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Design, test and build of a monopropellant thruster using 85% hydrogen peroxide

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Abstract. The objective of this research is to design, build, and test about a 5N Hydrogen Peroxide(H_2O_2) monopropellant thruster (MPT). It is utilized in remote sensing satellites for attitude control and orbit manoeuvres. The MPT uses high test peroxide (HTP) of 85 % concentration. Firstly, H_2O_2 ≈85% concertation by weight is prepared in the laboratory. A distillation and filtration units are built. The distillation and filtration processes are performed. Next, the design of the monopropellant thruster is done based on the developed mathematical model using NASA CEA rocket performance code. The test facility is developed which consists of the thruster, the feeding system, static test stand and data acquisition system with measuring sensors. An experimental test stand is designed and fabricated with Pendulum thrust mechanism for measurements of thrust. Finally, the silver catalyst is prepared and packed inside the MPT chamber where silver screens of high purity 99.96 % are used. The 10-firing tests are conducted under atmospheric conditions. The firings performed without heating are not completely successful. The analysis of the results shows that the thruster has a thrust range from 3.8-4.2 N. The performance of thruster starts to decay after consuming 6 kg of stabilized H_2O_2. The specific impulse (I_s) is evaluated to be ≈ 93-97s at decomposition pressure of ≈10 bars and mass flow rate ≈4.18 g/s. The performance evaluation is judged to be successful. However, using the whole potential of the 85 % concentrated H_2O_2, is expected to increase (I_s) up to ≈111.5s.

1. Introduction

High test hydrogen peroxide (HTP) has been used as a monopropellant and an oxidizer with propulsion systems many years ago. It has a long heritage in the aerospace propulsion as, it has been used in many manned and unmanned space systems since 1930s up to the present time [1].A lot of work has been done by NASA on H_2O_2 decomposition as a MPT [2].

A need for a higher I_s gradually led to the replacement of H_2O_2 with Hydrazine(N_2H_4). Moreover, the development of a superior catalyst bed for N_2H_4 (Shell 405) made N_2H_4 a better option. Also, dinitrogen tetroxide (N_2O_4) replaced H_2O_2 for use as a storable oxidizer. In contrast, the Russian Soyuz launch vehicle, which has been working in space for over forty years, still depends on H_2O_2 as a working medium for its gas generator to run the turbine pump and the reaction control system (RCS) thrusters used for the descent phase of the Soyuz spacecraft re-entry capsule [3],[4]. However, recently, environment concerns and significant cost saving associated with the drastic simplification of the health and safety protection procedures necessary during propellant production, storage and handling have led to a renewed interest in H_2O_2 for use in propulsion systems for low and medium thrust rocket engines as it is ITAR-free and environment-friendly [1],[5]. The nominal propulsive performance of H_2O_2 as a monopropellant is about 20% lower than N_2H_4, but the volume specific impulse achievable with 90% H_2O_2 is higher than for most other propellants due to its high density. This is particularly useful for systems with significant aerodynamic drag losses or firm volume constraints, as is often the case for small satellites [6].

The most important knowhow challenge in the field of H_2O_2 MPT is the development of active, dependable, startable and durable catalytic beds which have fast, and reproducible performance. Such developed catalyst beds must be resistive to poisoning by stabilizers and impurities exist in the propellant which slow down self-decomposition of H_2O_2 such as pyrophosphate ions. In addition, such thrusters need to be capable of sustaining the large number of operation cycles imposed by typical mission profiles in small satellite applications and preferably should not require pre-heating for efficient operation. Nowadays the most popular catalyst material for H_2O_2 is metallic silver [2]. The most significant drawback of the catalytic silver is the temperature limitation and poisoning [7]. As the H_2O_2 flows through silver mesh screens of 20x20 catalyst bed, the decomposition takes place in an exothermic reaction producing oxygen and water steam.

2. Thruster Design

The sequence of the design is performed according to the flowchart in Figure 1.The NASA CEA rocket performance code [8] is used to calculate the thruster theoretical performance, where a mathematical model is developed to carry out the design of the thruster [9].

