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DEVELOPMENT AND TESTING OF ALTERNATIVE PARAFFIN-BASED HYBRID ROCKET FUEL

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Abstract. *Hybrid rockets propulsion enjoy several advantages over liquid and solid propulsion systems as its safety, control capability, security and economy. However, the principal disadvantage of the conventional hybrid rocket is low regression rate of the fuel grain. In the last years a series of researchers are concentrating efforts to find alternative hybrid fuels that could put the hybrid technology in the main commercial aerospace applications. The interest in alternative fuels is due to their price, security, stability, and easy of handling. These advantages were shown in some studies that used combinations of paraffin with oils, for example, the one obtained from the lard. These new combinations can improve the regression rate of hybrid rockets, making the cost-benefit of this class of fuels excellent. This paper presents a study about the hybrid rocket regression rate using gaseous oxygen as oxidant and alternative paraffin as fuel, which is a mixed with tallow and paraffin. For this purpose an experimental assembly was built and a series of tests were performed. We obtained regression rate values similar to the pure paraffin (~1.8 mm/s) for a laboratory scale hybrid rocket (~200 N). It presents the advantages of being less pollutant and cheaper, and generate an economy up to 10% in the fuel cost. Also, Brazil is the greatest exporter of bovine meat in the world, so tallow is an abundant component that is usually rejected.*

Keywords: *hybrid rocket, paraffin, tallow, lard, regression rate.*

1. INTRODUCTION

The earliest studies on Hybrid Rocket Propulsion Systems (HRPS) were developed in 1930 in Russia. However, hybrid technology was despised in favor of liquid and solid propellants. Nowadays, hybrid propulsion has renewed attention due its comparative advantage over others chemical propulsion and has become an important technological option for space applications.

The return of interest in hybrid engines occurred in the final of seventies as consequence of cost and danger in storage, handling and operation Space Shuttle solid boosters. The interest deepened after Challenger spacecraft explosion and, some years later, the same happened with TITAN launch. These facts leveraged HRPS the researches at first for replace solid rockets.

The Hybrid rocket is a chemical system with one propellant stored in the solid phase while the other is stored in the liquid phase. In a classic hybrid, the fuel is a solid and the oxidizer is a liquid. The fact that the fuel is in the solid phase makes it very easy to add solid performance-enhancing materials. In addition, the liquid oxidant system requires one rather than two liquid containment and delivery systems, Karabeyoglu et al. (2004).

Among the disadvantages, we can mention: the mixing ratio varies with the progress of burning (so varying the performance parameters of the engine, which is not always desirable or permissible), the combustion efficiency is slightly lower than those in solid or liquid motor and the most significant, the lower regression rate carries a limited specific impulse for a given setting of fuel grain.

The regression rate of fuel is limited by the diffusion of the flame. In essence, the combustion process is accomplished by the rate of the reaction mixture and the pyrolysis of the fuel oxidant. Most hybrids rockets use as fuel carbon-based polymers, especially polymethyl methacrylate (PMM), polyethylene (PE) and polybutadiene (PB).

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A major step forward regression rate improvement was obtained by Karabeyoglu et al. (2004) that identified a class of paraffin based fuels that form a hydrodynamically unstable liquid layer over their surface and these makes the fuel burn rates three – to – four times higher than traditional hybrid fuels, such as HTPB.

Bertoldi (2007) introduces an enhancement method for regression rate improvement that consists in fast atomization of liquid oxidizer through a pressure swirl atomizer injector device. The research was conducted with nitrous oxide and paraffin as propellant and found regression rates above 4 mm/s.

Lyne et al. (2005) points that recent negative publicity regarding groundwater and foodstuff contamination by components of rocket fuel has brought to the forefront the need for new non-toxic materials that could be used in place of traditional propellant formulations. The ideal fuel would be highly energetic and non toxic. Readily available substances that meet these criteria include biologically derived hydrocarbons, in particular fats and oils from animals and plants. Specific candidates include lard (pork fat), tallow (beef fat), partially hydrogenated coconut oil and beeswax.

Among the considerations about the fuel, highlights the need for renewable resources, with special focus on reducing costs and environmental impacts. Paraffin is a fuel derived from petroleum, which gradually becomes more costly, and eventually scarce.

