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Testing and evaluation program of lab. scale hybrid propulsion system

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Abstract: The objective of the present paper is to prove the validity design and fully automatically operation of HPS, seeking to achieve its safety, low cost, and flexibility. In the stage of preliminary design, a coupling between experimental and theoretical work has been done, making use of available laboratory facilities and software packages (thermo-chemical calculation), to fully demonstrate all operating conditions. The HPS design includes the solid fuel grain configuration, essential operating parameters, oxidizer feed through control devices, measuring tools with calibration system, data recording and operating system. Commercial fuel materials as Polymethyl methacrylate (PMMA) and Polyethylene (PE) are used during experimental work to represent conventional generation fuel. Furthermore, new generation fuels as paraffin, beeswax, and paraffin with energetic additive metal (AL powder) are used. Gaseous oxygen is used as oxidizer. That may guide to design and fabricate high performance real rocket weapon or space propulsion system, targeting longer term storage and a propulsion system with available technology. The objective is extended to select appropriate ignition system (NiCr coil igniter) for laboratory firing of small-scale engine. One of the main problems (price, safety, available technology) of propulsion system today has been tackled. To that end, analysis has been established, to investigate the regression rate, solid fuel mass flow rate and combustion efficiency for each fuel grain group types.

1. Introduction

A recent trend in propulsion system conceptual design is directed to adopt available and emerging technologies to attain new system has a high degree of reliability, safety and available technology with low cost. Hybrid propulsion system (HPS) has been designed by a technology combination of two old propulsion systems types: a solid and liquid propulsion systems, such system is still requiring more investigations for a better performance parameters and space missions.

The HPS can be used practically in all applications where solid or liquid propulsion systems are employed, It has the advantages of versatility of propellant available, the large range of performance capability and flexibility including shutdown, throttling, low cost and available technology. The HPS characteristics are very competitive in many applications as space launcher booster [1,2], launcher upper stage [2,3], orbit transfer [4], gas generator [1], sounding rockets [1] and educational purposes [1,4]. This technology is applied in space missions as Dolphin booster stage for launch vehicle and in space tourists (space manned vehicle), recently tested and flight, sub-orbital manned vehicles in Space Ship One and Space Ship Two. On April 2013, the new version Space Ship Two is designed to carry 6 space tourists and 2 pilot crew at an altitude of 110 km, in a sub-orbital, [1,5], ‘figure 1’.

The exploration history of HPS can be divided into fourth stages [1,2,3,4]:

- from 1933 – 1960, the inventor stage, characterized by improve of concept and demonstration firing,
- from 1960 – 1970, the serious scientific research stage, characterized by many analyses of hybrid combustion and mathematical models with description of various phenomena,
- from 1971 – 1981, the quiet stage,
- from 1982 until today, the positive stage of real applications, many researches done in theoretical and experimental works, the lots of hybrid rocket groups worldwide inside laboratories, propulsion companies, research centres, space agencies, hobbits, ..etc.
-

Space ship one Space ship two

Figure 1. Sub-orbital manned vehicles

2. Hybrid propellant investigation

2.1. Selection trade-off

The list of possible solid fuels is virtually endless, as nearly all polymers fall into this category. The common used solid fuels are called conventional generation solid fuel materials as PMMA and PE. Each of these polymers has chain terminators, such as the hydroxyl or carboxyl ion. Using conventional solid fuel in hybrid combustion has the superiority of safety and low cost. Unfortunately, the conventional hybrid fuel has suffered from low regression rate and fuel mass flow rate. Choosing propellant for a certain mission is a very important step for the design of the HPS and aspects such as level of performance, safety, costs and environmental impact must be taken into consideration. Safety, cost factors and availability in local market, as well as the specific goals, are also key factors.

Originally, most of the work on hybrid combustion research used conventional fuel but paraffin and beeswax materials base are used recently. AL powder as additive is used to improve the internal ballistic parameters, it is common used, however, a main advantage of using AL powder with paraffin material in practical work is the low smoke availability, acceptable performance and toxicity content in exhaust gases, and low price [6,7].

Gaseous oxygen (GO2) as oxidizer has also been considered in many applied researches. Oxygen is one of the best known and best performing oxidizers in rocketry. However, oxygen has limited expansion and compressibility when compared with N2O.

Most of the chemical propellants are dangerous, toxic or expensive. The laboratory propulsion engine model for researches, requires propellants that are readily available, reasonably safe, easy to handle and inexpensive. Based on experience, it is recommended to use GO2 as oxidizer, PMMA, PE as conventional solid fuel generation and paraffin, paraffin+5%AL, beeswax as new solid fuel generation. PMMA as solid fuels are used during primary tests since it provides visibility of ignition and development of combustion flame inside active channel port with high degree of safety during firing.

Figure 2 shows the fuel materials that are used in solid fuel grain manufacture. Table 1 lists physical and thermodynamic properties of used solid fuels used [8, 9, 10, 11].

PMMA roils PE boils Paraffin wax Paraffin+5%AL powder Beeswax

Figure 2. Solid fuel grain original role material

Table 1. Physical and thermodynamic properties of selected role solid fuel items

	conventional fuel generation		New fuel generation		additives
properties	Polymethyl methacrylate (PMMA)	Polyethylene (PE)	Paraffin (PF-25)	Beeswax (BW)	Aluminum (AL)
Chemical formula	$C_5H_8O_2$	C_2H_4	$C_{25}H_{52}$	$C_{46}H_{92}O$	Al
State at room temperature	Clear, solid hard, polymer	White, solid hard, polymer	White, soft, waxy	Yellow, soft, waxy	Solid, metal powder
Molecular weight , g/mol	100.12	28.05	352.68	661.20	26.98
Density, kg/m^3.	1186.0	910.0↔940.0	801.0	958.0↔970.0	2702.0
Melting point, ˚C	160.0↔200.0	120.0 ↔ 130.0	54.0	62.0↔64.0	660.37
Ignition point, ˚C	≥460.0	≥380.0	≥113	≥204.4	----
heat of formation, Kcal/mol	-90.70↔39.90	-12.06↔-13.52	-186.00	-197.86	0.0
Heat of combustion, Kcal/mol	642.1↔789.9	311.4	---	---	200.25
$(O/F)_{sto}$. with GO_2, -	1.92	3.43	3.45	3.32	-----

2.2. Solid fuel grain design

The fuel grain port geometry is described by the channel diameter dpo, which increases with firing time and the fixed grain length Lfu. Since the regression surface Abu, and the cross section area Apo are both dependent on the active channel diameter, the fuel mass flow rate, $\dot{m}_{fu}$ will generally change as burning progresses. Both the mixture ratio (O/F) and the regression rate $\dot{r}_{fu}$ will therefore vary with time.