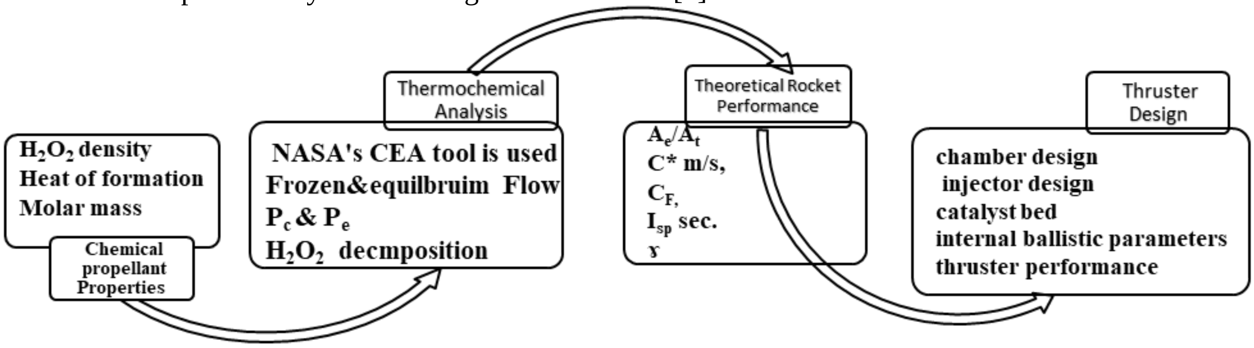

Figure 1.Thruster design flow chart

All the thruster design outcome parameters are listed in Table 1

Table 1. Design parameters of MPT.

	parameter	value
Propellant	H_2O_2	≈85%
	Mass flow rate, g/s	≈4.20
Catalytic bed	Silver mesh material 20x20 purity	99.96%
	Inner diameter, mm	14.60
	Length/diameter ratio	4.0
	Loading factor, kg/s.m^2	50.0
	Total number of packed screens	112
Nozzle part	Convergent-divergent nozzle shape	
	Throat diameter, mm	2.25
	Exit diameter, mm	3.32
	Nozzle half angle, deg	14.0°
Injection and retainer plate	Opening area, %	50
	Diameter, mm	14.6
	Orifice diameter, mm	1.50
	Number of orifices	23
	Thickness, mm	2.0

Thruster performance	Thrust range, N	≤ 5
	Specific impulse, s	≈ 111.49
	Characteristic velocity, m/s	≈ 884.50
	Chamber temperature, K	≈ 907.30
	Thrust coefficient	≈ 1.256
	Mass flow rate, g/s	≈ 4.19

3. Experimental Work

The concentration process and firing test are performed in chemistry and jet propulsion labs respectively in Military Technical College. The MPT is fabricated using stainless steel 316 in the AOI Engine Factory based on the mathematical model developed by Ah. Deif et al. [9]. It uses HTP of 85% concentration by weight. Commercial low concentration H_2O_2 solution 50% bought from the local market is concentrated by distillation of water due to the main impediment in getting the HTP from the local market in Egypt.

3.1 H_2O_2 distillation Unit:

A 50 litres of an industrial H_2O_2 of type HYPROX 500 manufactured in a multinational company called Evonik industries of concentration 50 % by weight is bought from the local market in Egypt. It is decided to concentrate the commercial HYPROX 500 to reach the desirable concentration but without removing all the undesirable stabilizers. A distillation unit has been built as shown in Figure 2. consists of:

1. Two flasks of 1-liter volume.
2. A glass gas trap
3. Condenser
4. Manometer
5. Vacuum pump
6. Thermometer
7. Workstation with ventilation, power source, and water source
8. Hot plate
9. Graduated cylinder
10. Sensitive weight scale
11. Water hose

(a)A 50-liter H_2O_2 drum (b) distillation Unit Set-up

Figure 2. H_2O_2 concentration process

3.1.1 Sequence of distillation. The distillation unit is designed and built in the Department of Chemistry (Military Technical College). All the safety precautions during work are taken based on H_2O_2 handbook. The sequence of distillation is performed as follows:

1. A low concentration H_2O_2 solution is stored in the flask over the hot plate.
2. Evacuation of the distillation unit to a pressure value of about 0.133322 bar by the vacuum pump which is continuously checked by the manometer.
3. The H_2O_2 solution flask heating temperature is about 70°C which is monitored by the thermometer.
4. The H_2O_2 solution begins to boil and the contained water in the solutions starts to evaporate and condense in the adjacent flask. Consequently, the H_2O_2 concentration keeps increasing with time.

5. The glass trap is connected to the vacuum line to prevent H_2O_2 vapor from flowing to the pump.
6. Cold water is flowing in the condenser to condensate the water vapor.
7. The concentration of the boiling H_2O_2 flask can be determined from the known H_2O_2 solution starting concentration and volume, and the condensed water volume in the adjacent flask.
8. When the needed concentration is obtained in H_2O_2 flask, the hot plate is turned off to stop heating. The unit is left to cool down to the atmospheric temperature, then the vacuum is released. the concentrated H_2O_2-solution is collected.
9. The density of H_2O_2 is determined precisely by weighing the condensed volume of the concentrated H_2O_2 using the graduated cylinder and the scale to check the mass. The density is calculated by dividing the mass by the volume If the H_2O_2 density is obtained at 1.36 gr/cm^3 and 25°C then, it corresponds to H_2O_2 of 85 % concentration at ambient temperature based on Evonik calculation model [10], the concentrated H_2O_2 still has some stabilizers which slow down the process of self-decomposition which has negative effect on the decomposition efficiency and the catalysts life time.
10. An 8 liters of concentrated H_2O_2 is produced, stored in a ventilated container, and saved in the refrigerator to slow down the self-decomposition rate.

