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Kobry El-Kobbah,
Cairo, Egypt.

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THEORETICAL AND EXPERIMENTAL INVESTIGATION OF RESISTO-JET THRUSTER

A. E. Makled* and M. A. Othman*

ABSTRACT

This article describes the theoretical and experimental search activities about resisto-jet thruster that can be used with small satellites (≈ 500 kg) and space stations for correction of launch insertion, orbit correction and station keeping respectively. In the past, many space propulsion systems are used for these missions, some systems have disadvantages as low performance, high power consumed, complicity and toxicity. Cold gas system has low performance, hydrazine and ammonia systems use toxic propellants, arc jet thruster has low thrust to input power ratio and bi-propellant system has more complicity integration.

Resisto-jet thruster is operating at low power (≈200 W). Using liquid or gas propellant like water, nitrogen or nitrous oxide have re-emerged as attractive propulsion options for small satellites and space stations. To obtain this goal, four phases of research were conceptually required (thruster selection, propellant choice, design criteria and engineering model). Three resisto-jet thrusters have been developed, which utilize three different packed bed materials (silicon carbide, copper and aluminum) with deferent cartridge heaters (100, 200 and 300W) for the heat exchanger. The design of resisto-jet is simple, safe and has a long lifetime that offers operational flexibility to space applications for station keeping and orbit or launch correction.

The present results show for the first time that water resisto-jet thruster has advantages for small satellite station keeping and launch correction missions. Resisto-jets have the advantages of simplicity, high thrust density and high heat transfer efficiency with given input power and wide spectrum of working fluid. The disadvantage is its low specific impulse compared with other electric thrusters.

KEY WORDS

Resisto-jet thruster, space propulsion, packed bed materials, station keeping

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* Egyptian Armed Forces.

INTRODUCTION

Propulsion systems (PS) are a common feature on several types of satellites (communication, remote sensing, military and space research) and a common system of space stations. However, cost, mass, size, integration, power, lifetime and safety have been essential for design considerations.PS performs a variety of tasks essential for spacecraft (SC) as launch correction, separation instability, orbit transfer, attitude control, de-orbiting and orbit maintenance (station-keeping and orbit correction).

This work summarizes the activity about suitable space PS to excite station keeping and launch correction missions for small satellites (≈ 500kg). The primary objective of this research is to investigate on shelf space PS types concerning low cost and safety options.

The various types of electric propulsion are overlapping in many cases; but broadly, they can be divided into three categories: electro-thermal (specific impulse $I_{sp}\approx$ 500-1000 s, thrust ≈ 0.01 to 0.58 N and with exhaust velocities ≈1000-5000 m/sec.), electro-static ($I_{sp}\approx$ 2000-100000 s) and electro-magnetic ($I_{sp}\approx$ 1000-7000 s). All of these thrusters have one common feature, which is high electric power requirement per thrust ratio (1-100 kw/N) depending on the type of system. This implies that application of electric propulsion in space may be limited up till now especially in low earth orbit (LEO) remote sensing satellites; the efficiency of thrusters is relatively good with chemical propulsion systems. Figure (1) shows power performance values for several types of electric propulsion systems (Resisto-jet, arc-jet, pulsed plasma thruster, ion thruster, hall thruster and magneto plasma dynamic thruster) [1,2,3,4].

Electro-thermal thruster is the system with least complexity, since its principle of operation is electrical heating of a working gas and expanding it through a nozzle part to produce thrust. Two methods of heating the gas are developed: electric arc (arc jet thruster) and resistance heating (Resisto-jet thruster).

The resisto-jet has some advantages over the arc jet thruster as the working fluid is heated to a lower temperature than in arc jet and the efficiency of the Resisto-jet is not impaired by ionization and dissociation losses. Both types of thrusters are limited in their performance by the limitation of high temperature materials that can be used.

The resisto-jet demonstrates $I_{sp}\approx$ 750-900 s in the thrust range less than ≈ 0.5 N with an efficiency over 70%. At low power level, pulsing operation of resisto-jet is a several hundred hours of steady state running time.

While the arc jet demonstrates I_{sp} of ≈ 800-1500 s in the thrust range of 30-100 mN at an efficiency of 35-60%.

Electric propulsion systems have low thrust (≈ 0.005-1 N), increasing the satellite velocity requires too many thrust pulses and hence it takes a long period of time (hours or days) to execute the maneuver.