Active channel port diameter

To predict the actual port diameter at a given firing time, let us assuming the oxidizer mass flow rate $\dot{m}_{ox}$ is constant during firing time, tub and uniform fuel grain port diameter, dpo along the active channel, the change of port diameter with firing time may be predicted as follows

$$d_{po}(t) = \left[2a\,(2n+1)\left(\frac{4\,\dot{m}_{ox}}{\pi}\right)^n L_{fu}^m\, t\, d_{po,i}^{(2n+1)}\right]^{\frac{1}{2n+1}} \tag{1}$$

If the oxidizer mass flow rate $\dot{m}_{ox}$ is changed during operating time, then

$$d_{po}(t) = \left[2a(2n+1)\left(\frac{4}{\pi}\right)^n L_{fu}^m \int_0^{t_{bu}} \left(\dot{m}_{ox}(t)\right)^n dt + d_{po,i}^{2n+1}\right]^{\frac{1}{2n+1}} \tag{2}$$

Active channel port length

The solid fuel grain length Lfu required for the initial design parameters, for all fuel grain configurations, can be derived from as

$$L_{fu} = \left(\frac{\dot{m}_{fu,i}}{N a \rho_{fu}\left(G_{ox,i}+G_{fu,i}\right)^n P_{fu,i}}\right)^{\frac{1}{m+1}} \tag{3}$$

where I, subscript to indicate initial conditions, N, number of fuel grain ports, Pfu, the fuel grain port perimeter, n, m, exponents of regression rate mass flux and port length respectively.
For a single fuel grain circular port configuration is described as

$$L_{fu} = \left(\left[\frac{\pi^{n-1}\dot{m}_{fu,i}}{a\rho_{fu}\left(4(G_{ox,i}+G_{fu,i})\right)^{n}}\right] d_{fu,i}^{2n-1}\right)^{\frac{1}{m+1}} \tag{4}$$

2.3. Thermochemistry Study

The role of thermochemical calculations is to get information on the effect of varying input parameters related to the propellants on the combustion performance prior to real testing which may be risky and expensive. For the present study on hybrid propellant combustion, the input allows trying different solid fuels and oxidizers, different mixture ratios and combustion pressures. Details of resulting properties of product gases can be examined and analyzed. A thermo-chemical calculation code is used for this purpose [11].

When designing a HPS, searching for propellant combinations that would result in very exothermic reactions required to satisfy the required mission. Highly exothermic reaction yields high combustion temperature, Tc, which leads to high performance parameters. If the temperature exceeds certain limit, dissociation reactions occur.

The thermochemical analysis is made, for a given propellant combination, based on three input parameters, mixture ratio, O/F, combustion pressure, Pc, and nozzle area ratio, ε. The parameters commonly used to describe thermo-chemical properties of the combustion exhaust gases are specific heat ratio ɤ, molecular weight MW, density ρ, and combustion temperature Tc, where from one can determine system performance parameters as illustrate in table 2. The values of these parameters vary depending on the assumption of shifting or frozen flow.

Theoretical and analytical investigation research is accomplished for various combustion of fuels materials (PMMA, PE, Paraffin, Paraffin+5%AL, beeswax) with GO2 as oxidizer at various firing pressures (1.5 to 25bar), the range of O/F ratios examined is 0.5 to 19. This is achieved by running the propellant combinations at a series of O/F ratios that resulted in the desired range of O/F ratios based on the stoichiometric O/F ratios. The stoichiometric O/F ratios for the hybrid propellant combinations are listed in table 2.

Table 2. Summary of performance parameters for thermo-chemical calculation

Fuel+ oxidizer	$(O/F)_{max}$ value	$(O/F)_{Sto.}$ value	$(O/F)_{max}$ value	$(O/F)_{Sto.}$ value	$(O/F)_{max}$ value	$(O/F)_{Sto.}$ Value	$(O/F)_{min}$ value	$(O/F)_{Sto.}$ value
	Characteristic velocity, C*, m/s		Combustion Temperature, T_C, K		Molecular weight, M_w, gm/mol		Specific heat ratio, γ, -	
PMMA+ GO_2	1.0	1.92	1.5	1.92	≥ 9.0	1.92	4.0	1.92
	1750-1825	1650-1700	3175–3600	3150-3600	≈31.5	24.5–25.5	≈1.22	1.23–1.22
PE+ GO_2	2.1	3.42	3.0	3.42	≥15.0	3.42	4.1	3.42
	1775-1825	1650-1725	3175–3575	3175-3550	≈31.9	24.0–25.0	≈1.22	1.21–1.23
Paraffin + GO_2	2.1	3.45	2.9	3.45	≥15.0	3.45	6.5	3.45
	1800-1850	1675-1750	3200–3600	3000-3500	≈31.9	25.0–26.0	≈1.22	1.22–1.23
Paraffin +5%AL+ O_2	2.0	3.44	2.4	3.44	≥14.0	(3.44	5.1	3.44
	1800-1875	1750-1650	3200–3700	3200-3600	≈31.0	24.0–25.2	≈1.22	1.21–1.23
Beeswax + GO_2	2.2	3.32	2.2	3.32	≥13.0	3.32	5.0	3.32
	1800-1875	1675-1750	3250–3525	3100-3500	≈30.1	24.5–23.5	≈1.22	1.22–1.23

3. Experimental work

3.1. Objective

The direct goal of the experimental work is to realize the proper function of a HPS (hybrid rocket motor (HRM) and oxidizer feed system) using different solid fuel types with various GO2 mass flow rates and new design lab-view software for system operation and data recording. Moreover, the objective is extended to examine green ignition system (without any pyrotechnic charge). Finally, to investigate the regression rate, fuel mass flow rate and combustion efficiency for each fuel material generation.

