pressure and temperature can be conveniently regulated, so it is possible to reproduce virtually any set of chosen conditions. Generators of cylindrical geometry are known as "connected-pipe" type.

A vitiated air generator, connected-pipe type was projected and instrumented in order to simulate an ideal ramjet engine in flight Mach number 2.2, at sea level.

The system is composed by three sections. The first one is the expansion chamber where the air is admitted, undergoing slight expansion and where the flow is streamlined. After passing the expansion chamber, the air traverses the heater where the reaction between oxygen and hydrogen takes place, transferring heat to it. Finally it enters into the ramjet body, with the selected values of pressure and temperature. There, it reacts with the solid fuel. All these chambers were properly sized and shaped to produce the expected air conditions.

Figure 2 shows the experimental arrangement used in this work.

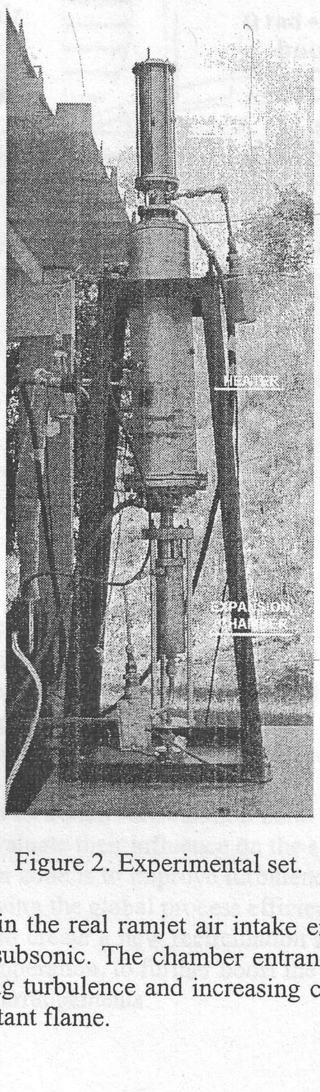

Figure 2. Experimental set.

Due to the existence of a normal shock in the real ramjet air intake entrance, the internal flow in the real and, of course, in the emulated ramjet chamber, is subsonic. The chamber entrance step is responsible for the formation of a recirculation region which, besides improving turbulence and increasing combustion reaction rates, plays the role of a flame holder, providing stability for the resultant flame.

Experimental works, often cited in literature, show that there is a critical height for this step, below which the flame cannot be hold and is blown away from the chamber. This was also observed by Migueis (1986) and Veras (1991). In this work the ratio between entrance step and the internal bore diameter suggested by Zvuloni (1989), H/D=1.33, was successfully used.

Figure 3 shows the processes taking place along the experimental ramjet chamber. Air enters in the chamber and establishes a recirculation zone whose length is proportional to the entrance step height, H. In this zone, high turbulence, elevated heat transfer rates and a very effective mixing between the incoming air and the gaseous fuel from HTPB pyrolysis are reached. These conditions lead to a high reaction rate while gaseous combustion products are formed.

This zone ends in a reattachment region where a turbulent boundary layer is established. A turbulent diffusion flame arises from the reaction between the species contained in the core gas and those coming from polymer pyrolysis. The convective and radiative heat transfer from the flame to the surface assures HTPB decomposition. The flame spreads out into the polymer bore.

In the post mixture chamber, the flow turbulence increases and the gases produced in the combustion chamber, which still contain oxidant and fuel species, continue to react, improving the system combustion efficiency. After the post mixture chamber, the resulting gases are expanded in a nozzle to produce thrust.