This works is the first combined effort of the Hybrid Propulsion Team of Laboratory of Energy and Environment (LEA/FT/ENM/UnB) and Aerospace Propulsion Team (FGA/UnB) in order to developed bio – derived fuels for use in hybrid rockets. The research presents the first studies using mixing paraffin-tallow. For the purpose of this work tallow means beef fat from bovine animals.

The objectives were to establish an appropriate proportion between tallow and paraffin to produce a fuel matrix and the determination of the regression rate law for the pair - propellant paraffin/tallow and gaseous oxygen (GOx).

2. EXPERIMENTAL SETUP AND METHODOLOGY

The tests were conducted in the Laboratory of Energy and Environment (LEA) at Mechanical Engineering Department (ENM) that has a horizontal test stand. The engine assembly is shown in the Figure 1 and contains: (1) fuel grain; (2) bolts; (3) head – ended flange; (4) back – ended flange; (5) tecnil envelop; (6) apparatus of oxidizer injection and ignition systems; (7) nozzle.

The experimental test bench is shown in Figure 2. The setting (8) allows us to test different grain sizes. In this work we perform test between 200 mm and 220 mm grain length. The experimental apparatus had all the necessary instrumentation for data acquisition and control.

The ignition systems was compound by a LPG (13) (Liquefied Petroleum Gas) and pressurized air (12). A mixture of LPG and air get into in the pre – camber (6) and an electric discharge starts a primitive flame. At this point, a main flux of oxidizer (GOx – Gaseous Oxygen) is released. When combustion starts we disable the ignition systems.

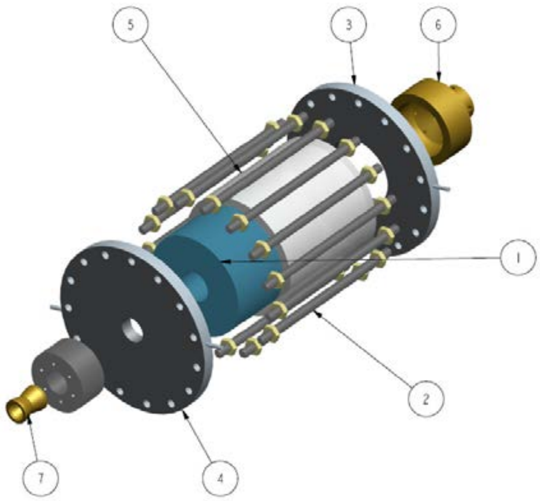

Figure 1. Combustion chamber

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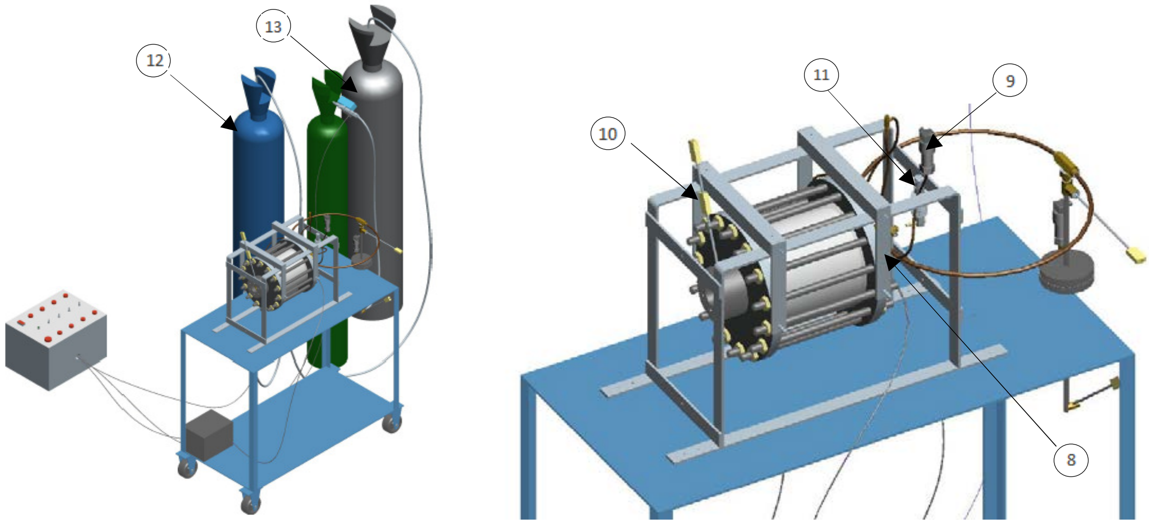

