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ASSESSMENT OF THE PROPULSIVE PERFORMANCE OF FUEL VAPOR PRESSURIZED HYDROGEN PEROXIDE-ETHANE ROCKET ENGINES

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ABSTRACT

In the last years low-toxicity "green" storable liquid propellants have become considerably more attractive as possible substitutes for nitrogen oxides and hydrazines. The main advantage of "green" propellants is represented by the significant cost savings associated with the drastic simplification of the health and safety protection procedures necessary during propellant production, storage and handling. Fuel Vapor Pressurization (FVP) technology of "green" bipropellant rocket engines potentially offers very significant additional advantages in terms of system cost, complexity, reliability, safety and mass, with practically no penalty in propulsive performance compared to traditional storable propellants such as mixed nitrogen oxides and hydrazines. Pioneering FVP experiments were carried out by Goddard, Wyld and others. Detailed studies have been conducted and several tests have been successfully performed since 1994 in the US, but no such experience is presently available in Europe, nor FVP has ever attained flight readiness anywhere in the world. The main characteristics of the FVP system examined in this work consist in the use of storable, non-toxic, inexpensive, non hypergolic, high-energy propellants such as hydrogen peroxide (HP, H_2O_2) and ethane (C_2H_6) and in the storage of these propellants in a single lightweight tank, using a flexible diaphragm or a bladder to separate the fuel from the oxidizer and a catalytic reactor to decompose the hydrogen peroxide before mixing and combustion with ethane. This configuration therefore yields a very simple and yet highly efficient and reliable propulsion system by eliminating the cost, the weight and complexity of propellant tanks and pressurization bottles, pressure and flow regulators and ignition systems. These advantages are of special relevance in low- or medium-thrust rocket engines for the rapidly expanding market of "small" space missions and led the authors to focus on the analysis and assessment of propulsion systems operating according to this concept. The present paper reports therefore the preliminary evaluation of fuel vapor pressurized H_2O_2-C_2H_6 rocket propulsion systems. The results of the analysis confirm that the development of FVP technology may represent a significant contribution to the containment of the propulsion cost of small- and medium-size spacecrafts.

NOMENCLATURE

Greek symbols

ϕ	fuel/oxidizer mass ratio	v_L	liquid fuel specific volume
ρ_L	liquid fuel density	v_O	liquid oxidizer specific volume
ρ_O	liquid oxidizer density	v_V	vapor fuel specific volume
ρ_V	vapor fuel density		

Latin symbols

FVP	Fuel Vapor Pressurization	m_O	liquid oxidizer mass	p	pressure
h_L	liquid fuel enthalpy	m_F	total fuel mass	T_i	initial temperature
h_o	liquid oxidizer enthalpy	m_L	liquid fuel mass	T_f	final temperature
h_V	vapor fuel enthalpy	*MMH*	MonoMethyl Hydrazine	*UDMH*	Unsymmetrical DiMethyl Hydrazine
HP	Hydrogen Peroxide	*NTO*	Nitrogen TetrOxide	V	tank volume
LEO	Low Earth Orbit	Q_v	heat of vaporization		

1. INTRODUCTION

As space missions become more ambitious, the need for reducing the costs and increasing the capabilities of rocket systems through the enhancement of their propulsion performance, safety and reliability represents a major aspect in the development of competitive space engines. A variety of factors have resulted in an increasing interest in the exploration of alternatives to widely employed cryogenic and hypergolic propellant combinations. These factors include heightened sensitivity to cost, environmental concerns and personnel protection from the hazards associated with the use of present highly toxic propellants.

The market of LEO satellites is the most promising one in this respect, due to their lower cost and the consequent reduction of the risk associated with the use of innovative technologies and propulsion concepts. The main producers of small and microsatellites for LEO applications show strong interest in alternative technologies and, in particular, in the use of "green" (non-toxic) propellants, which would significantly lower the handling costs of propulsive systems ([1], [2], [3], [4], [5]).

Because of their superior propulsive performance the current standard in high-performing, storable bipropellants is the combination of nitrogen tetroxide (NTO) and hydrazines (N_2H_4, MMH and UDMH). However, these propellants are extremely toxic, carcinogenic and explosive and therefore health protection and safety costs of hydrazine-based propulsion systems have raised to disproportionately high levels, especially for low and medium thrust applications. The use of non-toxic "green" propellants would greatly contribute to reduce these drawbacks and significantly lower the life-cycle cost of small- and medium-size spacecrafts. Besides, overcoming these limitations generally leads to propulsion systems with a smaller number of components, which is usually associated with the increase of in-flight reliability and the reduction of standard and contingency operations. Finally, the elimination of safety hazards associated with the use of dangerous propellants contributes to drastically decrease the environmental impact and clean-up costs in the case of inadvertent spills or satellite launch failures.