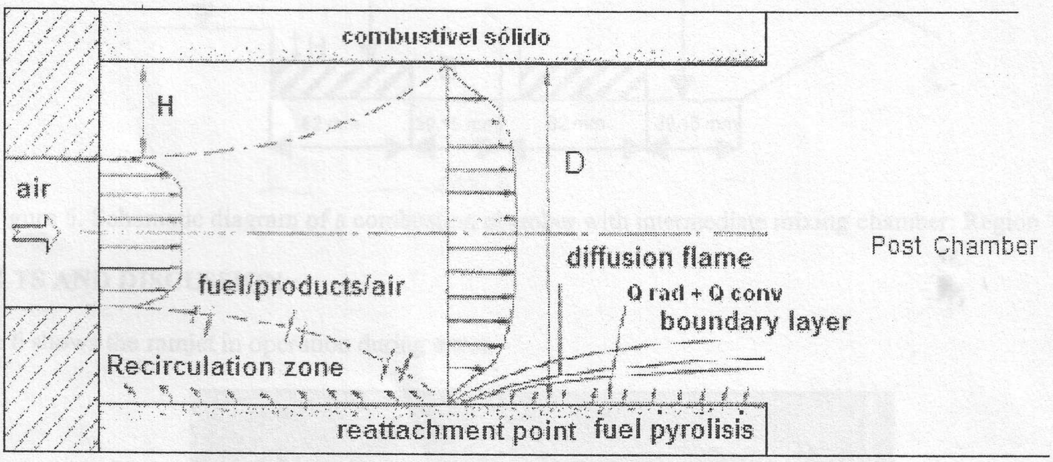

Figure 3. Schematic diagram of the combustion chamber.

The standard design parameters were:
L (length of grain)= 164 mm ,
H (height of recirculation step) = 6 mm,
D (grain bore diameter) = 35 mm,
$\dot{m}_{H2}$= 0,144 g/s,
$\dot{m}_{O2}$= 1.088 g/s,
$\dot{m}_{air}$= 57.2 g/s,
P_c(chamber pressure)= 6.7 atm,
T_{air}(air inlet temperature)= 586 K and
t (test time) = 20s.

To start the process, the igniter (a motorcycle spark plug) is turned on and hydrogen and oxygen are introduced in the heater. All gas streams come from commercial cylinders with initial 7.5 m^3 at 150 atm for hydrogen and 10 m^3 at 200 atm for oxygen, nitrogen and compressed air. The resulting stream of superheated water vapor is allowed to pass over the polymer surface for 20 s, increasing its temperature well above its ignition value (≈ 500°C). The air is then introduced in the system, passes through the vitiated air generator and enters in the ramjet chamber. The polymer ignition is instantaneous.

Experiments were also conducted with an extended recirculation zone and an intermediate mixing chamber, which were incorporated to the standard ramjet to evaluate their influence on the system performance.

The idea behind the extended recirculation zone is to improve turbulence, heat transfer rates and mixing beyond the levels attained with the normal one, so improving the global process efficiency.

The intermediate chamber was expected to create a new recirculation zone, with all the properties of the first one, this time dealing with reactants at a higher temperature, to further boost the combustion reaction.

Figures 4 and 5 show schematically these arrangements.

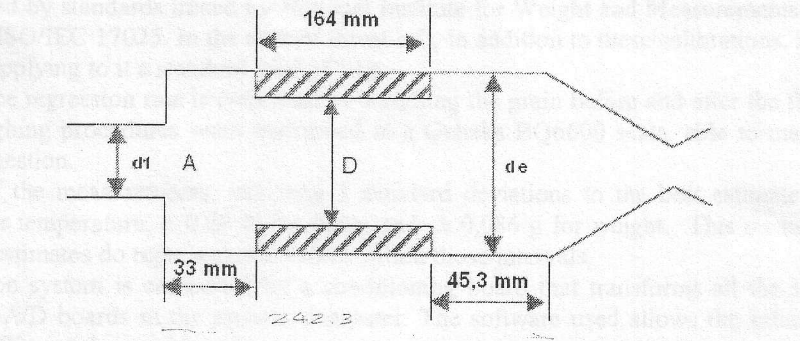

Figure 4. Schematic diagram of a combustion chamber with extended recirculation zone: Region "A".