3.2. Test Facility

The HPS test facility is located in the propulsion laboratory at the Military Technical College (MTC), ‘figure 3’.The laboratory test facility comprises two parts:

- Test stand zone (HRM, test stand, GO2 feed system with control accessories, ignition system, camera and safety area).
- Control room (computer system, recording data acquisition, DC power inverter, relay kit, digital weight scale, and calibration instrumentations).

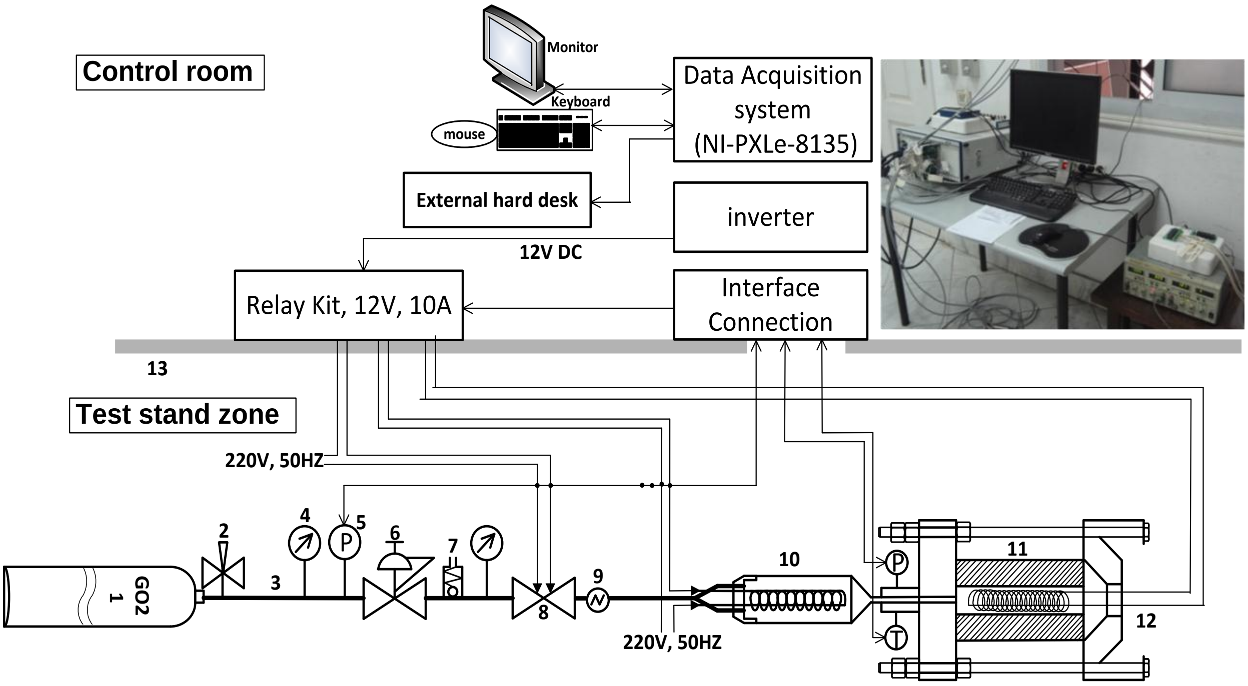
Figure 2 illustrates layout and schematic diagram of oxidizer (GO2 purity ≥99.5%) feed system and the components used for control and injection oxidizer via tested engine.

Solid fuel grain

Solid fuel grains are selected for experimental work in accordance with availability, good casting or machine ability, acceptable performance, environmentally safe, long storage without any change of physical and chemical properties. These could be grouped as follows:

- Polymer materials (PMMA and PE) manufactured and produced at KADER factory in full scale with external diameter 50mm, length 100mm and initial port diameters 7 to 25mm.
- Wax materials (paraffin, paraffin+5%AL, Beeswax) manufactured and produced at MTC, in small and full scales with external diameters 35mm, 50mm respectively, length 100mm and initial port diameter 7mm.

One of the most common processing methods used for manufacture of PMMA and PE fuel grains is injection plastics molding. The molding machine is based on the pressure die casting technique. ‘figure 4’ describes plastic and wax base material solid fuel grain after casting.



1-Oxidizer tank, 2-needle valve, 3-copper pipe lines (6mm&3mm diameter), 4-pressure gauge, 5-pressure transducer, 6-pressure Regulator, 7- safety regulator, 8- on- off valve (solenoid valve), 9- GO2 Rotameter, 10-Heat exchanger, 11-SSHRM, 12- igniter

