AiMT Advances in Military Technology
Vol. 4, No. 2, December 2009

Development of Wax Fuel Grain for Hybrid Rocket Motor

C. Boros[1] and P. Konečný[2*]

[1] Composite Innovations International, Ltd, Slovakia
[2]Department of Aerospace and Rocket Technologies, University of Defence, Brno, Czech Republic

The manuscript was received on 12 February 2009 and was accepted after revision for publication on 21 September 2009.

Abstract:

The paper deals with development of wax fuel grain for testing of small hybrid rocket motor. The possible wax composition is selected as solid fuel which in combination with nitrous oxide as oxidizer creates hybrid propellant. Rotary casting system specially developed for this case and wax grain manufacturing is described. The first practice with such hybrid rocket motor testing is introduced.

Keywords:

Hybrid rocket motor, wax fuel, Paraffin, HTPB, SP-1, wax grain manufacture

1. Introduction

The basic requirements necessary for successful whatever product are generally: the safety, environmentally benign and low cost systems. These three factors are dependent each other. For example, environmentally responsible and safe rocket system needs less protective testing facility and thus lower cost.

One of the most important advantages of the hybrid rocket motor is inherent safety, which is a direct consequence of the storage of a fuel and oxidizer separately each other in different phases. The mixing and explosion is practically impossible here. In comparison, liquid-propellant rocket engine is more dangerous due the liquid state of these propellants and solid rocket motors are practically phlegmatized explosive charges and are environmentally less benign (beyond exceptions they contain hydrochloric acid – HCl). As a flying system, hybrids are throttle able, restart able and are very safe to mission abort.

In contrast to solid propellants, pure solid fuels (like HTPB, polymers and waxes) are insensitive to mishaps or cracks and make the manufacturing process simpler,

* *Corresponding author: Department of Aerospace and Rocket Technology, University of Defence, Kounicova 65, CZ 662 10 Brno, Czech Republic, phone +420 973 445 147, Fax +420 973 445 147, E-mail Pavel.Konecny@unob.cz*

using classical machinery equipments. Wax was selected as a solid fuel – this fuel has several advantages over the classical e.g. HTPB system. These advantages are:

- very inherent, no toxic material;
- energy the same as a kerosene (per unit mass), but density is 16 % greater;
- regression rate is 3 to 5 time greater than HTPB fuel;
- low cost;
- no scrap possibility – reusable (recycling possibilities), long shelf life material.

The wax properties modifications, development and manufacturing are discussed here.

2. Wax Fuel Properties

The main requirements for new wax hybrid solid fuel are:

- easy to manufacturing, low cost;
- good mechanical properties to withstand internal chamber pressure or over pressurization due the ignition;
- no slosh possibility, good thermal stability;
- maximum density;
- maximum heat of formation;
- maximum regression rate.

The original content of well-known paraffin-based hybrid rocket fuel with trade name SP-1 developed by Stanford team [1] is secret – and otherwise, selection of liquefying wax fuel is patented, too [2]. Therefore, we were compelled to look for similar wax application, which had a potential to use in liquefying hybrid rocket solid fuel technology – e.g. candle industry, special wax casting, for example lost wax process, paraffin wax as a thermal storage medium (in a building industry), powder injection moulding process and hot melt glue bonding systems. Each of these technologies covers approximately the same problematic area – making the wax system more reliable, with enhanced mechanical and thermal properties and reusing capability.

The result of above mentioned research is wax fuel HPH-12, which contains following additives:

Microcrystalline wax..	56 %
Paraffin..	18 %
Polyethylene wax..	17 %
EVA (Ethylene-Vinyl-Acetate)................................	4 %
Tacky resin..	2 %
Carbon black..	2 %
Stearic acid..	1 %

In general, the micro wax is a mix of saturated hydrocarbons and has a more poorly defined crystallic structure than paraffinic waxes have. It means, that microcrystalline waxes have higher melting point, malleable, amorphous and more adhesive properties than paraffin waxes. Be sure, that this wax fuel has to be without some slosh possibility we decided to use more content of microcrystalline wax, which has more branched structure (better tenacity) and higher congeal point. On the other hand, we need the fuel which forms an unstable liquid layer on the melting surface – for this reason we used paraffin wax as an additive fuel for overall lower viscosity in melting layer.