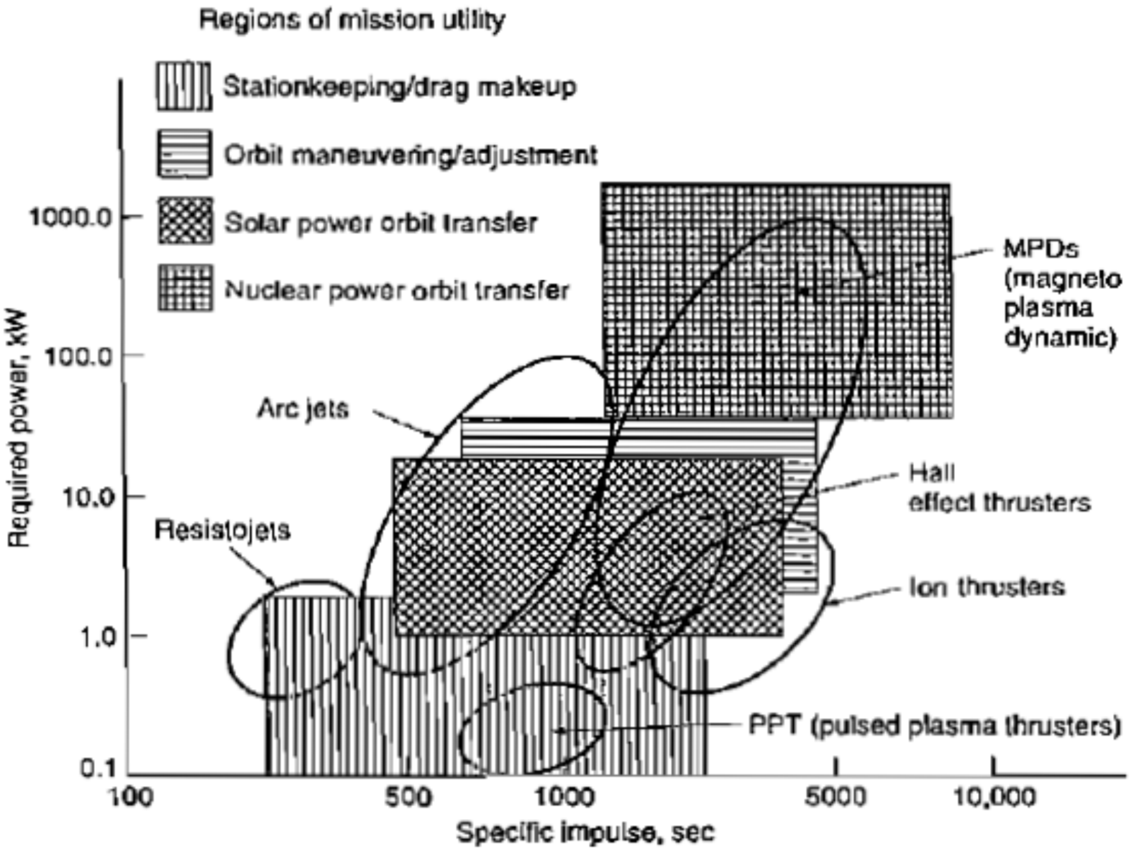


Fig. (1) Electric propulsion power consumed for station keeping mission [3].

RESISTO-JET FLIGHT HISTORY

The literature survey on the Resisto-jet thruster is focused on space missions as shown in Table (1). During 1965, the first space maneuvers of Resisto-jet thruster were excited successfully for 30 minutes to slightly adjust the position of the Vela satellite [4, 5].

Resisto-jet thruster can be designed with various working fluids (methane, hydrogen, water, carbon dioxide, helium, oxygen, air, argon, and combinations of fluids). Bio-waste water was of great attractive propellant for NASA space station applications [4].

THRUSTER EVALUATION

The basic problem in the Resisto-jet thruster design is intermittent heat transfer from the heater to the working fluid (conduction and radiation) since the thermal and physical parameters vary with temperature. Stream flow in the chamber is usually considered laminar, the heat transfer to the stream is mostly by conduction and chamber pressure is influenced by several factors as nozzle and chamber dimensions, heat transfer media and injected mass flow.

Table (1). Resisto-jet thruster flight experienced [4, 5].