Figure 3. Schematic test facility, main components

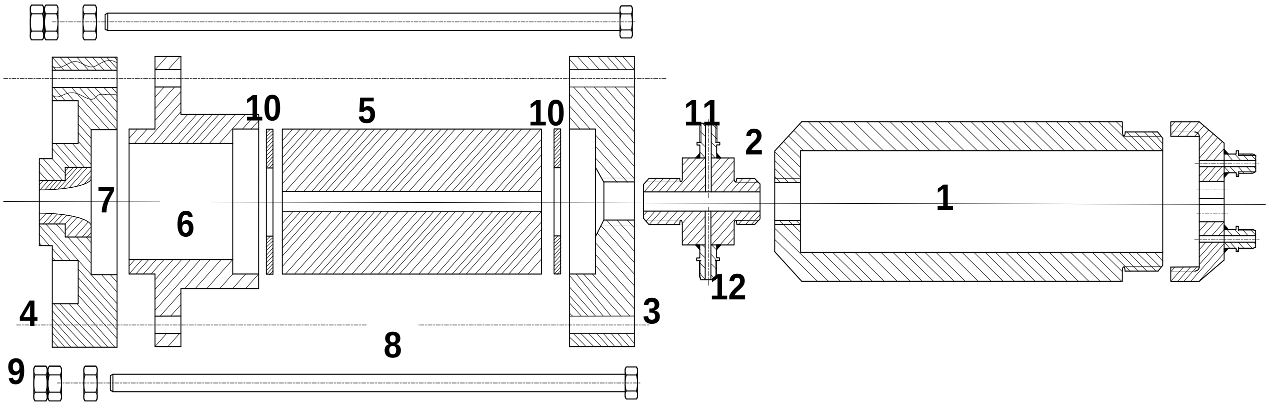
PMMA PE Paraffin Paraffin +5%AL besswax

Figure 4. Samples of the used solid fuel grains after casting

Test hybrid rocket motor

A complete design of a HRM has been made, the following activities have been accomplished at KADER factory: fabrication of most metal parts from steel alloy; fabrication of copper adaptors to connect pressure and temperature sensors; fabrication of nozzle from graphite to withstand the hot exhausting gases; production of PMMA and PE fuel grain charges using plunger injection plastics machine line and final X-ray inspection for the produced solid fuel grains. Activities at propulsion laboratory included: casting and machining of new generation solid fuel grains; final assembly of the engine and mounting on the test stand and elaborated calibrations and tests. ‘figure 5’ presents all parts of the HRM. The system can operate safely without problems for a maximum firing duration of 15 sec. This time period is considered enough for good inspection of performance characteristics. Accordingly, the duration of each test is limited to a period of 5-10 sec. Other limitation is related to excessive mass flow rate of GO2 (≤20gm/sec) that results in combustion temperature higher than 1300°C, with subsequent failure (melting) of the K-type thermocouples. The detail design characteristics of the HPS are summarized in table 3. The HRM is easily connected to heat exchanger through copper tube with external diameter 6mm and to GO2 gas supply system through a 2.5m high pressure Teflon hose with external diameter 6mm for easy handling. In addition, the tube plays a safety role, since the oxidizer supply will be interrupted at any hazardous combustion flame feedback. Solenoid valve is located before GO2 heat exchanger for controlling GO2 feed to the HRM (on-off operation).

The front flange has a 5mm diameter centre hole that acts as GO2 injector coaxial with the active port of fuel grain bore. The combustion takes place inside the fuel grain active channel port. GO2 oxidizer is supplied to the HRM grain port for firing time 10sec with old solid fuel generation, and 5sec with new generation solid fuel grains.



1-GO2 heat exchanger, 2- connector, 3-front flange, 4-rear flange, 5-fuel grain, 6-post-combustion chamber, 7-graphite nozzle, 8-thread rod, 9-M10x1.25 metric hex nuts, 10-teflon disc, 11-pressure transducer connector, 12-thermocouple connector

Figure 5. Drawing of the hybrid rocket motor main parts

Table 3. Hybrid propulsion system design parameters

Parameter	Value	Parameter	Value
Operating pressure, bar	up to 10	Oxidizer tank pressure, bar	over 30
Max. oxidizer flow rate, g/s	up to 20	Mean regression rate, mm/sec	up to 2.5
Initial fuel grain port diameter, mm	5 to 25	Graphite nozzle diameter, mm	8.2
External fuel grain diameter, mm	50	Mixture ratio, O/F	up to 20
Fuel grain length, mm	up to 100	Combustion efficiency	< 70%
Injection pressure, bar	< 15	Initial GO2 temperature, oC	up to 250
Power control source, v, Amp.	DC 12, 10	Ignition charge	NiCr coil
Solenoid valve power supply, v,Hz	AC 220, 50	firing time, sec	up to 15

Graphite nozzle

The HRM nozzle has an approximately 45deg convergent section ending at 8.2mm throat diameter without divergent part. The nozzle insert is made of high density graphite to avoid degradation due to the very excessive heat. The nozzle passed all experimental tests without any defects, ‘figure 6’ describes the dimensions and insertion of nozzle part with rear flange.

Ignition system

Three methods of ignitions are examined for safe and reliable ignition: pyrotechnical igniter, oxidizer heating, and thermal wire (NiCr or tungsten coil). For the selection of the proper igniter, PMMA, a transparent solid fuel is used. It ignites easily and keeps acceptable mechanical and environmental prosperities. As igniter generates heat, fuel surface undergoes pyrolysis and the volatile products burn with the injected oxidizer GO2. The generated igniter flame reaches maximum intensity within a delay time ≈ 0.25sec from ignition command. The most practical method that is used for the tests is the NiCr ignition system. Its main components are a heat generator charge (NiCr coil), connection wire, glue paper for fixation, control unit (DC 12 volt relay switch), and A/C 200V, 50Hz power supply source. Figure 7 described of NiCr igniter and the main characteristics parameters as in illustrates table 4.

Test stand

The test stand consists of a support cage containing test engine mounted on a transportable steel table, it is a horizontal installation fixed on 3 metal beam supports; two for HRM at front flange (GO2 injection head) and at the front GO2 heat exchanger with clamp ring and screw bolt, and other one for fixing the solenoid valve of GO2 by Teflon belt as shown in 'figure 8'.

The engine and GO2 feed system elements with metal beam supports are fixed on metal table with height 1m. The exhaust gases are directed to open area and the test stand is separated by concrete wall from the control room with special glass observation window.

Data acquisition system

The system allows for measurement of pressure profile in the GO2 bottle and HRM pre-chamber chamber. It also allows for measurement of temperature profiles for HRM pre-chamber gases. Commands are sent as 12volt DC to energize switch relays to activate heat exchanger, solenoid valve of GO2 for a specified period as illustrates in 'figure 3, 9'.

The recording is started just before ignition system triggering.

The tested HPS is operated fully automatically from the control room. The sequence of events is automatically controlled from a control panel of Lab-view software before start of firing. An emergency button is located for stop of any process in case of hazardous operation. The test facility and data acquisition system are shown in 'figure 9'.

Lab-View software control program

Lab-view software is adopted to control solenoid valve for opening/closing the GO2 gas supply line. The GO2 heat exchanger and ignition system can be operated from control room also by lab-view software commands according to required data. Lab-scale engine test front panel for lab-view software is shown in 'figure 10'. A lab-view software control program is created to manage the sequence of firing activities as indicated in 'figure 11'.