Polyethylene wax (PE wax) was used as an additive to provide desired mechanical properties, thermal stability and possible density increasing. EVA is copolymer of ethylene and vinyl acetate. Very important is vinyl acetate content level for wax reinforcement. EVA has high cohesive strength and good adhesion properties (it is often used in hot melt adhesives). Tacky resin as Dicyclopentadien (PCPD) has the main purpose to make the better adhesion of EVA with other additives. Stearic acid is often used in candle industry for better mechanical properties of paraffin waxes and better dipping properties of wax mainly with steel combustion chamber. The role of carbon black is to improve the radiation absorption of the fuel insuring that most of the radiation from the flame is absorbed at the fuel surface (to avoid possible sloughing of the wax fuel) [3].

The molecular formula of 1kg of wax fuel is

$$C_{70.737}H_{139.672}O_{0.601}$$

The density of this fuel is approximately 900 kg/m^3, the heat of formation ΔH_f^0 = –976 kJ/kg.

The thermodynamic calculations were done with REAL 2.1 version code. The gas flow through the nozzle was considered as balanced with polytrophic exponent, with equal enthalpy. Results of these calculations are the theoretical peak values of the possible reachable specific impulse (for very large engines with nozzle expansion to absolute vacuum). The next calculations have been done with "freezing flow" adiabatic condition. The results of these calculations represent the lowest possible theoretical specific impulses. In real, the adiabatic, "frozen" flow calculation is enough for the first rough calculations and for smaller rocket engines. But in case of bigger ones, the more exact equilibrium calculation is needed. The real value of $I_{sp,\ theor}$ will be lying somewhere among those extreme values. We decide to use these "middle" values of specific impulse as results of equilibrium and "frozen" flow calculations. The dependences of the theoretic specific impulse and combustion temperature on the propellant mixture ratio for various chamber pressures are presented on Fig. 1 and Fig. 2, respectively. The lowest curve corresponds to the chamber pressure value 0.5 MPa and the highest one to 7 MPa. The combustion pressure range is divided with step 0.5 MPa. The nozzle exit pressure is chosen 0.1 MPa.

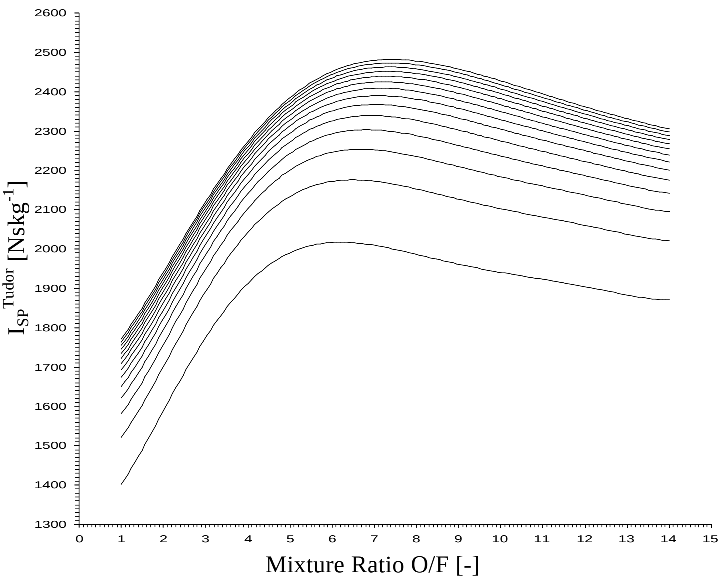

Fig.1 Theoretical values of specific impulse of HPH-12 mixture (nitrous oxide – N_2O/Wax). These curves represent middle values of equilibrium and "frozen" flow