Satellite	**1st flight (no of flight) (Country)**	**Propellant**	**Power (w)**	**Uses**
Vela	1965 (6) (USA)	N_2	30-90	Orbit adjustment
US Navy satellite	1965 (5) (USA)	NH_3	30	Orbit control, attitude control
ATS-A,C, D,E	1966 (4) (USA)		10-30	Research, attitude control
US Navy satellite	1971 (5) (USA)	NH_3, N_2H_4	-	Research
Sol Rad-10	1971 (-)(USA)		10	
INTELSAT V	1981 (4) (USA)		350	N-S station-keeping
SATCOM	1983 (25) (USA)		600	
UoSAT-12	1998 (1) (UK)	N_2O	100	Research
EHT-15 Thruster	Russian	Ammonia	100-450	Research

The life time of a Resisto-jet is often affected by the heat transfer media and nozzle throat life. The proper design chamber pressure in the range of 1-10 bar.

Thrusters efficiencies of Resisto-jet are about 65-85%, depending mainly on the type of working fluid and the exhaust gas temperature.

Specific Impulse (I_{sp})

The delivered Isp depends primarily on properties and character of the working fluid, chamber temperature and the nozzle configuration, it can be expressed as:

$$Isp = \frac{F}{\dot{m}} = W_{eff} \qquad \text{(m/s)} \qquad (1)$$

where:

$$W_{eff} = V_{ex} + A_{ex}(P_e - P_a)/\dot{m} \qquad (1\text{-a})$$

$$V_{ex} = \sqrt{\frac{2\gamma R_u T_c}{(\gamma-1)M}[1-(\frac{P_e}{P_c})^{\frac{\gamma-1}{\gamma}}]} \qquad (1\text{-b})$$

F	generated thrust (N),	P_e	nozzle exit pressure (Pa),
$\dot{m}$	working fluid mass flow rate (kg/s),	P_c	chamber pressure (Pa),
W_{eff}	effective exhaust velocity (m/s),	M	molar mass (g/mol),
V_{ex}	exhaust velocity (m/s),	γ	specific heat ratio (-),
R_u	universal gas constant (8314.41 J/kmol-K),	A_{ex}	nozzle exit area (m^2).
T_c	chamber temperature (K),		

Density Specific Impulse (dI_{sp})

The I_{sp} represents mass specific impulse, however for small satellite the volume can actually be more important than mass. Thus, it is important to consider dI_{sp} as a function of average specific gravity of propellants, ρ_{ave} as:

$$dI_{sp} = \rho_{ave}\, I_{sp} \qquad \mathrm{Kg/(m\ s)^2} \tag{2}$$

Consumed Power (P)

Since small satellites have very low power output (≈ 150 W) in LEO. It is vital to determine how much power is consumed by thruster to produce the thrust, F as:

$$F = \frac{2P}{w_{eff}} \tag{3}$$

where *P is the* input Power for thruster (W).

Integration and Safety Parameters

The design of small satellite thrusters is simple, long life time and low-risk, capable of using multi-propellants. Component technology has been successfully demonstrated in space applications with operational flexibility. The thrusters must offer various modes of operation, pulsed and continuous modes.

DESIGN AND RESEARCH PLAN

A Resisto-jet seems to be the best option for small satellite Launch correct and orbit correction missions. The issues and problems associated with Resisto-jet design and modeling are described and analyzed through conceptual phases. Each phase presents experimental and modeling results with synergistic goals for the next research phase. Figure (2) shows the working plan for the Resisto-jet research program.

THEORETICAL INVESTIGATION

Resisto-jet Design Approach

The Resisto-jet design and performance assumes a one dimensional adiabatic constant specific heat expansion through the nozzle. Solving the energy balance using the first law of thermodynamics to get V_{ex} as:

$$\frac{1}{2}V_{ex}{}^{2} = \frac{1}{2}V_{c}{}^{2} + C_{p}\,(T_{c} - T_{ex}) \approx C_{p}T_{c} \tag{4}$$