Hydrogen peroxide (HP, H_2O_2) is widely recognized to be one of the most promising "green" storable oxidizers. It has been widely used in the 50's and 60's as a monopropellant in thrusters and gas generators and as a liquid oxidizer in bipropellant rocket engines for low and medium thrust applications [11]. It has been later dismissed in performance-driven missions in favor of more efficient hydrazines and nitrogen oxides. However, hydrogen peroxide still possesses most of the key features which make it an ideal choice for low-cost propulsion systems.

Alta S.p.A. is already actively involved in this field through the development and testing of advanced catalytic beds for H_2O_2 decomposition and their application to monopropellant rocket thrusters. The expertise acquired in this sector led the authors to analyze and assess the propulsive and operational performance of innovative green bipropellant thrusters with Fuel Vapor Pressurization (FVP) of hydrogen peroxide and ethane (C_2H_6), where the catalytic reactor provides the oxidizing stream for C_2H_6 combustion. This propulsion concept has been pioneered in the 30's by Goddard, Wyld and others, who became the forerunners of a whole new era in rocket flight. In the US fuel vapor pressurization has been actively studied since 1994 ([6], [7], [8], [13]) and is now undergoing development tests [12]. However, no similar experience is presently available in Europe, nor FVP has ever attained flight readiness anywhere in the world.

The main advantages of fuel vapor pressurization of "green" propellants is represented by the significant reduction of the costs for health and safety protection during propellant production, storage and handling and by the drastic simplification of the propulsion system, with little or no impact on the propulsive performance. These advantages are of special relevance to low or medium thrust rocket engines and are perfectly in line with the driving requirements and guidelines established by ESA for the development of its future storable propulsion systems. Upper stage propulsion, on-board spacecraft propulsion, orbital maneuvers and de-orbiting are just some examples of the missions that would greatly benefit from the development of fuel vapor pressurized "green" bipropellant rocket engines with the above characteristics and multiple restart capability.

The present paper therefore aims at illustrating the results of the preliminary analyses of the propulsive performance and the feasibility of FVP for the realization of highly simplified, efficient, inexpensive, lightweight and compact rocket thrusters, covering a wide range of applications from microsatellite on-board propulsion to upper stage and re-entry propulsion, and potentially even boost stage systems.

2. PROPELLANT CHARACTERISTICS

Nitrogen tetroxide (NTO) and hydrazines (N2H4, MMH and UDMH) are currently the standard choice as storable rocket propellants because of their superior propulsive performance. Typical values of the specific impulse and combustion temperature developed by NTO-hydrazines systems are shown in Figure 1. However, hydrazines are highly toxic and carcinogenic and bear the risk of unwanted detonation if exposed to high rates of change of pressure and temperature, depending also on the containment conditions. Hydrazine-propelled satellite systems must therefore be designed to incorporate preventive measures against all identified hazards. On-ground operations as well as transportation and handling of hydrazines are subjected to very restrictive safety procedures and have to be carried out with costly dedicated special precautions and specific infrastructure provisions (Figure 2).

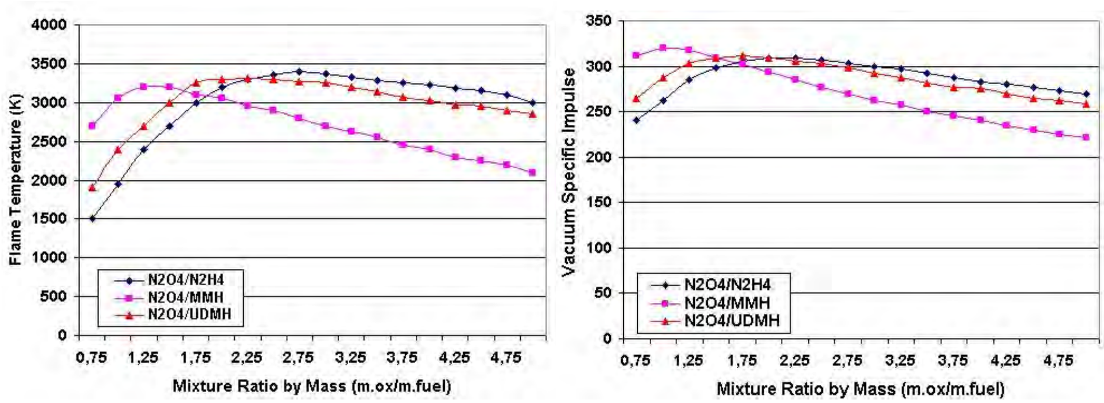

Figure 1 – Flame temperature (left) and specific impulse (right) versus oxidizer/fuel mass ratio for equilibrium adiabatic reaction at 3.45 MPa and frozen flow expansion to 13.8 kPa of nitrogen tetroxide, N_2O_4, and several hydrazine fuels (hydrazine, N_2H_4, monomethyl hydrazine, MMH, and unsymmetrical dimethyl hydrazine, UDMH).