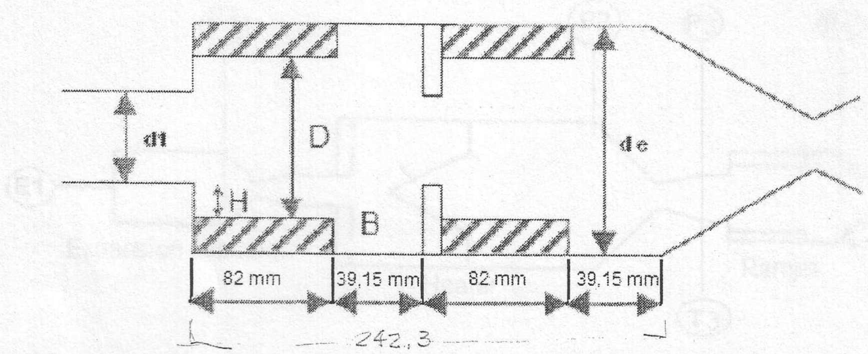

Figure 5. Schematic diagram of a combustion chamber with intermediate mixing chamber: Region "B".

4. RESULTS AND DISCUSSION

Figure 6 shows the ramjet in operation during a test.

Figure 6. Ramjet operation.

Pressures (P), temperatures (T) and thrust (E) were measured at the points shown in Figure 7.

The pressures were measured using integrated transmitters strain gage devices, with 4-20 mA outputs.

The temperatures were measured by K type thermocouples with stainless steel sheath and mineral insulation, internal cold joint compensation and 4-20 mA outputs, linked to local reading transmitters

The thrust was measured by a compression measurement strain gage device (thrust cell), linked to a transmitter with 0-5 V output and local reading indicator which allows zero adjustment at each test. In vertical tests the entire weight of the system is also applied on the thrust cell, so zero adjustments are needed to compensate this initial load, plus any other system influence due to the existence of additional stresses caused by the gas hoses.

All these measurement devices used were calibrated in a Presys multiple calibration apparatus, composed by a Pressure Calibrator PC-507, a Temperature Calibrator T-350P and an Universal Calibrator Isocal MSC-10 which are periodically recalibrated by standards traced by National Institute for Weight and Measurements (INPM) and have got the certification NBR ISO/IEC 17025. In the case of thrust cell, in addition to these calibrations, its readings are always checked, in place, by applying to it a standard load of 5 kg.

The polymer surface regression rate is estimated by weighing the grain before and after the firing (HTPB density = 0.92 g/cm^3). The weighing procedures were performed in a Gehaka BQ6600 scale, able to measure hundredths of a gram in the range in question.

The uncertainty of the measurements, attaching 3 standard deviations to the best estimates, are ± 0.07 atm for pressure, ± 6.30 °C for temperature, ± 0.29 N for thrust and ± 0.086 g for weight. This means that we have 99.7% certainty that the best estimates do represent real values within those intervals.

The data acquisition system is composed by a conditioning board that transforms all the input signals in 0-5 V outputs to the 12 bits A/D boards in the process computer. The software used allows the selection of sampling rate, which was chosen as 300 samples per second.

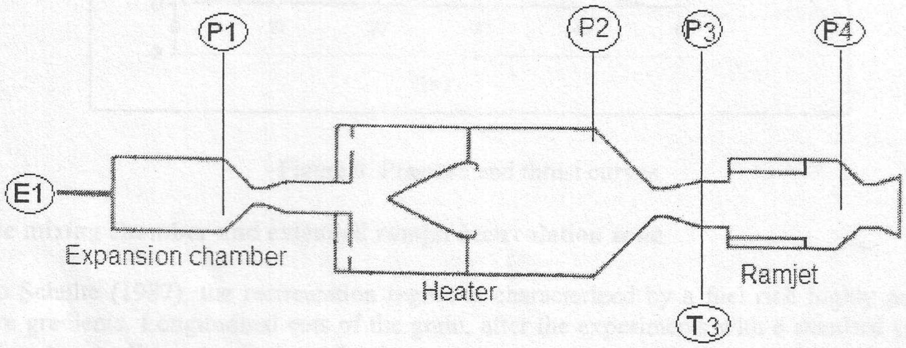

Figure 7. Measurement points in the experimental set.