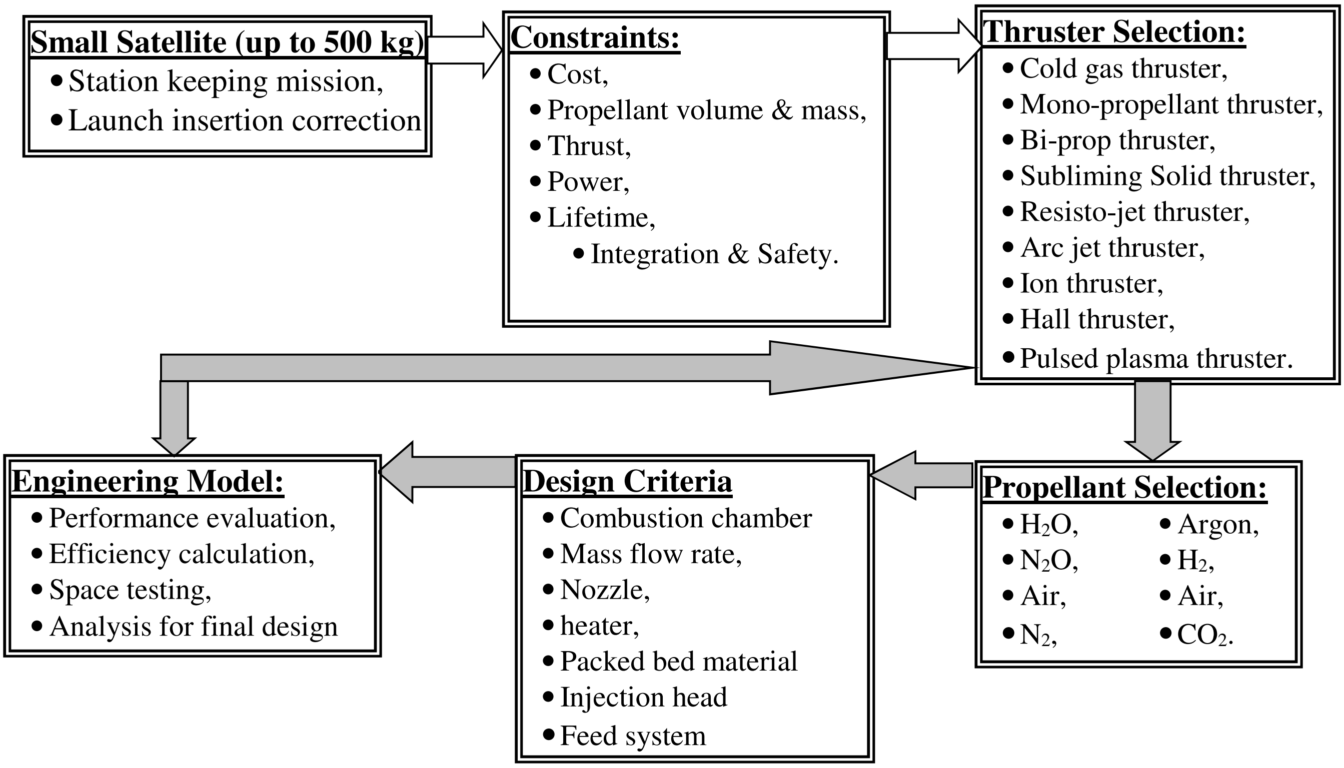


Fig. (2). Resisto-jet Thruster Design loop.

The chamber flow velocity V_c and the exit temperature T_{ex} are negligible in a first approximation. The specific heat of working fluid C_p is a significant parameter.

The N_2 seems very attractive propellant, since its high I_{sp} with low molecular mass M, high C_p. Table (2) presents a comparison of N_2, H_2O and N_2O working fluid at operating temperature T_c (≈ 1000 K), efficiency 100% and consumed power 100 W. Table (2) shows the attractiveness of a H_2O and N_2O as working fluid for Resisto-jet thruster design; this conclusion is respectable for initial performance estimation.

The design approach is modified by the using thermo-chemical code [7]. Table (3) summarizes initial performance for various working fluid conditions (P_c=10bar, heat transfer efficiency ≈50%, nozzle expansion ratio ≈100 and ambient pressure of =8 N/m^2).

Table (2). Resisto-jet various working fluids (P=100 W and T_c=1000 K).

Working fluid	**F mN**	**I_{sp} Sec.**	**C_p kJ/kg.K**
Hydrogen (H_2)	37	546	14.3
Water (H_2O)	93	219	2.3
Nitrous oxide (N_2O)	141	144	1.0

Table (3). Theoretical calculation of Resisto-jet performance.