The data acquisition system records the measured pressure profiles at pre-chamber of HRM and GO2 storage tank, the read sample rate is set to 1000 read/s.

Video recording camera

A Sony Cyber-Shot WX50.video camera is used to record each firing run in order to spot potential up-normal phenomena and off nominal situations. An annotation system provided timing to be recorded during the run. The camera is utilized with a shutter speed of 1/10sec and a frame rate of 10 per second to enable analysis of ignition phenomena, exhaust flame plume and unexpected phenomena. The camera system is adjusted during test preparation. It is turned on 90sec before the firing command and 100sec after shut off to record any unexpected incident as shown in 'figure 11'.

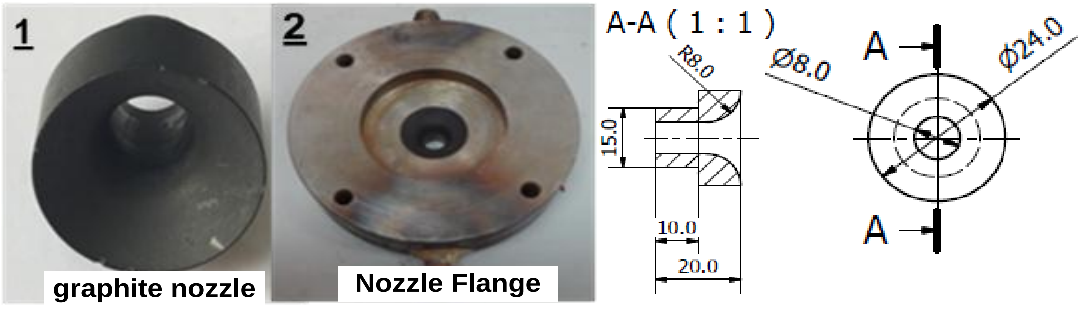


Figure 6. Graphite nozzle part

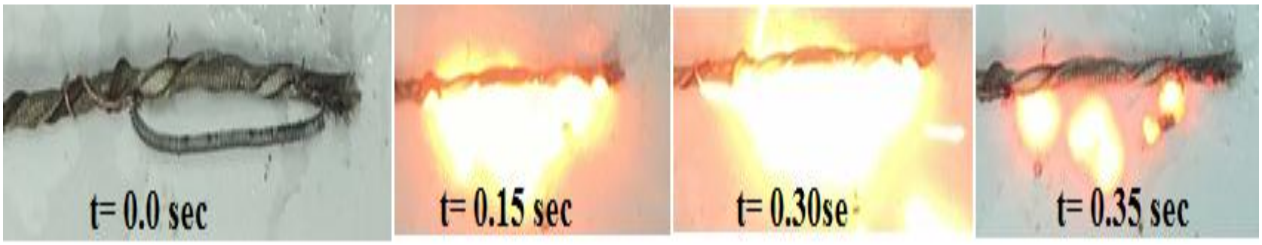


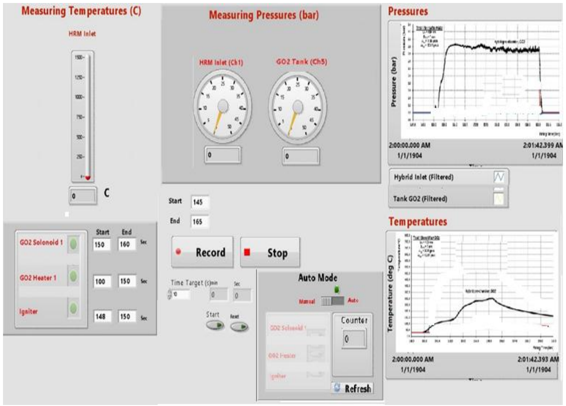
Figure 7. NiCr coil charge igniter during demonstration tests

Table 4. NiCr igniter parameters

NiCr igniter parameter	Value	NiCr igniter parameter	Value
NiCr wire diameter, mm	0.30	Max design power, W	150.0
NiCr wire length, mm	350.0	Applied volt, V/Hz	220/50
Coil number of turns,	75	Operating time, sec	Less than 0.5
Coil diameter, mm	1.75	Generated temperature,°C	600–1500
Coil length, mm	38.0		

Figure 8. Tested engine mounted on test stand

Figure 9. The data acquisition system with control devices and test facility


Measuring Temperatures (C)
HRM Inlet
0 C

	Start	End	
GO2 Solonoid 1	150	160	Sec
GO2 Heater 1	100	150	Sec
Igniter	148	150	Sec

Measuring Pressures (bar)
HRM Inlet (Ch1) 0
GO2 Tank (Ch5) 0
Start 145
End 165
Time Target (s) min 10 0 Sec 0
Auto Mode Manual Auto
Counter 0
Pressures
2:00:00.000 AM 1/1/1904
2:01:42.399 AM 1/1/1904
Hybrid Inlet (Filtered)
Tank GO2 (Filtered)
Temperatures
2:00:00.000 AM 1/1/1904
2:01:42.393 AM 1/1/1904