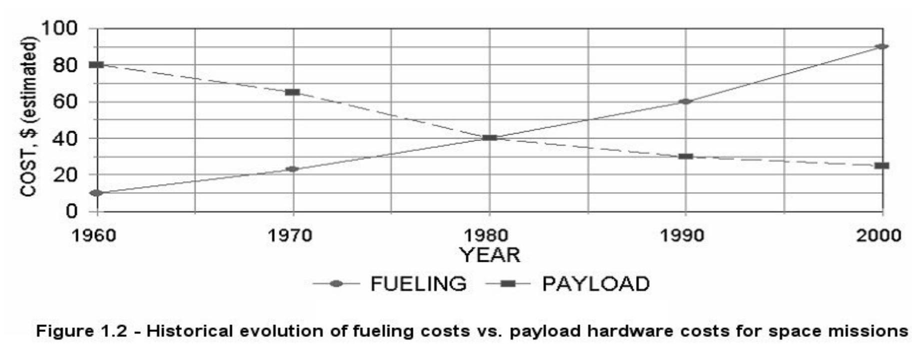

Figure 2 – Historical evaluation of fueling costs versus payload hardware costs for space missions

The high operational complexity associated with these propellants leads to renewed consideration of alternatives aiming at reducing both the involved costs and risks. To this purpose, in fact, low toxicity, or "green", storable liquid propellants have recently become considerably more attractive as possible substitutes for NTO and hydrazines. In a number of respects hydrogen peroxide and ethane represent an ideal combination of high-performance, "green" bipropellant propulsion systems ([6], [7], [8], [13]).

In particular, ethane is a stable, low-toxicity, inexpensive hydrocarbon with critical state at 5.01 MPa and 305.9 K (Figure 3). At room temperature (280 to 300 K) its vapor pressure is ideally suited for propellant pressurization, given the desired values of the thrust chamber pressure (1 to 3 MPa) and the expected losses in the feed system (20 to 40% of the chamber pressure).

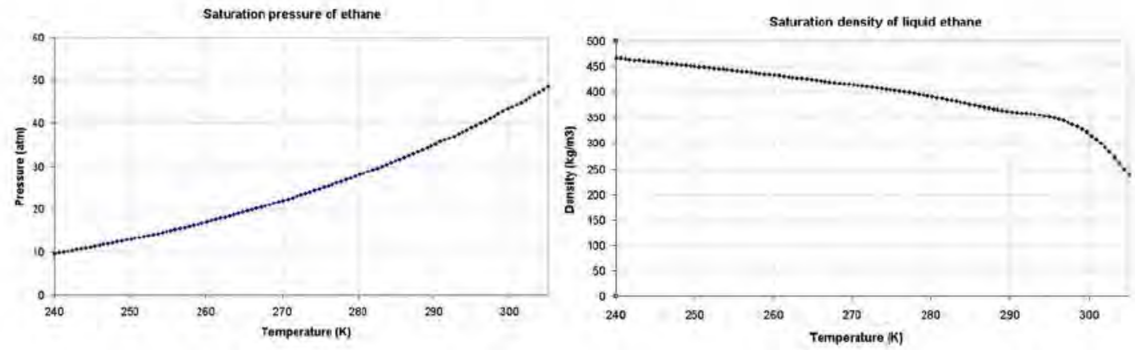

Figure 3 – Saturation pressure (left) and density (right) of ethane as function of the temperature

Hydrogen peroxide is a storable, low-toxicity, relatively inexpensive liquid oxidizer with high density (1440 kg/m3) and specific heat (89.1 J/mole*K) [14]. It does not react with the elements and compounds in the atmosphere, unlike hydrazine, which in contact with carbon dioxide forms compounds that can seriously attack the structural materials of the thrust chambers. HP's very low vapor pressure allows pumping machinery, if present, to operate without cavitation at lower inlet pressures [11]. Hydrogen peroxide is non-hypergolic with ethane, but in contact with suitable catalysts (usually silver, platinum or manganese oxides, MnO_2, Mn_2O_3) decomposes exothermically into hot oxygen and steam, capable to ignite and sustain ethane combustion. Table 1 summarizes the main characteristics of hydrazine, hydrogen peroxide and ethane, while Table 2 presents the main features and benefits connected with the use of hydrogen peroxide as a propellant.

Characteristic	Hydrazine	Hydrogen Peroxide (90%)	Ethane
Melting Point, °C	1.5	-11.5	-183
Boiling Point, °C	113.5	141.7	88.6
Specific Gravity at 20°C, gm/ml	1	1.4	1.049
Explosion Temperature, °C	232	149	472
Vapor Pressure at 20°C, kPa	1.4	0.3	3850
Long-Term Storage Stability	Excellent if kept blanketed with inert gas	Slowly decomposes to form oxygen and water	Excellent if prevent leakage
Other Precautions	Corrosive, Flammable, toxic	Need to be stabilized, corrosive	Flammable, explosive with air.