Initial parameters		**I_{sp} sec.**	
T_c K	P_c bar	H_2O	N_2O
700	2.5	116	117
	10	168	117
800	2.5	175	126
	10	177	126
900	2.5	185	134
	10	185	134

The next step is evaluation of the power P as Eq. (5) and mass flow $\dot{m}$ required to satisfy performance parameters in Table (3) as shown in Fig. (3).

$$P = \dot{m} \times C_P \times \Delta T \tag{5}$$

The efficiency of thruster η_c could be calculated by comparing the average theoretical characteristic velocity c^*_{th} determined by thermo-chemistry code [7] and experimental value c^*_{ex} as in the following equations:

$$c^*_{ex} = \frac{P_c A_{th}}{\dot{m}} \tag{6}$$

$$c^*_{th} = \frac{\sqrt{RT_c}}{\Gamma} \tag{7}$$

$$\eta_c = \frac{c^*_{\exp}}{c^*_{th}} \tag{8}$$

where $\Gamma = \sqrt{\gamma}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}$, γ is the ratio of specific heats of exhaust gases and R is the gas constant. The characteristic velocity is slightly dependent on γ but is quite sensitive to the values of temperature T_c and molecular mass M.

The nozzle throat diameter d_{th} up to 1 mm depending on the amount of mass flow rate, the expansion area ratio of the nozzle ε reaches to 100 in space applications; it is used to determine the exit nozzle diameter d_{ex} as:

$$\varepsilon = \frac{A_{ex}}{A_{th}} = \left(\frac{d_{ex}}{d_{th}}\right)^2 \tag{9}$$

EXPERIMENTAL WORK AND ANALYSIS

The direct goal of the experimental work is to realize a functioning test, evaluate the mathematical model and investigate lifetime of Resisto-jet thruster.

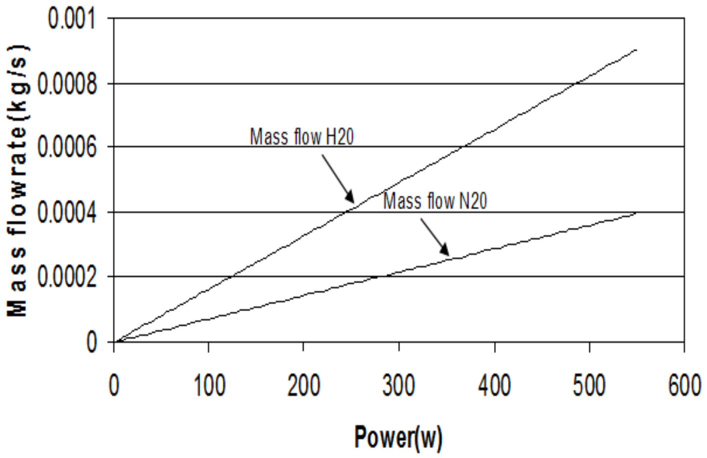


Fig. (3). Input power vs. mass flow rate for a theoretical Resisto-jet operating at 900 K and 10 bars

A simple pressured feeding system was constructed using H_2O as working fluid, Resisto-jet thruster shown in Fig. (4) consists mainly of pure aluminum cylindrical chamber (Ø30 mm,110 mm length), two distributer disc (6x Ø 0.5 mm holes) with stainless screen 40x40 mesh, 1.0 mm throat diameter nozzle (expansion area ratio ≈ 25), 6mm commercial rod cartridge heater (100, 200 and 300 W)as shown in Fig. (5). The chamber is packed with the various heat transfer bed materials (stainless steel, silicon carbide, copper, sand and aluminum). Up to 0.1 g/s H_2O mass flow rate is used to get up to 10 bars inside chamber, where H_2O was stored in a 2 liters aluminum tank. The nozzle is set so close to the thin plate such that one can consider the plate deflection is almost caused by the thrust. In other words, the applied loads are fairly representative of thrust. Figure (6) describes the system items with measuring devices. The system allows to measure feed line, pressurized gas, H_2O working fluid tank and chamber pressures, H_2O flow rates, chamber temperatures and thrust during a test run. The measuring system is supported by novel temperature and thrust evaluation methods. The layout of the temperature measurement is shown in Fig. (7), using a circular laser spot – Raynger-MX up to 1000℃, with or without thermocouple.