Figure 10. Lab-view engine test front panel

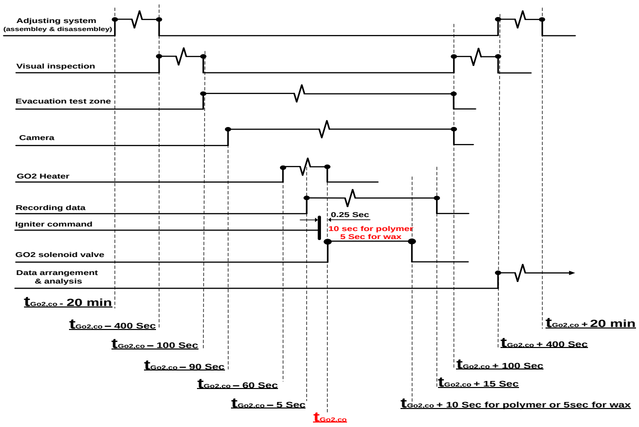
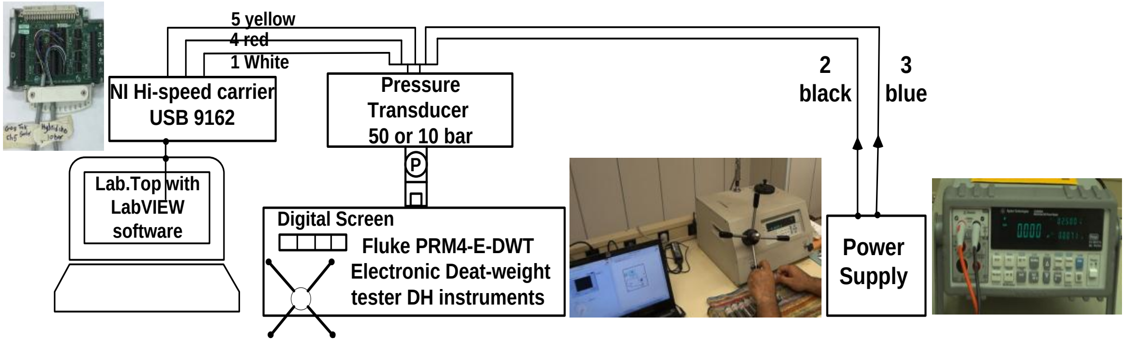


Figure 11. Firing system procedure activates

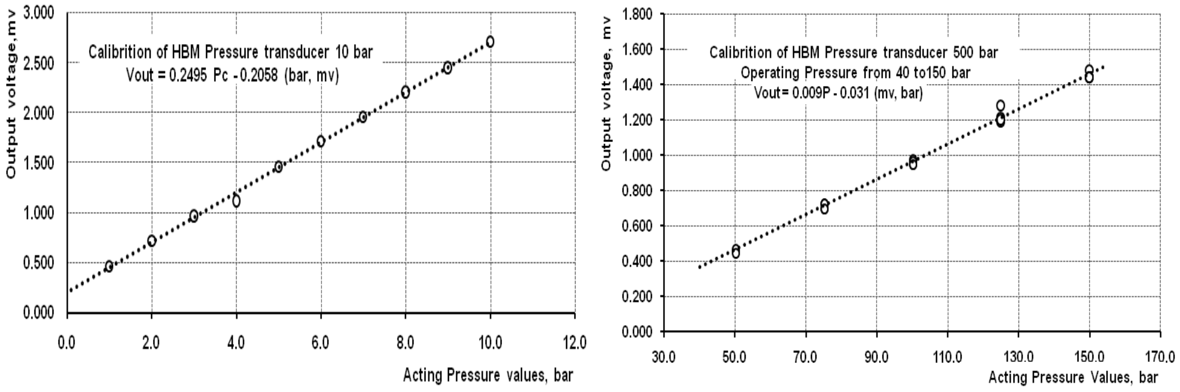
3.3. Measuring tool Calibration

The pressure transducers and thermocouple are calibrated before every 10 tests to determine the relationship between the voltage outputs of the measuring values. The calibration is accomplished by placing values from 0 to 10bar, 50 to 150bar for pressure and 0 to100°C for temperature, and then recording the corresponding voltages. The range of pressures used in the calibration covered the range of pressure values measured during the testing.

The calibration set-up and procedure for each HBM pressure transducer as shown in ‘figure 12’ and K-thermocouple sensor and resulting data sheet as shown in ‘figure 13’.



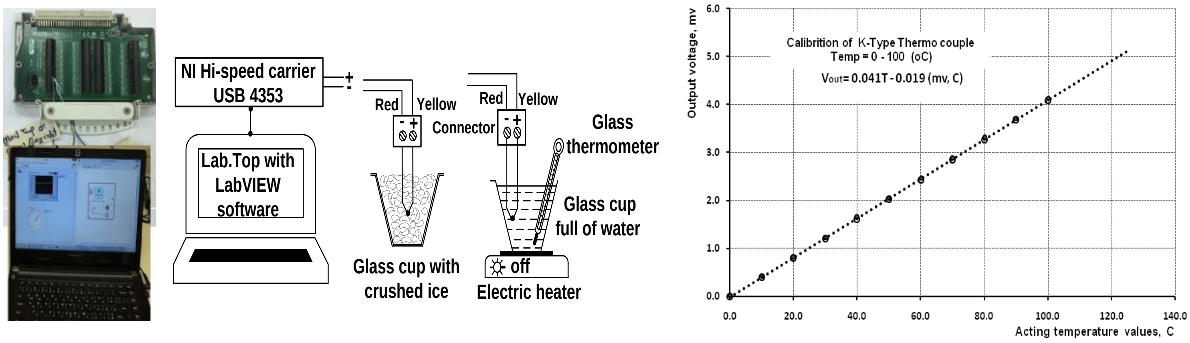
(a) Schematic layout of calibration system



Pressure transducer 10bar Pressure transducer 500bar

(b) Calibration data

Figure 12. Pressure transducer calibration system



(a) Schematic layout of calibration system (b) Type k-thermocouple calibration data

Figure 13. Type k-thermocouple calibration system

3.4. Static firing tests

Cold test

The HPS test (HRM and GO2 feed line) should pass a series of cold tests to minimize the risk of damage and to adjust design parameters during firing. Cold testing (hydrostatic test) has been accomplished on the all system components and connections, using high-pressure GO2 with high temperature (from heat exchanger). During that phase, the GO2 feed system assembly is tested for leakage free operation and proper functioning part by part for all components of system (valves, measuring instruments, heat exchanger, ……. etc.).

Silicon materials, being convenient for oxidizer environments, are employed to ensure a static force seal for the system. The high temperature silicon (thermal silicon) is also utilized to create a static seal for high temperature connections like the fuel grain, grain support interface, and connections of heat exchangers. A hydrostatic test is performed on the engine to ensure that it could withstand at least 15bar. The engine is held at that pressure for 10 minutes without leakage or failure.