Table 1 – Comparison of hydrazine, hydrogen peroxide and ethane main characteristics

Features	Benefits
Non-toxic and storable	Commercial, easier propellant packaging and no insulation, simplified ground operations
Favorable thermo-chemistry	High density impulse, simpler thermal management
Oxidizer/monopropellant	No separate ignition systems required, high range of thrust variation, smoother starts and shutdowns, low cost pump feed systems
Gas-liquid injection	Increased stability margin, high combustion efficiency, simple injection system

Table 2 – Features and benefits of hydrogen peroxide as propellant

Typical values of the specific impulse and combustion temperature of H_2O_2-C_2H_6 systems are shown in Figure 4. Computations have assumed adiabatic equilibrium reaction at constant pressure (3.45 MPa) in the combustion chamber and frozen flow expansion to 13.8 kPa in the nozzle.
The maximum specific impulse (298 s at 98% H_2O_2 concentration and O/F = 7) is less than 7% lower than for NTO/MMH systems (320 s) and relatively insensitive to mixture ratio changes. For optimum specific impulse NTO-hydrazines systems operate fuel-rich at dangerously high temperatures (3050 K) lower than the maximum, and are therefore easily exposed to the risk of local overheating due to uneven propellant injection and mixing. Conversely, H_2O_2-C_2H_6 systems operate oxidizer-rich near their maximum flame temperature (and therefore with no risk of soothing and dangerous hot spots) at 2872 K, which is fully compatible with current radiation-cooled coated-niobium thrust chambers.

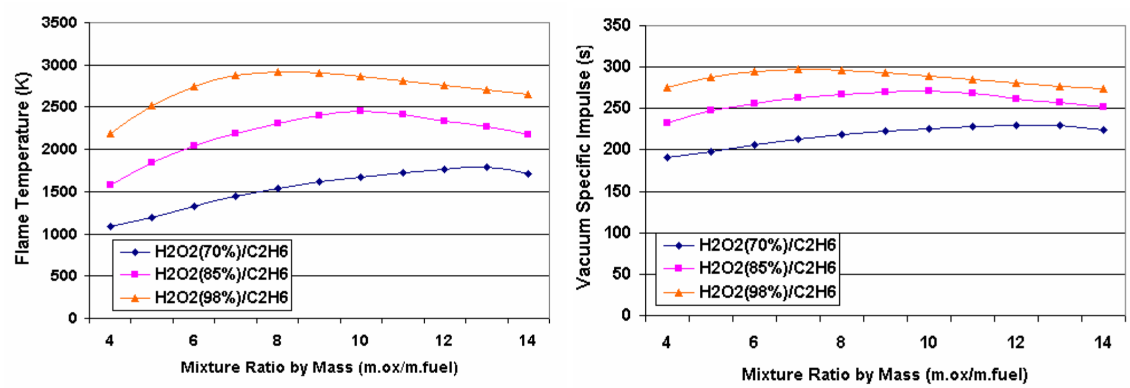

Figure 4 – Combustion temperature (left) and specific impulse (right) versus oxidizer/fuel mass ratio for equilibrium adiabatic reaction at 3.45 MPa and frozen flow expansion to 13.8 kPa of hydrogen peroxide and ethane for different H_2O_2 mass concentration (0.70; 0.85; 0.98).

The density of hydrogen peroxide at high concentrations (above 70%) is comparable to that of nitric acid and nitrogen tetroxide and significantly higher than that of liquid oxygen. As a consequence, the volume and dry mass of the oxidizer tank can be reduced significantly and, as shown in Figure 5, the volume specific impulse of 90% HP is higher than of most other propellants. This is particularly useful for systems with significant aerodynamic drag losses and/or stringent volumetric constraints.

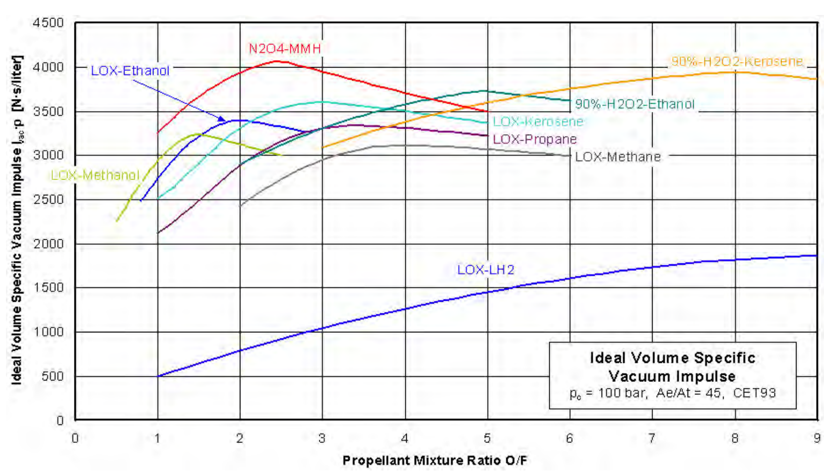

Figure 5 - Ideal volume specific impulse of several bipropellants, as a function of the oxidizer/fuel mixture ratio