Figure 2. Experimental setup

The LPG and GOx fluxes are remotely controlled by electric – pneumatic valves by Valmicro, model AT051. The air flux control was made by a solenoid valve by ASCO and all the lines had uniflow valves. The data acquisition systems were ADS500 board and A/D converter ADS1000 IP by lynx technology with 4 kHz maximum sample frequency. The software interface was AqDados and the for data treatments was used the software AqAnalysis both by Lynx Technology.

The primary data elements (Figure 2) were a load cell type MACT - 100 kg by Micro – Análise (11), and ECO -1, 60 bar, pressure – transducer (9) by Wika to get chamber pressure data; two pressure – transducer ECO 2 by Wika, 0 – 100 bar both, for acquisition pressure downstream and upstream sonic orifice. Finally, we have four thermocouples (10); two in the nozzle and other one downstream and other upstream sonic orifice.

The new fuel matrix developed by us was composed by a mix of 80% paraffin and 20% tallow. The averaged fuel regression rate was calculated by:

$$\bar{\dot{r}} = \frac{d_f - d_i}{2t_b} \qquad (1)$$

Where t_b is the burning time (defined as the time between the ignition and the oxidizer valve closing events), d_i is the initial port diameter and d_f the final port diameter. Usually, is relatively complicated evaluate with precision the final port diameter because it is not uniform after combustion process. But, it is possible write the final port diameter in terms of mass variation, which is more accurate than the direct final port diameter measurement. So, equation (2) drives us:

$$d_f = \left(d_i^2 + \frac{4\Delta M_f}{\pi \rho_f L}\right)^{\frac{1}{2}} \qquad (2)$$

Where ΔM_f is the total mass of the fuel burned, that is, difference of two weight measurement before and after the test, and L is the fuel length. The fuel density ρ_f was taken to be 0,871 g /cm³ based on independent measurements.

The averaged oxidizer mass flux is given by Eq. (3):

$$\bar{G}_{ox} = \frac{16\bar{\dot{m}}_{ox}}{\pi (d_i + d_f)^2} \qquad (3)$$

Where $\bar{\dot{m}}_{ox}$ is the average oxidizer mass flow rate.

It is often useful, and certainly more convenient, to have simple analytical expression that can predict the behavior of the various ballistics parameters with reasonable accuracy. For hybrid motors investigators have fund suitable for this purpose the simplified regression rate expression (Humble et al., 1995) presented in Eq. (4):

$$\bar{\dot{r}} = a\bar{G}_{ox}^n \qquad (4)$$

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Note that a and n are the regression rate coefficient and exponent for the propellant system of interest, in this case paraffin/ tallow and gaseous oxigen (GOx). The averaged oxidizer mass flow rate can be expressed as:

$$\bar{\dot{m}}_{ox} = \frac{p_f A_{or} C_d}{C^*_{ox}} \quad (5)$$

Where p_f is the feed system pressure, A_{or} sonic orifice throat area, C_d is the discharge coeficientandand C^*_{ox} is the caracteristic velocity of GOx. The discharge coeficient was develped like Karabeyoglu (1999) and designed to be 0,615.

3. RESULTS AND DISCUSSION

A baseline test was conducted using the tallow oil mixed with paraffin. The tests two and twelve (Table 1) were performed without the tallow with the objective to evaluate the performance of this new fuel combination. In the preliminary studies we determined the percentage of 80 % paraffin and 20 % tallow for the others ten tests.

The summary of the tests results conducted by our team is given in Table 1 and Table 2. Table 1 shows the length of the fuel grain (L), initial port diameter (d_i), burn time (t_q) and the mass of fuel before (m_i) and after (m_f) fire test, respectively. In table 2 we have averaged oxidizer mass flow rate ($\bar{\dot{m}}_{ox}$), averaged oxidizer mass flux ($\bar{G}_{ox}$), averaged regression rate ($\bar{r}$), chamber pressure (P_c), Thrust and O/F ratio.