3.2 Filtration Process:

The concentrated H_2O_2 underwent filtration process to get rid of the stabilizers using G3, G4 sintered discs which are categorized into 5 grades G1, G2, G3, G4 and G5. The grades are determined by maximum pore size, which is determined by measuring pressure at which the first air bubble penetrates the filter under specific circumstances.

Table 2. porosity grades and their general use. [11]

Porosity Grade	Pore Size (Microns)	General use
1	90-150	Filtration of coarse materials / precipitates, gas dispersion, gas washing, extractor bed, and support for other filter materials.
2	40-90	Filtration of medium precipitates gas disperations and gas washing.
3	15-40	Filtration of fine grain precipitates, Analytical work with medium precipitates, and Mercury filtration.
4	5-15	Analytical work with fine and very fine precipitates, Non-return mercury valves.
5	1-2	Bacteriological filtration.

3.2.1Sequence of filtration. Filtration sequence is performed as follows:

1. The sintered disc (1) is mounted on a vacuum flask with a neck and a vacuum line is connected to a connector socket as shown in Figure 3.
2. The vacuum pump evacuates the flask (2) through a trap (4) to create a pressure differential between the two sides of the disc to let H_2O_2 flow through it.
3. A trap is connected through the line to prevent the filtered H_2O_2 to enter the vacuum pump (3).
4. Firstly, H_2O_2 is filtered using G3 sintered disc of pore size 15-40 microns to filter out the impurities bigger than this size,.
5. Secondly, a finer filtration process is performed using G4 sintered disc of pore size 5-15 microns to avoid blockage of the sintered disc which was harder and longer process because, it takes longer time to let H_2O_2 pass through the filter.
6. It is necessary to clean the sintered disc with distilled water to avoid blockage of the flow.
7. The filtered H_2O_2 will be collected and saved in ventilated bottle in a refrigerator.

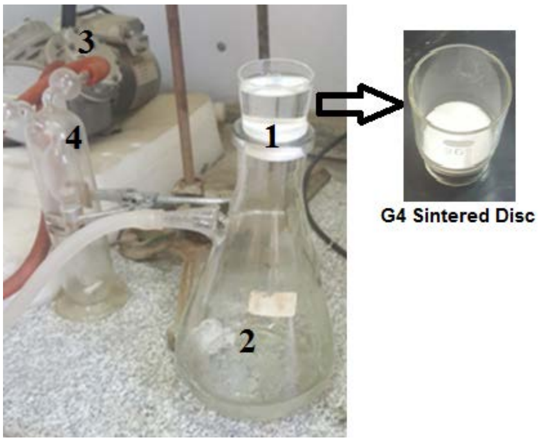

Figure 3. Filtration process set-up

3.3 Test Facility

The experimental testing of the 5N MPT prototype is done using H_2O_2 test facility. It consists of MPT, a feeding system, a custom-made test bench and data measuring system designed for delivering H_2O_2 to the MPT at the desired mass flow rate and pressure as shown in Figure 4.