3. PRINCIPLE OF OPERATION

Fuel vapor pressurization (Figure 6) systems exploit the high vapor pressure of light hydrocarbons to transfer both the fuel and the oxidizer into the combustion chamber. Exploratory analyses of propellants thermodynamic and propulsive properties have indicated that hydrogen peroxide and ethane represent the most promising propellant combination that best exploits the potential advantages of FVP for the realization of simple, safe, reliable, inexpensive and high-performance rocket propulsion systems.

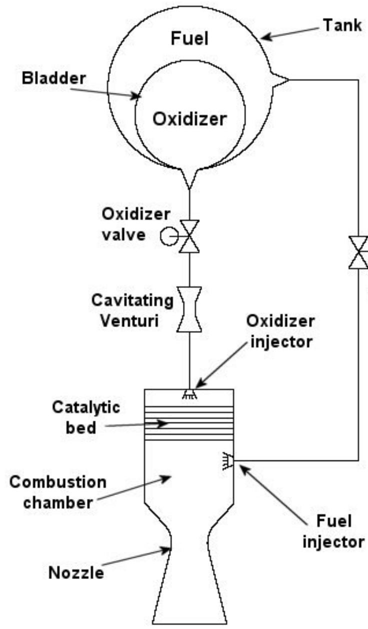

Figure 6 – Schematic of H_2O_2-C_2H_6 rocket engine with fuel pressurization

The main elements which characterize the configuration of FVP systems are:

- the dual tank for the pressurization of both fuel and oxidizer;
- the injection plate, for supply and distribution of liquid hydrogen peroxide to the catalytic reactor;
- the catalytic bed, which effects the decomposition of HP in gaseous oxygen and steam;
- the convergent/divergent nozzle, for accelerating the exhaust gases and generating the propulsive thrust.

When the oxidizer valve is opened, allowing the oxidizer flow from the tank to reach the injection plate and the catalytic bed, hydrogen peroxide undergoes an energetic exothermic decomposition, creating a hot oxidizing gas downstream of the catalytic reactor. After a short delay, the fuel valve is also opened and gaseous ethane is tapped from the upper end of the propellant tank and delivered to the injector. As it expands through the injection orifices, almost the 95% of the ethane stays in its vapor state, while the remainder condenses into liquid droplets, which are immediately vaporized again in the combustion chamber. The fuel spray impinges on the hot, high velocity oxidizer stream, resulting in spontaneous ignition and rapid, efficient gas-gas combustion.
Since the same pressure drives both the oxidizer and fuel flows, only passive devices (cavitating venturis for the liquid oxidizer and sonic injectors for the gaseous fuel) can be used to accurately control the oxidizer/fuel ratio regardless of the value of the driving pressure. No pressurization tanks, pressure regulators and flow control valves are needed, realizing a very simple and reliable propellant management system where the only active components are the propellant shut-off valves.
Because of the moderately high value of hydrogen peroxide/ethane combustion temperature (about 3000 K for 90% H_2O_2), the radiation-cooled thrust chambers and nozzles do not require the use of rare and extremely expensive materials like Iridium-coated Rhenium, but can be realized with the more traditional coated-Niobium technology.

3.1 The Propellant Tank

An important aspect of fuel vapor pressurization systems consists in the use of just one tank for both propellants. Significant savings of system mass and complexity are gained by storing the two propellants in the same tank, using a flexible diaphragm or a bladder to separate the fuel and the oxidizer. In this configuration ethane and hydrogen peroxide are in thermal contact with each other and the heat capacity of the oxidizer can be exploited to minimize the tank temperature and pressure drifts due to fuel evaporation during propellant extraction.

As the propellants are expelled from the tank, the fuel temperature and pressure will tend to decrease as a consequence of the evaporation required to fill the larger available volume. Counteracting this effect is the transfer of heat from the oxidizer to the fuel through the thickness of the separating bladder. Since the fuel is initially close to its critical temperature, the latent heat of vaporization is low. Besides, since the O/F mass ratio is relatively large (between 7 to 9), the thermal inertia of the oxidizer effectively reduces the drift of the tank temperature and pressure during propellant extraction.

Preliminary calculations (Figure 7) indicate that the high value of the optimum oxidizer/fuel ratio (O/F) is indeed quite beneficial in stabilizing the tank temperature and pressure, whose drifts for adiabatic propellant extraction do not exceed 20 K and 1.5 MPa, respectively. These calculations are based on a simplified thermodynamic model of the propellants in the tank where the following assumptions have been introduced:

- adiabatic conditions;
- incompressible oxidizer;
- uniform temperature and pressure;
- constant mixture ratio ϕ;
- constant tank volume V;
- thermodynamic equilibrium between liquid fuel and its vapor.