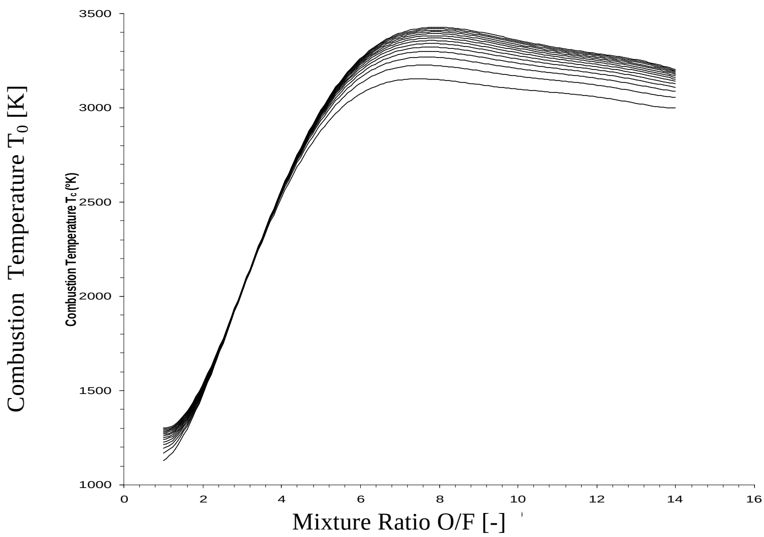

Fig.2 Combustion temperature of HPH-12 mixture

3. Wax Grain Manufacture

Two mixtures have been mixed simultaneously. The first, containing micro wax mixture, paraffin, stearic acid and carbon black, was heated up to 95 °C and mixed approximately 30 minutes. The second containing PE Wax, EVA, PCPD and small quantity of previous mixture was mixed approximately 20 minutes at temperature 150 °C. Next these two mixtures were mixed together and were heated up to maximum temperature 175 °C and than directly casted.

A special rotary casting machine has been made for wax grain manufacturing. It is based on rotational casting procedure (Stanford). The change-speed motor was used in it. Facility has casting capability for wax grain manufacturing to maximum 60 mm in diameter to 500 mm in length. The overall view of this machine is presented on the Fig. 3.

The process of grain preparation is following: the wax mixture in liquid phase is filled directly in steel cylindrical combustion chamber; the ends of it are capped and the tube is fastening in horizontal position and immediately spinning around its longitudinal axis at about 700 to 2600 rev/min (rpm). The changeable spinning rate in chosen range is important because of homogenous distribution of carbon black in cross section of this wax fuel grain. Next requirement on it is wax shrinkage elimination (from 17 to 19 %). The centrifugal force forms the central port with a glass-smooth finish, with tolerances ±0.7 mm. The final view on complete grain is presented on Fig. 4.

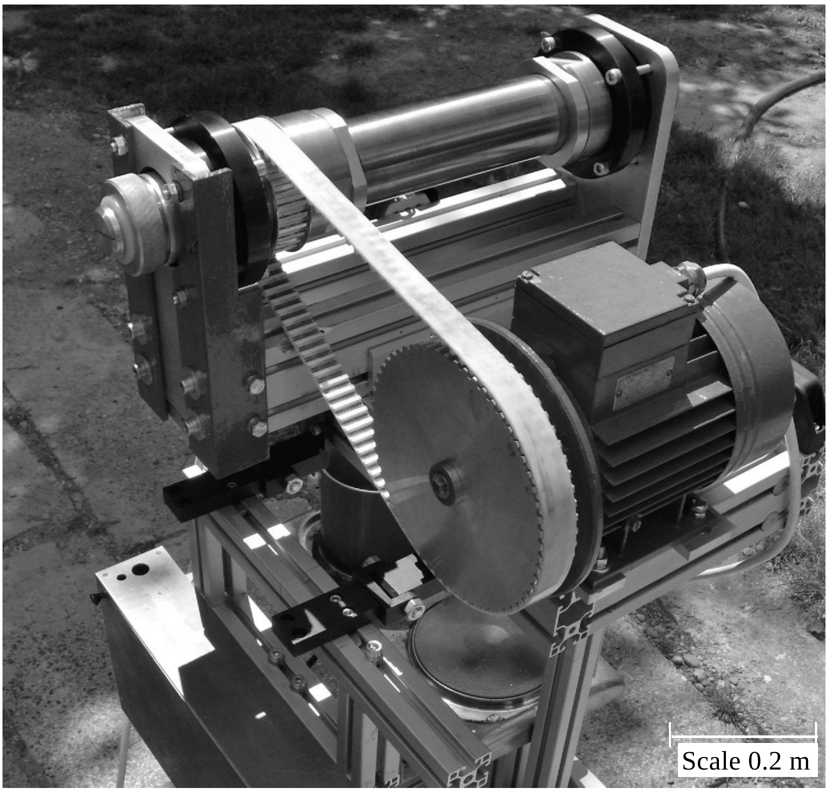

Fig. 3 Rotary wax casting machine

Fig. 4 Wax grain after casting procedure

4. Conclusion

We can asses after several hybrid rocket motor tests with wax fuel grain that this wax fuel mixture practically meet all requirements, e.g. higher regression rate, withstanding of over pressurization at ignition. Combustion products were very pure, smokeless, and environmentally responsible, without significant instability (see Fig.5).