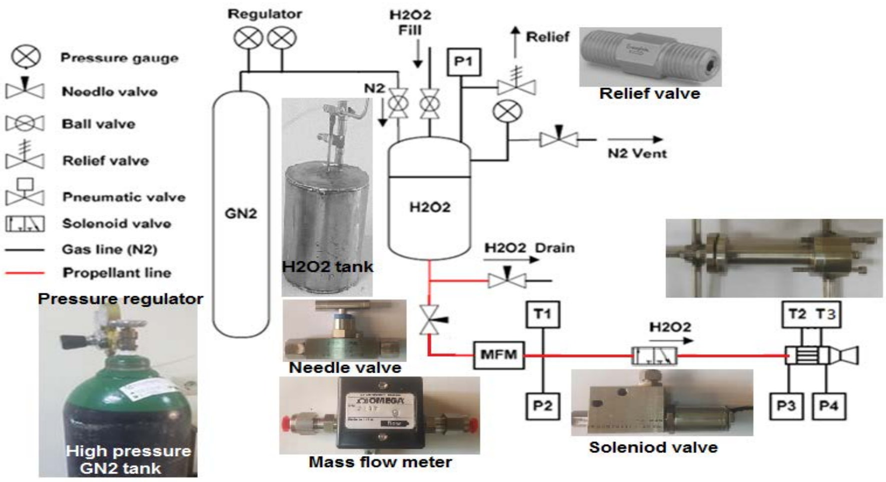

Figure 4. Thruster feeding system

3.3.1 The thruster. The MPT is made of stainless steel 316 to withstand the thermal and mechanical stresses generated during firing based on mathematical model developed by Ah. Deif et al [9]. It is manufactured on modular base where it consists of 3 parts: the injector (1) where the liquid hydrogen is entered and injected, the cylindrical parts which holds the catalyst bed where the hydrogen peroxide is decomposed by flowing through it, and the nozzle (3) where the gaseous products are accelerated into the critical section. The injector plate is designed to distribute the propellant on the surface of the catalyst, the retainer (4) is designed to block the catalyst to go out from the chamber, and an anti-channeling disc to redirect the flow into the core of the catalyst Figure 5.

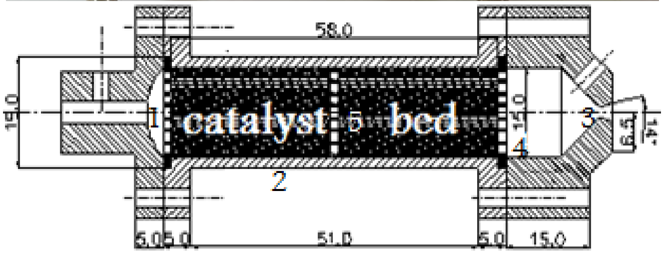

Figure 5. Thruster design

3.3.2 The feeding system. The feeding system consists of a high purity nitrogen high pressure vessel connected to pressure regulator to regulate the exit pressure. It is used as a pressurizing gas to pressurize the propellant feeding line, and purging/cleaning the pipes from propellant residuals when needed as shown in Figure 4.The H_2O_2 is stored in a stainless-steel tank of ≈3.5 liters volume and wall thickness of 3 mm is designed and manufactured to withstand the high pressure up to 25 bar, noticing that high concentration H_2O_2 is compatible with the stainless-steel 316 [12]. The pressure in the tank is monitored by a dial gauge. The tank is connected to Stainless Steel 1-Piece Poppet relief Valve with adjustable Pressure (10.4 to 24.2 bar) to release any overpressure may happen if it exceeds 15 bar. A fill valve is connected to the tank to fill the tank with H_2O_2. A manually operated ball valve is used to feed the compressed H_2O_2. A vent is connected to the circuit to make sure no air or nitrogen bubbles in the flow of the circuit. The mass flow rate of H_2O_2 is regulated by a Needle Valve. The compressed H_2O_2 flows in the thruster using electrically switching on solenoid valve remotely by a command from the Ni-user software interface, Figure 4.

3.3.3 The test Bench. The MPT is installed, by properly designed interfaces on an assembly which is composed of two L-shape beams. The MPT (1) is installed by two small brackets (2) on the small L-shape (3) by screws which in turn is hanged freely to a bigger and rigid L-shape beam (4) by two flexures (5) made of (0.5) mm thickness spring steel sheets. The thrust force generated during the operation of the thruster is transferred to the small L-shape beam (3) which, in turn transfers the thrust to the load cell through a stud screwed to it and is touched to the load cell. The compensation of the cables and connections loads to assure zero loads before of the firing test is done by tightening or untightening the screw. The bigger L-shape structure is fixed to the test bench considering the horizontal position of the MPT axis and alignment with the load cell axis. A series of longitudinal and transverse holes (6)are also incorporated into the design of the big L shaped beams to allow the alignment and adjustment in both directions A Swagelok NPT connection (7) and 5 mm diameter Teflon tube (8)are used for feeding the H_2O_2 to the MPT which is perpendicular to the thruster axis to eliminate the reaction of the fuel flow and fitted without applying any further forces in the thrust direction as shown in Figure 6.

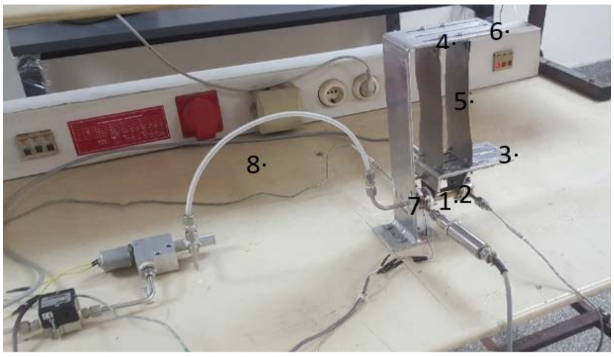

Figure 6. The H_2O_2 MPT Test Bench

3.3.4 Measurement tools and Data Acquisition System. The measurements collected during testing can be classified into two different types:

A) Measurements for detecting HTP feeding system status:
- The tank output pressure, which is associated with HTP mass flow. Additionally, irregular pressure rise is typically a sign of early decomposition of the stored HTP which is monitored by a pressure gauge.
- The propellant flow rate is measured by an omega FLR10009TH. A DC source of 12 output volt is used to provide the flow meter with the required excitation voltage.