The behaviors of pressure and temperature of the air in the regions shown in figure 7, and the resulting thrust are shown in the Figures 8 and 9. They are representative results of tests performed with a standard ramjet (chamber combustion + post mixing chamber).

Figure 8 shows the evolution of temperature in T3 region. When the H_2/O_2 reaction starts in the vitiated air generator, the water vapor produced sharply increases the temperature in that region far above the fuel ignition value, (remark that it does not reach steady state during the first 20 seconds of the test). After that polymer surface warming period, low temperature air, coming from the cylinder, is introduced in the system, and T3 temperature decreases down to the expected ramjet entrance value, remaining stable during the solid fuel burning.

Figure 9 shows the thrust and the successive air expansions in the circuit. In the expansion chamber (P_1), air pressure drops from cylinder exit regulator valve conditions to P1 value. Then it falls to a value P2 in the heater and to P3 in ramjet entrance.

The measured values for pressure and temperature fit the ones expected for the chosen ramjet operation conditions.

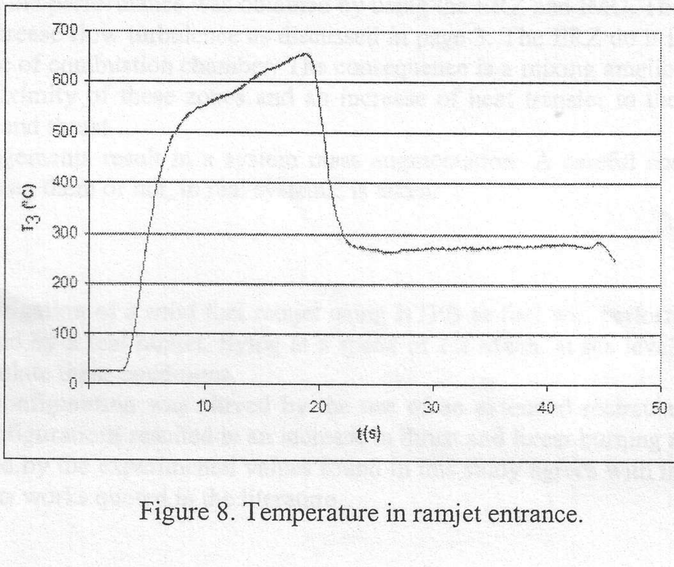

Figure 8. Temperature in ramjet entrance.

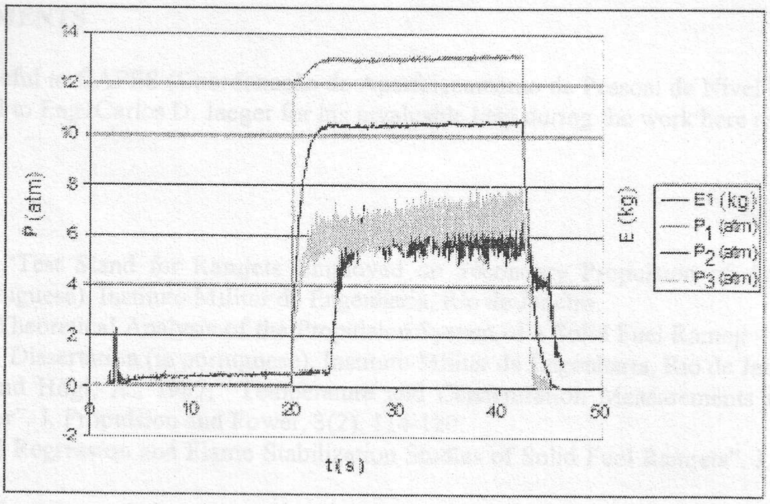

Figure 9. Pressure and thrust curves.