For comparison, two different kinds of solid fuel have been tested – wax and one remaining solid fuel grain from previous work [3] – HTPB mixed with 5% ammonium perchlorate as an additive for enhancing the regression rate. In summary, we have tested 15 chambers with various fuel grain lengths (150 and 200 mm) and internal port diameters (from 20 to 28 mm) for basic, regression law determination.

From manufacturing point of view, this wax mixture needs special handling (it needs double casting procedure for smaller central port due the high tensile stress on central port surface). Next, the rising content of stiffening agents, like EVA or stearic acid, has a large effect to a heat of formation overall value. The real wax fuel has to be some compromise between low cost, manufacturing, mechanical properties, regression rate and energetic efficiency, respectively. Therefore the results presented here seem to be good base for future development of wax fuel grain for hybrid rocket motor application.

Acknowledgement

This work was supported by University of Defence in Brno (theoretical background and grant) and VÚPCH Explosia Pardubice-Semtín (test stand, testing facility).

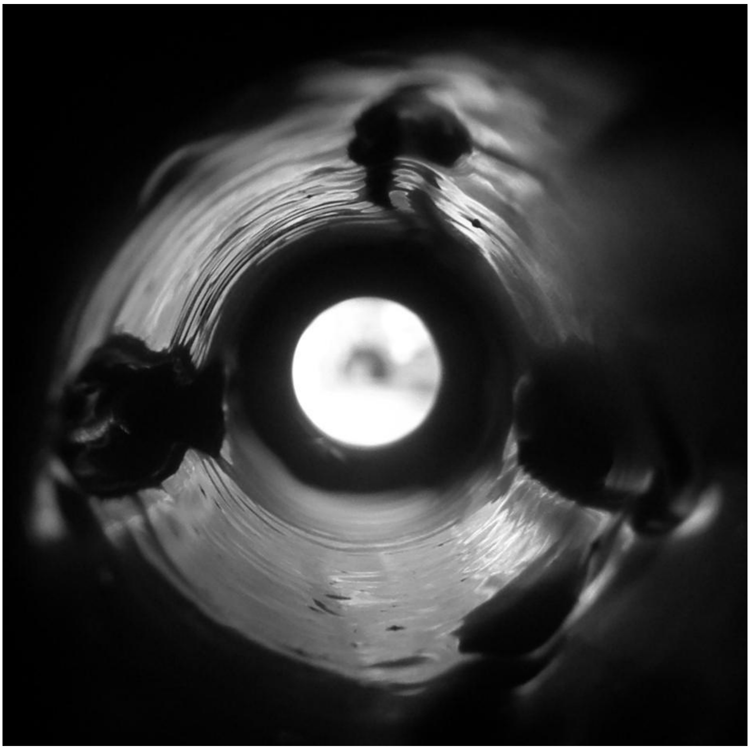

Fig. 5 Wax fuel grain after first firing test. The hollows and depressions are caused by nitrous oxide injector malfunction

References

[1] KARABEYOGLU, MA; CANTWELL, BJ. and ALTMAN, D. Development and Testing of Paraffin-Based Hybrid Rocket Fuels. In *37^{th} AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit. AIAA-2001-4503*. Salt Lake City, UT, July 8-11, 2001.

[2] KARABEYOGLU, MA., CANTWELL, BJ. and ALTMAN, D. *High Regression Rate Hybrid Rocket Propellants.* U.S. Patent US 6,684,624 B2, Febr. 3, 2004.

[3] HOSSAM EM. *Theory of Hybrid Propellant Engines.* [Dissertation Thesis]. Brno : Military Academy in Brno, Faculty of Air Forces and Air Defence, Department of Rocketry, 2001.