Function test

For achieving a successful firing, it is necessary to make several attempts to adjust ignition system with GO2 injection command, operational engine parameters for a fixed grain length and various operating parameters and various types of fuel grain material. The adjustable parameters are igniter characteristics (power, number of coil turns, cartridge material), heat exchanger operating time, HRM operating times, chamber pressures for HRM, GO2 mass flow rate and nozzle throat. Demonstration of sample successful function tests using GO2 as oxidizer for HRM and different solid fuel materials (PMMA, PE, paraffin, paraffin+5%AL and beeswax) with various oxidizer mass flow rate.

A transparent solid fuel grain of PMMA and paraffin are used during function test. HRM is designed, manufactured, inspected, cold tested, and prepared for laboratory firing tests. Command operations and control, measurements and data processing are performed during these tests, allowing detailed investigations and analyses inside control room.

HPS is constructed to demonstrate the concept of SSHRM producing fuel rich exhaust gases. Off-the shelf, safe oxidizer, solid fuel and reliable ignition system are used.

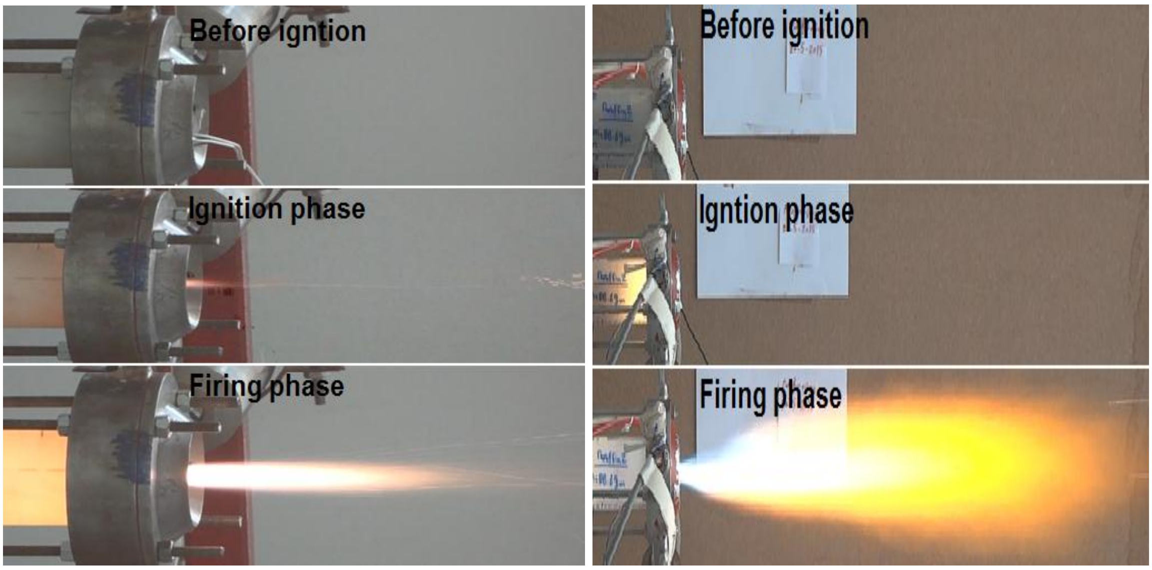
Firing test

The final hot testing of the system is accomplished, through large number of firings. Over 50 tests are run using GO2 with PMMA, PE, Paraffin; paraffin+5%AL and beeswax solid fuel to investigate the ignition and combustion phenomena. Many variables have to be measured in order to obtain information about the performance of engine.

The experimental activity is focused on three main arguments of interest to investigate, regression rate, solid fuel mass flow rate and combustion efficiency for solid fuels. ‘figure 14’ shows the firing phases for new and old generation solid fuel grain combustion.

4. Experimental results

A total of 56 test runs are performed with five different fuel materials in order to complete the test matrix. The firings included 18 with PMMA; 17 with PE, 7 with Paraffin, 7 with praffine+5%AL, 7 with beeswax. One of the tests with beeswax experienced early failure of the fuel grain seal. Photos of fuel grain and metal parts after firing are shown in 'figure 15'. 'Figures 16 and 17' show the comparison between measured and calculated regression rate and solid fuel mass flow rates data respectively, indicates a maximum deviation less than 7.76% for regression rate and less than 5.58% for solid fuel mass flow rate. Figure 18 shows the comparison between old and new generation of combustion efficiency, the combustion efficiency for new generation of solid fuel (50% to 70%) less than old generation (60% to 90%).