Table1. Grain characteristics

Test nº	Fuels	m_i (kg)	m_f (kg)	L (mm)	d_i (mm)	t_q (s)
01	Paraffin 80% - tallow 20%	6,56	5,98	201	50	11,0
02	Paraffin 100%	6,36	5,87	201	50	7,9
03	Paraffin 80% - tallow 20%	6,41	5,96	201	53	11,0
04	Paraffin 80% - tallow 20%	6,70	6,09	201	40	11,2
05	Paraffin 80% - tallow 20%	7,24	6,52	218	40	11,3
06	Paraffin 80% - tallow 20%	7,10	6,53	216	40	10,8
07	Paraffin 80% - tallow 20%	6,63	6,49	216	70	5,6
08	Paraffin 80% - tallow 20%	6,49	6,10	203	50	8,1
09	Paraffin 80% - tallow 20%	6,45	6,08	201	50	10,0
10	Paraffin 80% - tallow 20%	6,82	6,49	217	60	7,8
11	Paraffin 80% - tallow 20%	6,93	6,29	218	60	10,6
12	Paraffin 100%	7,06	6,39	202	39	12,3

Table 2. Experimental results

Test nº	$\bar{\dot{m}}_{ox}$ (g/s)	$\overline{G_{ox}}$ $(g/cm^2 s)$	$\bar{r}$ (mm/s)	P_C (bar)	Thrust (N)	O/F
01	33,1	0,97	1,5	3,2	155,8	0,6
02	36,7	1,15	1,8	4,0	203,8	0,6
03	36,4	1,09	1,1	3,5	76,4	0,9
04	42,6	1,56	1,7	4,2	196,0	0,8
05	45,3	1,60	1,8	4,9	222,5	0,7
06	43,2	1,69	1,6	4,7	195,0	0,8
07	44,2	1,05	0,6	4,5	175,4	1,7
08	46,5	1,57	1,4	5,3	231,3	1,0
09	45,8	1,56	1,1	4,7	200,9	1,2
10	50,9	1,40	1,0	5,3	267,5	1,2
11	41,7	0,96	1,4	4,8	217,6	0,7
12	38,4	1,39	1,7	4,0	191,1	0,7

During the burning tests we did not observe any great discrepancy between the results of the conventional paraffin and the matrix here developed. Comparing the test twelve (100% paraffin) with tests four, five and six (80% paraffin - 20% tallow) which possess similar combustion port, we obtained regression rates closer each other.

In Table 3, shows some tests performed at Stanford University with an engine similar that was used in this work. The high pressure levels in the chamber are explained by the nozzle throat that is smaller than in this work (20 mm against 12.7 mm) to oxidizer mass flow rate very close. Comparing Table 3 with Table 2 we propose further

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experiments with increased mass flows, to study this effect over paraffin/tallow regression rate. In general, regression rate is independent of pressure, except for very high and very low pressure (Sutton, 1992). This research proves this fact for low chamber pressure.

It is clear (comparing the results of Table 2 and Table 3) the high regression rate of the paraffin/tallow based fuels compared to other standard hybrid fuels. Table 3 shows regression rates for HTPB and GOx.

Table 3. Regression rate and burning conditions of lab-scale hybrid motor (Karabeyoglu 1999, adapted)

Fuel	$\bar{\dot{m}}_{ox}$ (g/s)	$\overline{G_{ox}}$ $\left(g/_{cm^2s}\right)$	$\bar{\dot{r}}$ $(mm/_{s})$	P_C (bar)	Thrust (N)	O/F
Wax/GOx	21,4	4,2	1,2	3,79	48,1	1,3
Wax/GOx	38,5	7,6	2,8	6,4	87	1,06
Wax/GOx	80,7	7,0	2,5	13,8	207	1,63
HTPB/GOx	45,36	5,27	0,4826	3.45	107	2,0
HTPB/GOx	28,58	11,53	0,762	5.17	63	2,4
HTPB/GOx	54,432	10,62	0,762	4.14	134	2,0