B) Measurements for evaluating the performance of the MPT prototype:
- The two-pressure transducer used for static pressure measurements are produced by HBM, type P3MB-20 are selected for its high precision (accuracy is 1% FSO). The first one is installed in the injection part upstream while the second is installed downstream before the convergent part of the nozzle Figure 9(a). The data coming from the pressure transducers are acquired and transferred to a laptop by National Instruments acquisition board number 9237 which supplies the excitation voltage needed by the pressure transducer.
- Temperature measurements are performed using K-type thermocouples with 0.5 mm diameter and 150 mm Figure 9(b). The data coming from thermocouples are collected and carried to a laptop using a National Instruments acquisition board number NI 9219 which supplies the excitation voltage needed by the thermocouples.

(a)Pressure transducer **(b) Thermocouple** **(c)Load cell**

Figure 7. Measuring tools

- The thrust force is measured by a load cell manufactured by 3132_0 - Micro Load Cell (0-780g) - CZL616C. This Single Point Load Cell is used in small jewelry scales, Figure 7(c).
- The data coming from the loadcell are collected and carried to a laptop using a National Instruments acquisition board number NI 9219.

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- A 24 volts power source provides the solenoid valve with the required electric operating power. The solenoid valve is controlled by a laptop using a National Instrument relay card NI9481 to start the firing, Figure 8.

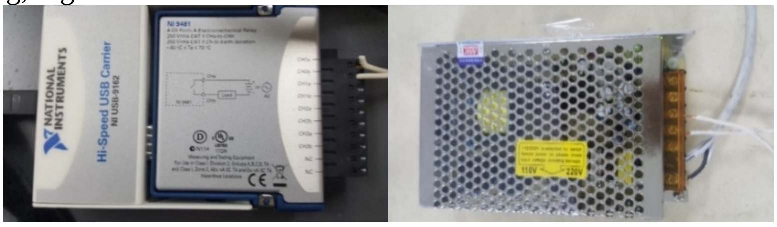
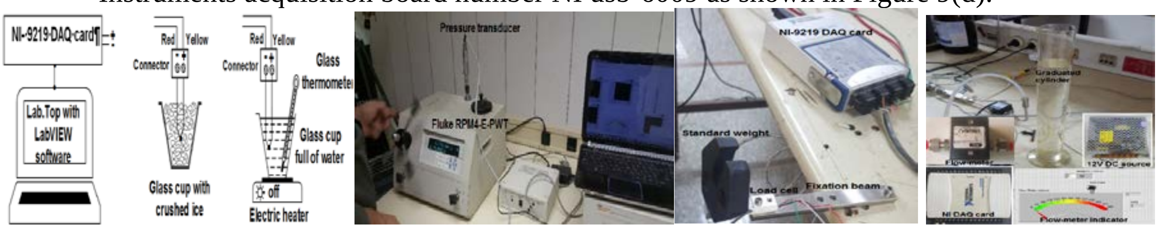


Figure 8.NI relay card NI9481& solenoid valve power source

3.3.5 Measuring tools calibration system

- Thermocouples are calibrated in the lab using a cup filled with ice cubes and cold water to fill the gaps, and another cup filled boiled water Figure 9(a).
- Two-pressure transducer are calibrated in the lab using fluke RPM4-E-PWT electronic deadweight tester and the reading matches perfectly the test report included with the transducer Figure 9(b).
- load cell is calibrated using different standard weights Figure 9(c).
- The flow meter is calibrated using a 500ml graduated cylinder and a timer at different flow rates. The data coming from flow meter is collected and carried to a laptop using a National Instruments acquisition board number NI usb-6009 as shown in Figure 9(d).