From the continuity equation:

$$m_F = m_V + m_L \tag{1}$$

where m_F is the fuel mass in its liquid (m_L) and vapor (m_V) state. Using the assumptions of constant tank volume and mixture ratio:

$$dV = d\left(m_L v_L + m_V v_V + m_O v_O\right) = v_L\, dm_L + v_V\, dm_V + v_O\, dm_O + m_L\, dv_L + m_V\, dv_V = 0 \tag{2}$$

$$\phi = \frac{-dm_F}{-dm_O} = \frac{dm_V + dm_L}{dm_O} = \text{constant} \tag{3}$$

where m_O is the oxidizer mass, v_O is the oxidizer specific volume and v_V, v_L are the specific volumes of the fuel in its vapor and liquid states on the saturation line. Finally, from the enthalpy equation for the tank:

$$d(m_L h_L + m_V h_V + m_O h_O) - h_V\, dm_F - h_O\, dm_O = V\, dp \tag{4}$$

where h_O is the specific enthalpy of the oxidizer, h_V, h_L and p are the specific enthalpies of the fuel phases and the tank pressure at saturation conditions.

Solving the above equations for dm_L, dm_O and dm_V, the following ordinary differential equation system for the mass changes of the liquid fuel, oxidizer and fuel vapor in the tank as functions of the temperature is obtained:

$$\frac{dm_L}{dT} = \frac{m_L}{Q_V}\frac{dh_L}{dT} + \frac{m_V}{Q_V}\frac{dh_V}{dT} + \frac{m_O}{Q_V}\frac{dh_O}{dT} - \frac{V}{Q_V}\frac{dp}{dT} \tag{5}$$

$$\frac{dm_O}{dT}=\frac{\left(\frac{m_L}{Q_V}\frac{dh_L}{dT}+\frac{m_V}{Q_V}\frac{dh_V}{dT}+\frac{m_O}{Q_V}\frac{dh_O}{dT}-\frac{V}{Q_V}\frac{dp}{dT}\right)(\nu_V-\nu_L)-m_L\frac{d\nu_L}{dT}-m_V\frac{d\nu_V}{dT}}{\phi\nu_V+\nu_O} \tag{6}$$

$$\frac{dm_O}{dT}=\frac{\left(\frac{m_L}{Q_V}\frac{dh_L}{dT}+\frac{m_V}{Q_V}\frac{dh_V}{dT}+\frac{m_O}{Q_V}\frac{dh_O}{dT}-\frac{V}{Q_V}\frac{dp}{dT}\right)(\nu_V-\nu_L)-m_L\frac{d\nu_L}{dT}-m_V\frac{d\nu_V}{dT}}{\phi\nu_V+\nu_O} \tag{7}$$

with the relevant initial conditions:

$$m_L(T_i)=m_{Fi} \qquad m_O(T_i)=\frac{m_{Fi}}{\phi} \qquad m_V(T_i)=0 \tag{8}$$

The temperature T_f at the end of the liquid fuel evaporation is then determined by the condition:

$$m_L(T_f)=0 \tag{9}$$

while the corresponding pressure change in the tank is:

$$\Delta p = p(T_i)-p(T_f) \tag{10}$$

In this model it was assumed that both vapor and liquid fuel were in equilibrium inside the tank but, as propellant consumption develops, all liquid fuel will evaporate and only fuel vapor will remain in the tank. In order to analyze the evolution of the tank temperature after the evaporation of the liquid fuel, a second model was developed considering only the residual oxidizer and fuel vapor in the tank. Assuming the vapor to behave as a van der Waals gas:

$$p=\frac{RT}{v_V-b}-\frac{a}{v_V^2} \quad \text{and} \quad h_V=c_{vV}T+RT\frac{v_V}{v_V-b} \tag{11}$$

in order to approximately account for real gas effects, a new ordinary differential equation system was thus obtained:

$$\frac{dm_V}{dT}=\phi\frac{dm_O}{dT}=-\frac{m_V\left(c_{vV}+R\frac{v_V}{v_V-b}\right)+m_Oc_{pO}-\frac{RV}{v_V-b_V}}{\left[m_V\frac{RTb}{\left(v_V-b\right)^2}+V\left(\frac{2a_V}{v_V^3}-\frac{RT}{\left(v_V-b\right)^2}\right)\right]\frac{v_V+v_O/\phi}{m_V}} \tag{12}$$

and solved numerically, using as initial conditions the state of the system computed with the previous model at the end of the fuel evaporation.