The average regression rate as function of average oxidizer mass fluxes (blue triangles) for all the tests (excepted tests two and twelve – red squares) are shown in Figure 3. The curve fit to the data point for this research results in a mass flux exponent of 0.61. This value for mass flux exponent has good agreement with obtained by Karabeyoglu et al. (2004)

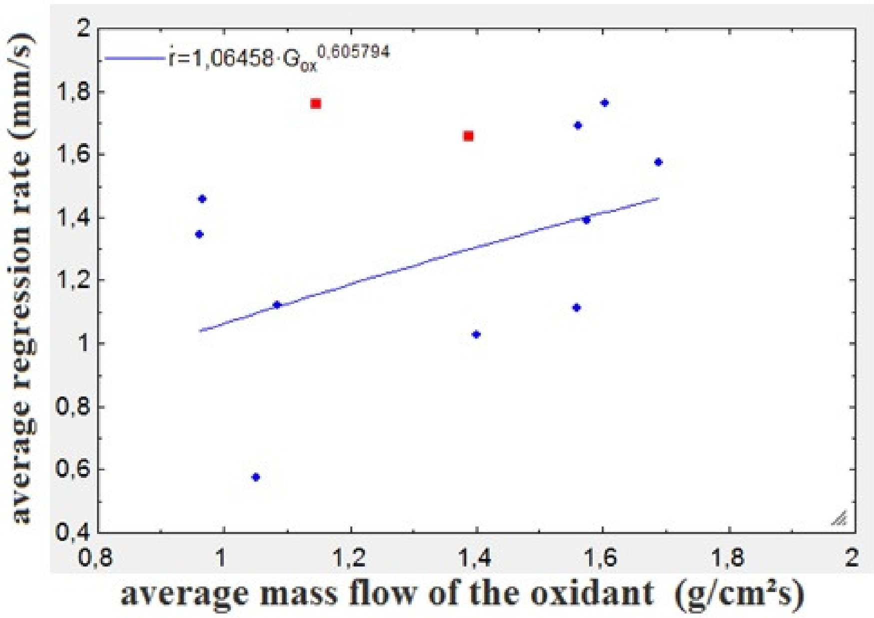

Figure 3. Average regression rate as function of average oxidizer mass fluxes

Based on the data analysis of this research, we suggest the following regression rate law for the paraffin/tallow – Gox propellant.

$$\bar{\dot{r}} = 1{,}065\ \bar{G}_{ox}^{0{,}606} \tag{6}$$

The Figures 4 and 5 shows a typical thrust measurement. The Figure 4 was the thrust profile for test twelve and figure 5 shows the thrust profile of test eight.

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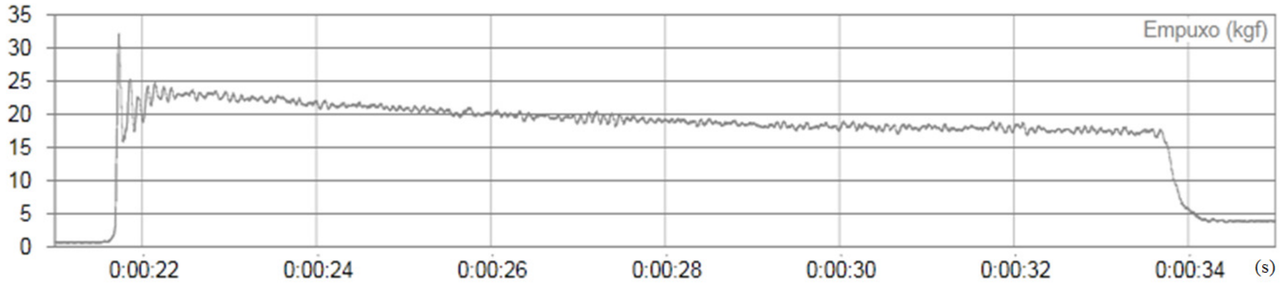