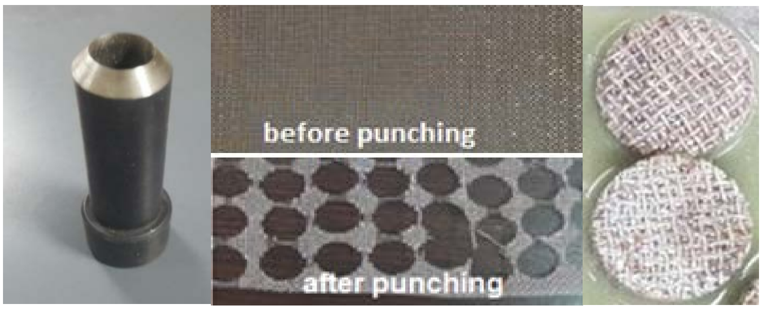


(a) Thermocouple (b) Pressure transducer (c) Load cell (d)Flowmeter

Figure 9. Measuring tools calibration system

3.4 Silver catalyst bed procurement and preparation:

The silver mesh should be cut into discs of 15 mm to be packed in the thruster. A punch tool is designed, machined and heat treated to cut the silver screen sheet as shown in Figure 10(a) The silver sheet is mounted on acrylic sheet and hammered using the punching tool to cut the silver discs as shown in Figure 10(b),(c). The discs are compacted in the thruster using a hydraulic press to increase the packing factor of the silver screens in the thruster.



(a) punching tool (b) Silver mesh sheet (c) sliver discs

Figure 10. Silver catalyst preparation

3.5 Firing Test:

Initial testing begins with leak tightness of the system without the thruster connected, the cracking pressure of the relief valve was set to 15 bar. The system is pressurized with nitrogen gas to ≈14 bar and checked for leakage. The third test is performed with water to check the functionality of the feeding system elements, the functionality of data acquisition system, adjustment volume flow rate using the flowmeter and the needle valve by the user front panel of NI control software as shown in Figure 11.

Figure 11. Thruster performance user front panel

Propellant is filled into the tank through filling valve. Pressure regulator is set to the required propellant tank pressure. Nitrogen supply is opened, and it enters the gas pressurization tank of 3.3L volume. Once the propellant tank pressure is stabilized, solenoid valve is switched on to initiate the engine operation. The thruster is fired until the solenoid valve is switched off by the relay signal from Ni control software based on the required pulse time. The thruster is purged by deionized water after firing to remove the residual H_2O_2 in the thruster and catalyst bed.

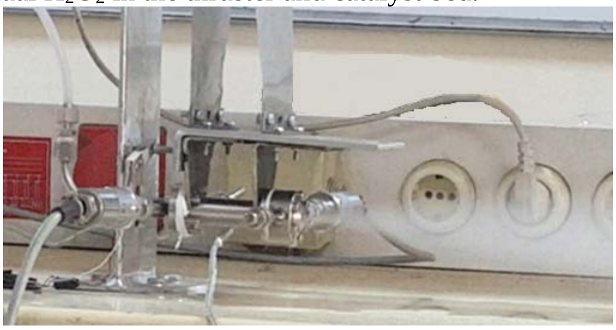


Figure 12. Thruster hot firing

4. **Results and Discussion**

The firing test of the thruster with and without heating is investigated

4.1 Firing without catalyst preheating:

The initial trials are performed without heating to fire the thruster, the initial input catalyst bed temperature is 25C°, injecting pressure 10 bar, and the silver mesh is compacted to 10 MPa in the decomposition chamber of 15 mm diameter and 58 mm length. The results are not successful. It is shown in Figure 13.The firing is comprised of injecting the concentrated H_2O_2 for a duration of ≈ 13 s. The Chamber input pressure is≈ 6.59 bar and the output pressure is ≈ 6.24 bar, where the difference is 0.36 bar represents the pressure drop due to the catalyst bed.

It is noticed that the decomposition is not complete and partial quenching takes part. The chamber input & output pressures are fluctuating, it takes ≈ 7.0.s as a rise time to reach the decomposition pressure. A white smoke is released, and an acidic odor was smelled in the decomposition products because, H_2O_2 is not decomposed completely. The thrust force reaches ≈2N which is much lower than the theoretical designed value. The possible reasons for the H_2O_2 is not decomposed at the catalyst bed could be the temperature of the catalyst and H_2O_2. At the time of the test the atmospheric temperature is

≈ 25°C. Willis [13] stated that the most noticeable effect on the initial ignition time delay is the thruster body temperature and majority of his testing were done at catalyst bed temperature of 200°C.The second possibility might be the inadequate surface contact of the catalyst material with the H_2O_2 especially the compaction pressure is low.10 MPa. Moreover, the used silver mesh 20x20 has high free volume ratio of 0.7 after compaction, knowingly that silver mesh 40x40 has less free volume fraction which increase the effective surface area used to the decompose the H_2O_2 flowing through the silver and gives better performance. however, it is more expensive and has higher pressure drop through the catalyst Runkle et al. [2] stated that mesh silver gauzes 40x40 has better performance than 20x20 mesh silver gauzes. Long M.R. et al [14],[15] revealed that catalytic beds with high packing density lead to more complete decomposition and higher produced temperatures with respect to low packing density ones. Another reason might be the contamination in the H_2O_2 which was not removed by the filtration process because soluble stabilizers cannot be removed by such filtration process especially nitric acids.