The overall dependence of the tank temperature as a function of the residual propellant is shown in Figure 7. The results show that during most of the propellant extraction the drift of the tank temperature can be reduced below 20 K. The corresponding pressure drop can be evaluated using data presented in Figure 3 and demonstrates that the proposed fuel vapor pressurization system is able to effectively stabilize the propellant pressure even in the rather conservative assumption of adiabatic tank operation.

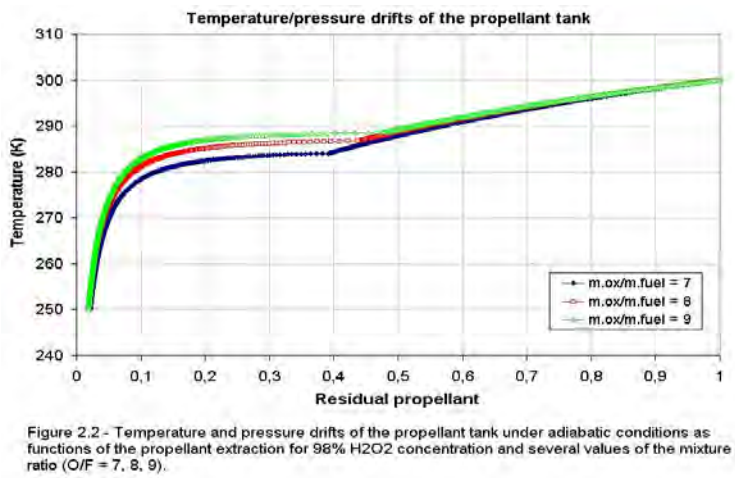

Figure 7 – Temperature drifts of the propellant tank under adiabatic conditions as function of the propellant extraction for 98% H_2O_2 mass concentration and several values of the mass mixture ratio (O/F= 7, 8, 9)

3.2 The Catalytic Reactor

The choice of the characteristics of the catalytic bed and its most appropriate coupling with the injector plate and the thrust chamber are some of the most significant challenges, together with the tank design, to be addressed for the effective design of rocket engines working with hydrogen peroxide [10]. The main aspects to consider for the integration of the catalytic bed in the engine are:

- the injection of the HP into the catalytic bed must be sufficiently uniform to avoid local saturation and flow channeling, which would result in incomplete decomposition and reduced propulsive efficiency;
- the length of the catalytic bed must be optimized for minimal pressure losses and complete HP decomposition with reference to the envisaged operational conditions and catalyst degradation/clogging;
- the HP mass flux must be optimized with reference to the decomposition performance and flow pressure losses of the catalytic bed;
- the chamber pressure and the mass flow rate have to be determined based on the desired size of the thruster, the acceptable value of the pressure losses in the reactor, the thrust requirements and the structural and thermal design of the thrust chamber;
- the internal structure of the catalytic bed has to be selected in order to avoid flow channeling;
- the combined geometry of the reactor and the thrust chamber must be chosen in order to avoid, suppress or control the onset of coupled flow instabilities.

Silver gauzes are the most common choice for catalytic bed for the decomposition of hydrogen peroxide, even if they tend to be affected by poisoning for concentrations higher than 95% [9]. Currently Alta S.p.A. is involved in this field through the development and testing of advanced catalytic beds for H_2O_2 decomposition and their application to monopropellant rocket thrusters.

4. SOME TARGET MISSIONS FOR FVP THRUSTERS

The characteristics of FVP rocket engines make them particularly attractive for low and medium thrust space applications and, in particular, for LEO commercial satellites (for Earth observation or telecommunications), LEO scientific satellites and for some interplanetary scientific missions. In these cases the requirement for a lower power level is driven by budget considerations, but the components are typically designed in order to obtain the best possible performance: the trend during the last years has been towards miniaturization and reduction of the life-cycle costs.

Nearly 95% of the present on-orbit satellites and interplanetary missions perform attitude control and orbital maneuvering by means of monopropellant or bipropellant chemical thrusters. In this sense, the use of hydrogen peroxide gives potential advantages in terms of ease of handling, low cost of the propulsion subsystem, low toxicity and high volume specific impulse.
It is possible to identify several specific missions, scheduled in the next years, for which the use of FVP rocket engines fed by ethane and hydrogen peroxide should be attractive. The following are some of the possible target missions:

- the second stage of the main propulsion system of the MAV (Mars Ascent Vehicle) of the ESA Mars Sample Return mission (scheduled in 2011 or, as a second launch window, in 2013), with a required thrust level of about 500 N;
- the main propulsion system and unique stage of a miniaturized MAV with a global take off weight of 100-200 kg, with a required thrust level of about 250-500 N;
- the apogee motor for large GTO satellites such as the AlphaBus (scheduled in 2008), which will allow to increase payload capability lowering the costs, with a required thrust level of around 500 N.