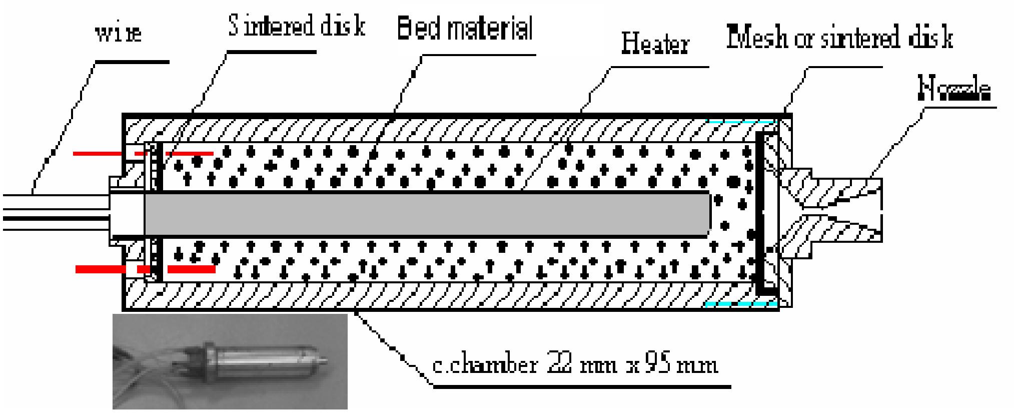


Fig. (4). The Resisto-jet thruster final design.

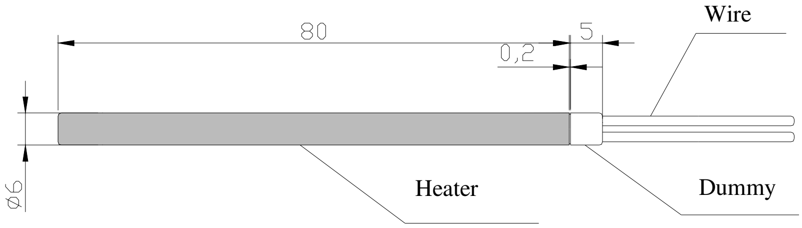
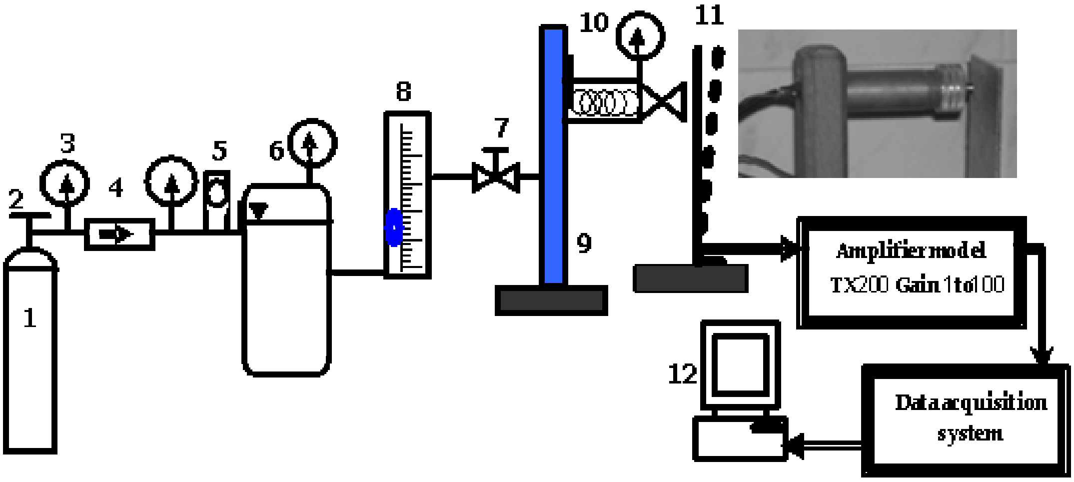


Fig. (5). Cartridge heater.



1-pressurized gas tank; 2- on-off valve; 3- pressure gauge; 4- pressure regulator; 5- safety valve; 6- working fluid tank; 7- solenoid valve (off-on); 8- Rota-meter; 9- test stand; 10- Resisto-jet thruster;11- elastic beam + strain gauge, 12- Computer

Fig. (6). Schematic of feeding system with measuring system.