Old generation solid fuel new generation solid fuel

Figure 14. 7mm fuel grain+GO2 firing phases

Solid fuel grain inlet port after firing

Metal parts after firing

Figure 15. Solid fuel grain ports and metal parts after firing

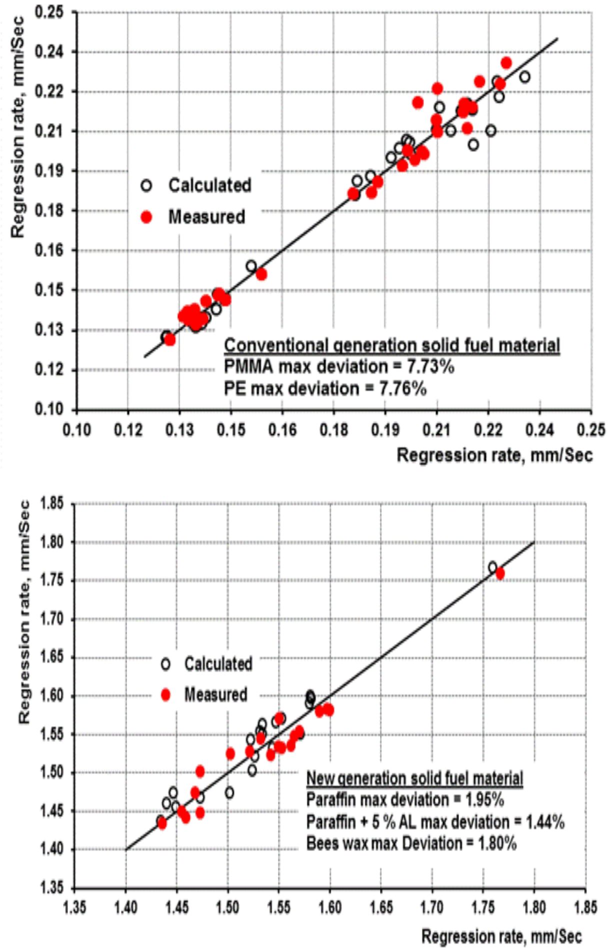


Figure 16. Comparison of measured and calculated solid fuel regression rates

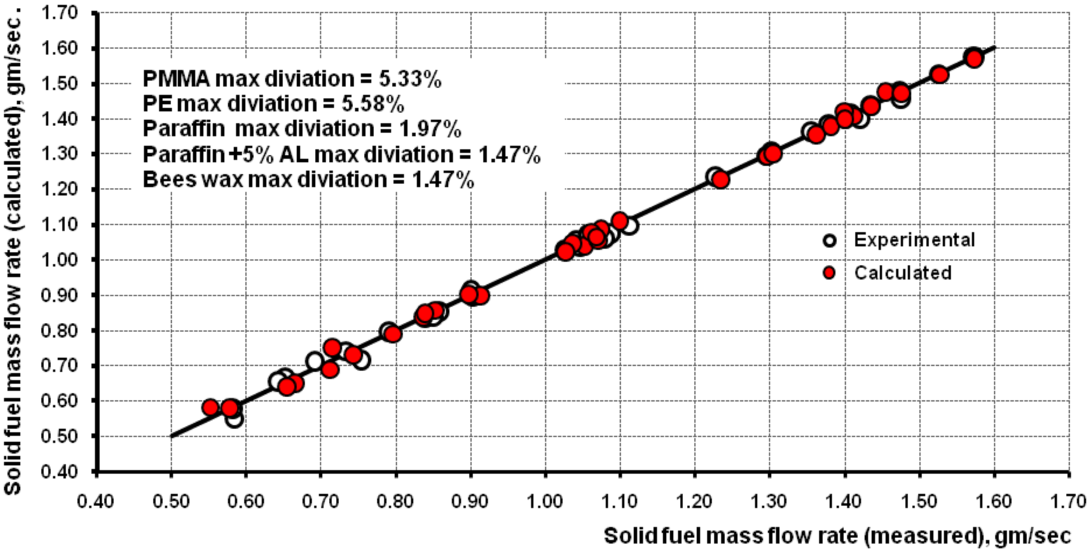


Figure 17. Comparison of solid fuel regression rate measured and calculated

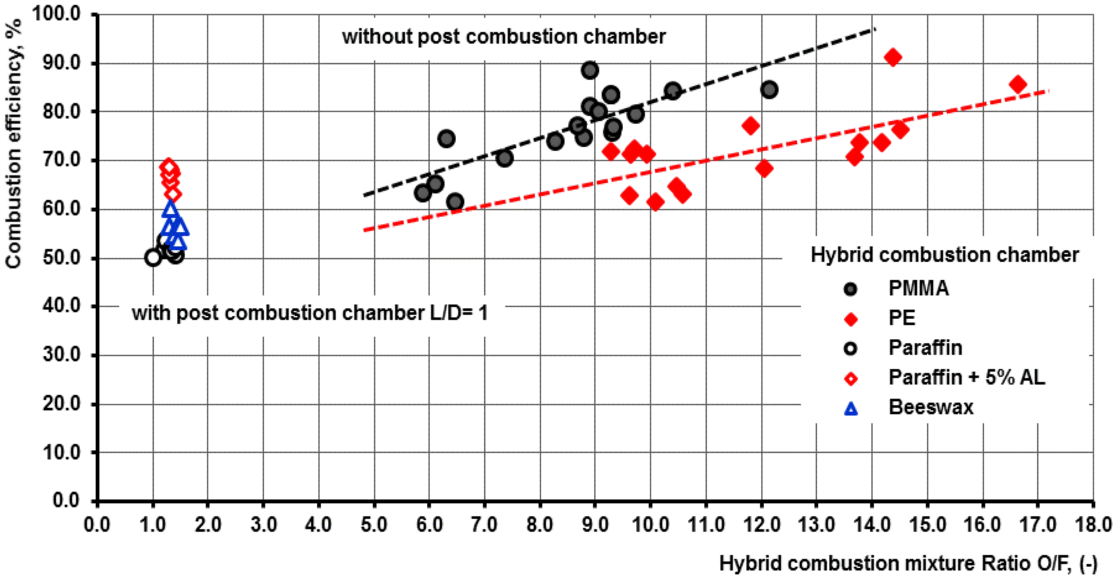


Figure 18. Engine combustion efficiency versus mixture ratio

5. Conclusion

A test rig has been prepared to allow the control of events through a build in Lab-view software. The conventional and new solid fuel grains are prepared (one part in laboratory and other part in the factory) from local raw materials to fit the predetermined dimensions. The final specimens are inspected via x-ray before firing. A series of different solid fuels have been studied experimentally in a laboratory-scale engine. Many trials have been made to reach acceptable ignition technique. A controlled source of GO2 has been provided to the system to complete the elements of a hybrid propulsion system. Measurement pickups (pressure transducers and thermocouple) with reasonable sensitivity are fixed at determined locations and connected to the data acquisition system that permits recording of measurement parameters with reasonable accuracy.

Conventional generations of fuel grain material as (PMMA, PE), have low regression rate, a drawback that limits their use with hybrids. In this work, new generation fuel grain materials (Paraffin, Beeswax) are tested, and the results have proven higher regression rate, easy ignition and better compatibility with this type of propulsion. However, there is still more to be done to improve the mechanical properties of the new generation fuel grain materials.

It is observed that the regression rate of solid fuel new generation is about 3-4 times that of the conventional generation polymeric fuel grain.

The NiCr ignition system has shown longer delay time is noticed as low performance parameter, the observed temperature is higher, which favored the use of high power throughout the tests.

6. References

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