Finally, it is worth noticing that liquid bipropellant rocket propulsion will also greatly benefit from the development of advanced HP catalytic beds, opening the way to the widespread application of hydrogen peroxide/hydrocarbon rocket engines. As mentioned earlier, the propulsive performance of these engines is only slightly inferior to that of the traditional NTO/MMH solution, but the cost and volume savings associated with the use of “green” propellants like hydrogen peroxide and hydrocarbons make it a competitive solution in a large number of space applications.

5. ADVANTAGE OUTLINE

5.1 System Advantages

The main advantage of using the above described propellant combination, other than its specific impulse, is the ability to auto-ignite. When hydrogen peroxide passes through the catalytic bed rapid decomposition occurs, generating high temperature oxygen and steam. With 90% peroxide (90% H_2O_2 and 10% H_2O by mass) adiabatic decomposition temperatures over 900 K can be expected. These decomposition products, when mixed with ethane, result in combustion of the fuel, provided that the chamber pressure is few atmospheres. Besides, the injection of gaseous C_2H_6 downstream of the H_2O_2 catalytic reactor greatly simplifies propellant mixing, reduces the danger of combustion instabilities and eliminates the occurrence of hard starts due to presence of liquid propellant residues in the chamber.
In conclusion, the extreme simplicity of the system, the absence of active components other than the shut-off valves, the use of relatively high energy-density “green” propellants have the potential for drastically improving the reliability, development and production cost, propellant mass fraction and safety of vapor pressurized rocket engines with respect to traditional NTO-hydrazine systems.

5.2 Estimated Technical Benefits

The proposed technology combines simplicity and ease of use comparable to that of a monopropellant system with the typical performance characteristics of bipropellant engines: vacuum specific impulse of about 300 seconds, vacuum thrust in the range 100-500 N, high volumetric specific impulse, increased reliability and 30-35% dry mass reduction with respect to comparable gas-pressurized rocket engines due to the drastic simplification of the fuel management system.
This technology, if successfully proven and developed, would therefore be a significant innovation in the field of space propulsion systems, giving the possibility of being used either for spacecraft main propulsion or attitude control. In addition, the unit production costs are estimated to be significantly lower than those of conventional propulsion systems presently used in small spacecrafts, due to the elimination of additional propellant pressurization bottles, pressure regulators and ignition systems.

5.3 Estimated Business Benefits

The European market of LEO satellites for the years 2005-2015 has been estimated in the range 700-1000 MEuro (Euroconsult data). The quote of this market related to propulsion is in the range 70- 100 MEuro. Thanks to the use of “green” propellants and to the peculiar characteristics of the proposed self-pressurized propulsion technology, a 10% quote of the estimated market is thought to be attainable when this new technology will be fully developed and flight-qualified. This reflects in a potential market of about 7-10 MEuro in the next 10 years, leading to a significant profit even if the costs related to development and production are taken into account.

5. CONCLUSIONS AND FUTURE ACTIVITIES

Fuel vapor pressurization technology of low-toxicity “green” bipropellant rocket engines potentially offers very significant advantages in terms of system cost, complexity, reliability, safety and mass, with practically no penalty in propulsive performance with respect to traditional storable propulsion concepts. The most interesting conclusions drawn by the present preliminary analysis can be summarized as follows:

- in storable bi-propellant rocket applications, the use of HP and ethane is extremely attractive because it provides comparable performance with significant economic and safety advantages and increased volumetric efficiency. In particular the thrust ranges can be 100-500 N (equal to comparably sized NTO-hydrazine systems), the vacuum specific impulse is around 300 s (v/s 315 s of comparable NTO-hydrazines systems), the total impulse is around 40,000 N s (equal to comparably sized NTO-hydrazine systems);
- for low- and medium-thrust applications FVP system engines based on ethane-hydrogen peroxide decomposition represent an attractive solution because of their significantly lower cost due to the dramatic reduction in system complexity. The self-pressurized “green” propellant technology through a propellant pressurization bottle allows the reduction of the 30-35% dry mass with respect to NTO-hydrazines systems;
- upper stage propulsion, on-board spacecraft propulsion, orbital maneuvers and de-orbiting are some examples of the missions that would greatly benefit from the development of fuel vapor pressurized “green” bipropellant rocket engines with the above characteristics and multiple restart capability.

In the next future, it is Alta S.p.A.’s intention to practically demonstrate the feasibility of FVP fed H_2O_2- C_2H_6 propulsion systems, giving the possibility of planning a further effort for its industrial development and flight qualification. The future activities will be organized as follows:

- definition, analysis, trade-off and selection of alternative FVP concepts;
- design of a breadboard for static-test demonstration;
- breadboard realization and integration in a suitable test bench;
- breadboard experimental demonstration in static tests for the characterization of the main propulsive parameters: thrust, specific impulse, c* efficiency and flow stability;
- analysis of the results and assessment of the cost, mass, safety and reliability gains potentially attainable in the development of the selected FVP concept up to a flight-qualified propulsion system.

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