Figure 4. Thrust curve versus time for test number 12

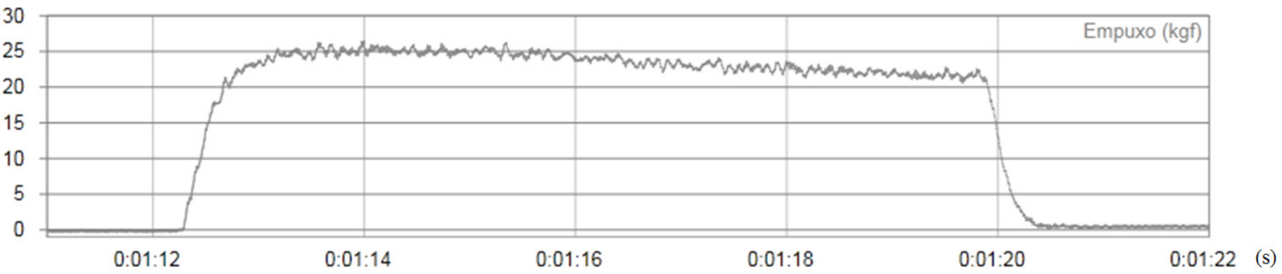

Figure 5. Thrust curve versus time for test number 8

The behavior of chamber pressure versus time is showed in Figure 6 for paraffin grain fuel (test 12) and Figure 7 for paraffin/tallow grain fuel (test 8). Note that the curves are quite similar. In fact test 8 showed a ignition lag transient, a phenomenon observed during all he test with paraffin/tallow based fuel and needs to be further studied.

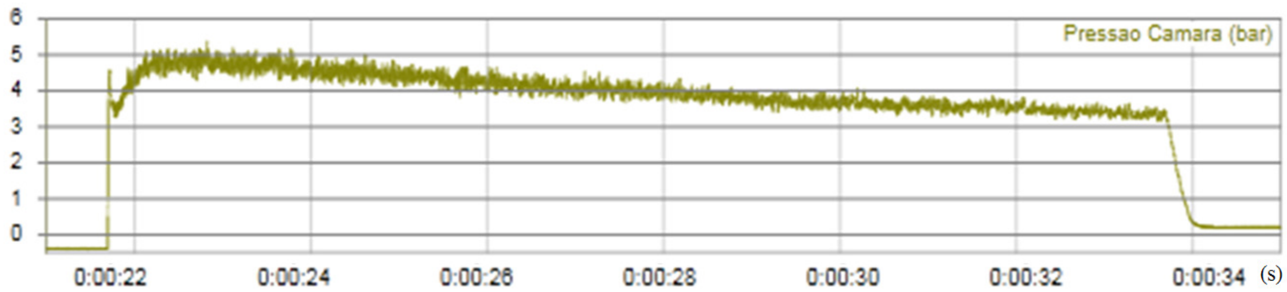

Figure 6. Pressure chamber versus time for test number 12

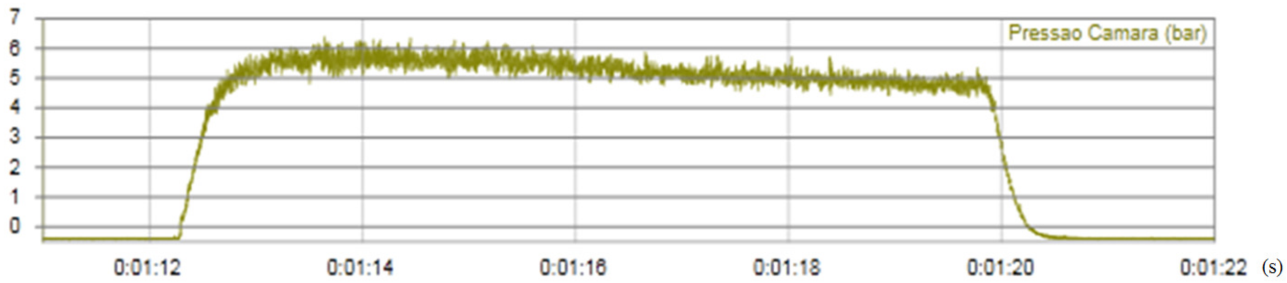

Figure7. Pressure chamber versus time for test number 12

Figure 8 shows the results published by Lyne et al. (2005), where 50/50 indicate a 50/50 mix of lard and paraffin. Note that results are very close that was obtained in this study using 80/20 mix of paraffin and tallow.