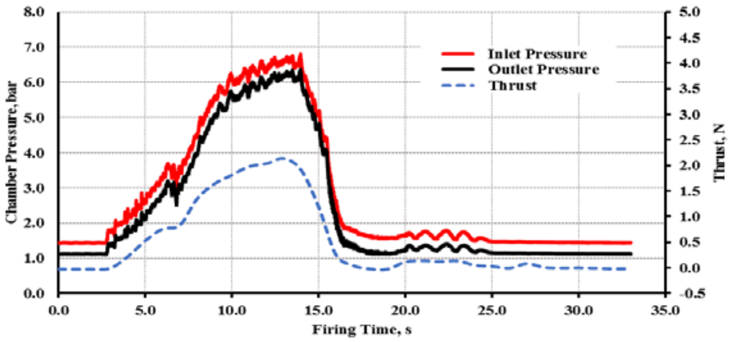


Figure 13. Thruster performance (pressures and thrust) vs firing time without preheating

4.2 Firing with catalyst preheating and increased packing factor:

This run is conducted after two taken corrective actions which are heating including propellant pulsing to pre-heat the silver screens before firing and increasing the compaction pressure from 10MPa to 12MPa to increase the contact area to enhance the decomposition process. It is better to increase the compaction pressure more than 12MPa, but the lack of silver screens won't allow to increase it as pure silver screens are not available in the local market. The results show that firing test is successful, Figure 14.

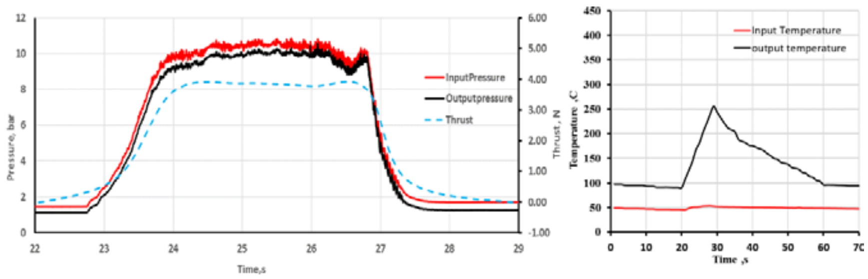


Figure 14. Thruster performance (pressures, thrust& Temp.) vs firing time with preheating

The firing is comprised of injecting the concentrated H_2O_2 for ≈ 5s, the chart shows the decomposition chamber input pressure rises to pressure 10.3 bar and the input temperature is 50°C. While the output pressure is around 10.0 bar the difference is 0.3 bar which represents the pressure drop due to the catalyst bed and the output temperature rises to 256°C and starts to drop after the end of the firing. The graph also shows the pressure is somehow stable and the H_2O_2 almost decomposes into steam and oxygen. A complete decomposition of the monopropellant is mostly obtained. The thrust reaches the value of 3.8N and the average mass flow rate is around 4.20 g/s. So, the experimental specific impulse (I_s) is calculated as in equation(1).

$$I_s = \frac{\int F dt}{mg} \qquad (1)$$

where F is the measured thrust, g = 9.8065 m/s^2 is the standard gravity acceleration. As a result, an average experimental I_s ≈93s is obtained where the value calculated by the NASA CEA code is 111.4s. Therefore, the experimental result is acceptable, because several losses happen in the decomposition process (silver contact area, silver purity, starting temperature, heat losses through the thruster body, and H_2O_2 Purity), as well as, the nozzle is not adiabatic.

The H_2O_2 pulses heat the catalyst bed itself during pre-firing, but the fuel is still at the room temperature. It is noticed from the pressure time chart that it takes almost 0.65 s as a rise time to reach the working pressure and produce the required thrust. To decease the rise time of the operating pressure and accelerate the decomposition process, the catalyst bed need to be heated to higher temperature around the thruster casing before firing and also to decrease the heat losses and the dead volume should be minimized as Y. A. Chan [5] revealed that increasing the temperature to 150°C provides adequate energy to decompose the catalyst bed and the pressure rises to maximum in 100ms after opening the solenoid valve. Moreover, silver compaction pressure needs to be increased and the silver screens need to be pickled by samarium nitrate [12] but it is very expensive and not available in the local market. The H_2O_2 purity needs to be enhanced to avoid the poisoning of the catalyst bed and decay of the catalyst performance. It is noticed that temperature of the decomposition products is not high because the duration of the firing is short to heat the catalyst especially the thruster body is not insulated.