4.1 Intermediate mixing chamber and extended ramjet recirculation zone

According to Schulte (1987), the recirculation region is characterized by a fuel rich highly perturbed flow, with large temperature gradients. Longitudinal cuts of the grain, after the experiments with a standard system, showed that higher fuel consumption really occurs in the recirculation region, compared with the rest of the grain.

An intermediate mixing chamber (IMC) was introduced in the system in order to verify the effects of a second recirculation zone on the fuel regression rate. For that, the position of the reattachment zone was roughly estimated, the intermediate chamber was attached to the fore part of the combustion chamber and the grain was split in two parts, maintaining its total length constant.

An extended recirculation also (ERZ) was also attached, leading to increased thrust and regression rate.

Table 1 presents the results obtained at a condition equivalent to 2.2 Mach speed at sea level:

Table 1. Experimental results

Test	Thrust (N)	$\dot{r}$ (mm s^{-1})
Standard[1]	53 ± 0,29	0,35 ± 0,0043
ERZ	61 ± 0,29	0,46 ± 0,0043
IMC	81 ± 0,29	0,53 ± 0,0043

[1]: chamber combustion + post mixing chamber

A significant effect on the performance was obtained by using the ERZ and IMC. The main reason for it is that both those arrangements do increase flow turbulence as discussed in page 3. The ERZ do it in the entrance of the grain and the IMC acts in the middle of combustion chamber. The consequence is a mixing amelioration, a reduction in boundary layer thickness in the proximity of these zones and an increase of heat transfer to the polymer surface, resulting in higher linear burning rate and thrust.

Obviously these arrangements result in a system mass augmentation. A careful cost-benefit evaluation is needed before a decision about using them or not, in real systems, is taken.

5. CONCLUSIONS

An experimental investigation of a solid fuel ramjet using HTPB as fuel was performed. The conditions chosen for this study were those found by a real ramjet, flying at a speed of 2.2 Mach, at sea level. A connected-pipe vitiated air generator was used to simulate these conditions.

The standard ramjet configuration was altered by the use of an extended recirculation zone and an intermediate mixing chamber. Both configurations resulted in an increase in thrust and linear burning rate.

The trend demonstrated by the experimental values found in this study agrees with the theoretical and experimental results obtained in previous works quoted in the literature.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Migueis, C. E., 1986, "Test Stand for Ramjets Employed on Secondary Propulsion of Artillery grenades. M.Sc. Dissertation (in portuguese). Instituto Militar de Engenharia, Rio de Janeiro.

Ronzani, E. R., 1989. "Theoretical Analysis of the Propulsion System of a Solid Fuel Ramejt – Application in Missiles and Grenades. M.Sc. Dissertation (in portuguese). Instituto Militar de Engenharia, Rio de Janeiro.

Schulte, G., Pein, R. and Högl, A., 1987, "Temperature and Concentration Measurements in a Solid Fuel Ramjet Combustion Chamber". J. Propulsion and Power, 3(2), 114-120.

Schulte, G., 1986, "Fuel Regression and Flame Stabilization Studies of Solid Fuel Ramjets". J. Propulsion and Power, 2(4), 301-304.

Silva, M. G., 1995, "Experimental Determination of the Polyethylene Regression Rate when used in Solid Fuel Ramjets". M. Sc. Dissertation (in portuguese). Faculdade de Engenharia de Guaratinguetá, Guaratinguetá.

Veras, C. A. G., 1991, "Experimental Analysis of the Combustion Chamber of a Solid Fuel Ramjet". M. Sc. Dissertation (in portuguese). Instituto Militar de Engenharia, Rio de Janeiro.

Zvuloni, R., Gany, A., Levy, Yeshavahou, 1989, "Geometric Effects on the Combustion in Solid Fuel Ramjets". Jornal on Propulsion and Power, 5(1).

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