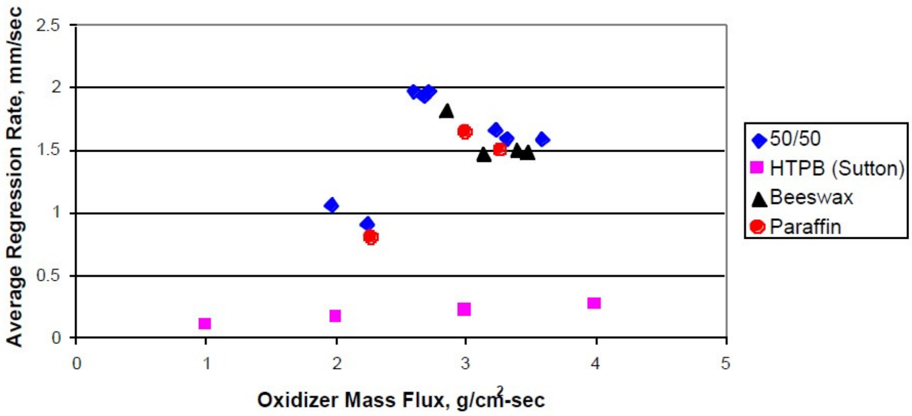

Figure 8. Average regression rate as function of oxidizer mass flux, *Lyne et al.* (2005)

4. CONCLUSIONS

This work was an unedited study of doping paraffin with tallow oil in order to develop a new matrix for a solid combustible grain for hybrid rockets.

Of a total of twelve tests, ten were conducted with the new matrix fuel (80 % paraffin – 20 % tallow) and two were made with paraffin (100 % paraffin). It was observed that for the same combustion fuel port the regression rate of the paraffin was very close to the regression rate of the doped paraffin with tallow.

This leads us to propose, for future studies, the use of tallow and paraffin into engines with high oxidizer (~ 1000 g/s) as a form of study of the behavior of this propellant pair in bigger limits of thrust and mass flow.

The main advantage for the use of tallow is its price. While a kilogram of paraffin costs R$ 10,00 the same amount of tallow costs R$ 6,60.

A negative aspect of the tallow is the amount of dross, besides the difficulty of controlling its properties, due to the variation among the samples. To preserve sample uniformity it is necessary to work with a huge quantity of tallow. In other hand, tallow is considered a waste product of the meatpacking industry.

The results of this research together with the results published by Lyne et al (2005) indicated that paraffin combinations with animals and vegetables oils merit further study as economical, highly energetic and possible non – toxic combinations for hybrid rocket fuel.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Bertoldi, A. E. M. (2007). Avaliação Experimental da Queima de Paraffin e Óxido Nitroso em Motores Híbridos. Dissertação de Mestrado em Ciências Mecânicas, *Publicação ENM.DM-120A/07*, Departamento de Engenharia Mecânica, Universidade de Brasília, Brasília, DF, 115p.

Humble, R. W., Henry, G. N., Larson, W. J., (1995) “Space Propulsion Analysis And Design”, *MacGraw-Hill Companies*, Inc. Primis Custom Publishing.

Karabeyoglu, M., A., (1999) "Transient Combustion in Hybrid Rockets", tese de doutorado, 236 páginas.

Karabeyoglu, M., A., Cantwell, B. J., Zilliac, G., Dezilwa. S., Castellucci, P., (2004)“Scale-Up Tests of High Regression Rate Paraffin-Based Hybrid Rockets Fuel”, *Journal ofPropulsion and Power*, Vol. 20, No. 6.

Lyne, J. E., Naoumov, V. I, Scholes J., Dodge, M., Elton, B., Wozniak P., Austind., Combs C., (2005) “First Steps in the Development and Testing of Nontoxic, Bioderived Fuels forHybrid Rocket Motors”, *43rd AIAA Aerospace Sciences Meeting and Exhibit*, Reno, Nevada.

ISSN 2176-5480

Sutton, G. P., (1992) “Rocket Propulsion Elements”, *John Wiley & Sons* INC. 7TH edition.

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