This third run is conducted with heating including propellant pulsing to pre-heat the silver screens before firing. The thruster initial input temperature is about 50°C and the output initial temperature is ≈120°C after heating which is higher than the previous two runs. It is shown in Figure 14 that the chamber input pressure rises to 11 bar and the input temperature is 50°C after firing, the output pressure and temperature are around 10.6 bar and 268°c respectively. The pressure difference is 0.4 bar which represents the pressure drop due to the catalyst. The thrust reaches the value of 4.1 N and the average mass flow rate is about 4.19 g/s so the experimental I_{sp} is =97s. It is noticed that the pressure and thrust increases due to the increase in the initial temperature at the same mass flow rate which agrees with [3], [9].

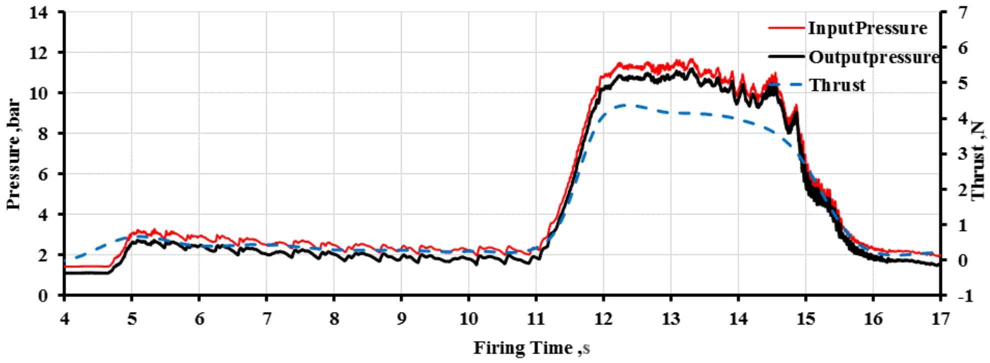


Figure 15. Thruster performance (pressures and thrust) vs firing time with heating

In the last firing of the thruster, the initial input temperature is 48 °C, the initial output temperature is 90 °C, the injecting pressure is 10 bar, The results show they are not successful, it is shown in Figure 16. the firing is comprised of injecting the concentrated H_2O_2 for a duration of about 12s, but no decomposition takes part and a white smoke was released, and an acidic odour was detected in the combustion products because, the H_2O_2 is not decomposed. The main reasons for the H_2O_2 is not decomposed by catalyst bed could be the poisoning effect which insulates and stops the reaction to take part especially the H_2O_2 which is used is in this run is not filtered so the contaminations and stabilizers especially chromium chloride and sodium stannate which agrees with the result given by [16] are not removed and stick on the surface of the silver mesh as shown in Figure 16 which prevents the contact with H_2O_2. Whitehead [12] highlights the necessity of decreasing the contaminations during preparation of concentrated H_2O_2.

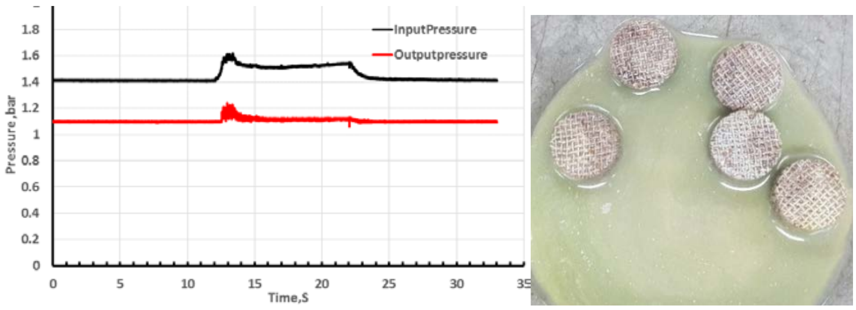


Figure 16. Poor decomposition due to silver poisoning

5. **Conclusion**:

The main conclusions of the present work can be summarized as:

- Building a distillation unit and concentrating the H_2O_2 successfully using the available commercial 50 % H_2O_2 to the reach the required 85 % concentration
- Building a filtration unit and removal of the solid stabilizers using mechanical filtration is achieved which enhances the service life of the catalyst bed.
- Design and development of the test facility capable of performing the MPT firing successfully and safely. The test facility includes the feeding system which capable of providing the MPT with required operating conditions. The test bench can measure all the thruster performance parameters precisely and remotely using developed automated front panel interface.
- Design, manufacture, and test of 5 newton H_2O_2 monopropellant thruster which can be utilized in remote sensing satellites for attitude control and orbit maneuver. However, the actual measured thrust reaches the value of ≈ 4.1 N, the average mass flow rate is ≈ 4.19 g/s and the thruster experimental I_{sp} is =97s. which is an accepted performance due to the prementioned difficulties in the present work.

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