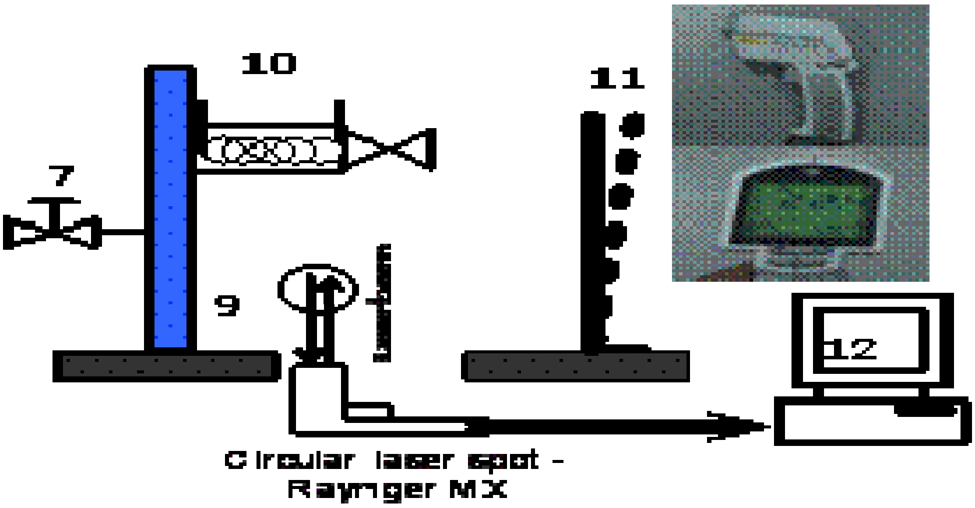


Fig. (7). Measuring temperature for Chamberwall.

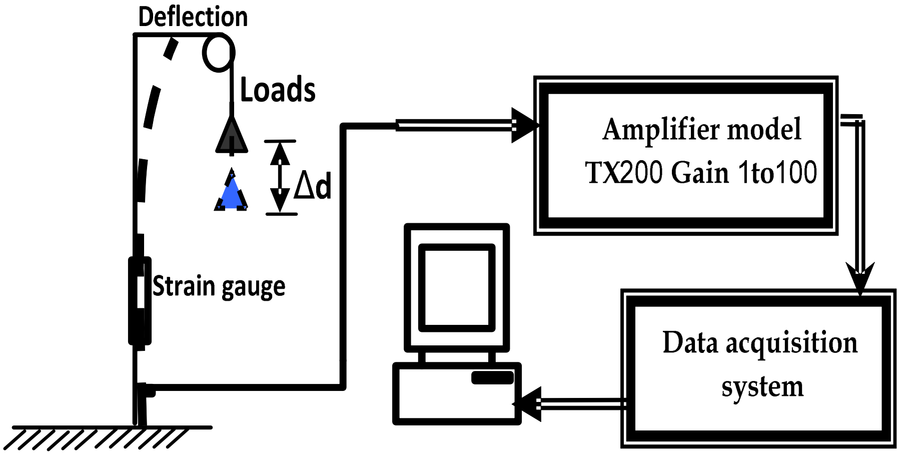


Fig. (8). Calibration of flat plate deflection.

During the development of the testing program, unfortunately, during the 1st test, the plastic tubes melted due to chamber heat transfer. Epoxy and silicon materials are not beneficial.

To solve that problem, Resisto-jet thruster new design was used, 22 mm diameter with 120 mm length copper chamber, cartridge heater (Ø6 mm by length 80 mm) installed in the center.

Measuring low thrust value (less than 1N) is a very challenging; this problem is solved by using indirect technique. Flat plate (elastic beam) with wire strain gauge is used to measure the deflection, due to exhaust gases from thruster. The elastic plate applied loads is calibrated and recorded as shown in Fig. (8).

Bed Materials Investigation

The total cumulative test time exceeds 3 hours while a variety of bed materials, stainless steel, silicon carbide, copper, sand and aluminum are used. The bed materials are chosen to satisfy the following characteristics:

- Good thermal characteristics- combination of material density, thermal conductivity, and heat capacity,
- Low cost,
- Material lifetime, resistant to material degradation,
- Quick availability.

Stainless steel

Stainless steel particles (less than 1mm) are chosen due to its good heat capacity and thermal conductivity. The thermal expansion and density are big problems to handle during experiment. The observations during tests are as follows:

- Long time to reach steady state operation (≈5minutes) to generate an exhaust stream compared with another material that may be due to high density bed material;
- Produced H_2O droplets during operation that may be due to high porosity of bed material;
- Long delay time to stop (after shut down the system), that may be due to high heat capacity of bed material;
- Change of color after 30minutes of operation that may be due to change of thermal and mechanical properties;
- The heater cartridges are crashed easily.

Silicon carbide

Silicon carbide (SiC) is selected due to its good heat transfer characteristics, availability in the local market, low density compared to stainless steel, low cost and material compatibility. Just less than 4 hours of test data are collected on (SiC). The (SiC) reached steady state of operation with no water droplets out from the exit and more quickly than stainless steel by ≈ 3 minutes. Inspecting the Resisto-jet chamber after tests, the bed material is not centered or discolored in any form.

Foundry sand

One test was conducted to evaluate sand packed bed for 30 minutes. The thruster reached steady state of operation with no water droplets after 5 minutes. The sand particles prosperities are changed after test, especially grain size mainly is destroyed in the zone around the heater. Poor packing densities appeared after one test.

Aluminum

One test is conducted to evaluate aluminum particles for 15 minutes. The thruster reached steady state very fast. The Resisto-jet thruster reached failure also very fast. Aluminum bed material showed high material degradation, which makes poor packing densities; it may be from the kind of available aluminum particles that can be used.

Copper

Copper powder is selected for test due to its very high thermal conductivity (2.5 times better than stainless steel). A smaller particle diameter is also selected (less than 1 mm) to test the impact of particle size on performance. This particle size is also chosen due to its availability in the local market. The bed is heated up very rapidly, since high thermal conductivity. The power supply is shut down and also the bed is cooled down quite rapidly. Water instantly started coming out through the nozzle due to poor heat transfer.

During disassembly of the Resisto-jet copper bed, it is noticed that the copper is completely centered around, a fact that occur due to poor packing copper particle densities. Poor packing densities can create movement of the particles in the chamber making small channels through bed materials. Resisto-jet with poor packing densities leads to low performance parameters.

Mixture of copper and sand

The mixture of the foundry sand and copper insert in Resisto-jet thruster chamber. The copper is first inserted around the heater with the sand going from the middle of the bed to the inner chamber wall. This approach tried to increase the heat transfer, having a copper media of high conductivity around the heater to improve thermal heat transfer efficiency.

Different thermal expansions for two types of media are a main problem, creating cavities in the bed that allowed the flow to find a direct path and took longer time to reach steady state.

RESULTS AND DISCUSSIONS

Table (4) shows the summary of the tests observation for the Resisto-jet various bed materials tested using water as the working fluid. The following several observations are noted during experimental work:

1- Resisto-jet heater for space mission needs higher temperature and higher lifetime than commercial one (off-self), the heater failed after about 2 hours, the thruster can operate in space up to 500 °C, redundant heater coils must be considered during design inside the thrust chamber,
2- Steady state operation, the Resisto-jet reached this state after certain time depending on bed material and heater power without the presence of any water droplets from the nozzle part,
3- Silicon carbide showed no material degradation and a good response time to reach steady state,
4- Packed bed density showed a good effect on the Resisto-jet performance.

Figure (9) shows the results of chamber wall temperature behavior, which give an indication to the performance of each bed material.

Water Resisto-Jet Experimental Test

For better understanding of the behavior of H_2O for (Sic) (bed material) Resisto-jet thruster, measuring thrust, H_2O mass flow rate and temperature various operating periods are important to investigate.

Typical axial thrust behavior is shown in Fig. (10). Several phases of operations are shown as, warm-up phase, initial pressure rise (build-up), pseudo equilibrium operation and the final phase is tail-off phase.

The steady state thrust values reach 75 mN at 200 W, the time needed to reach complete thermal equilibrium starting from cold conditions is about 230 s, for Silicon carbide bed material warm-up reaches after 150 s and build-up phase takes about100 s without H_2O injecting.

The effect of changing the thermal sate of (SiC) and pressure in chamber, the H_2O mass flow rates behavior are shown in Fig. (11). The large mass flow rate drop during the initial operation, may be attributed to low chamber pressure up to reach

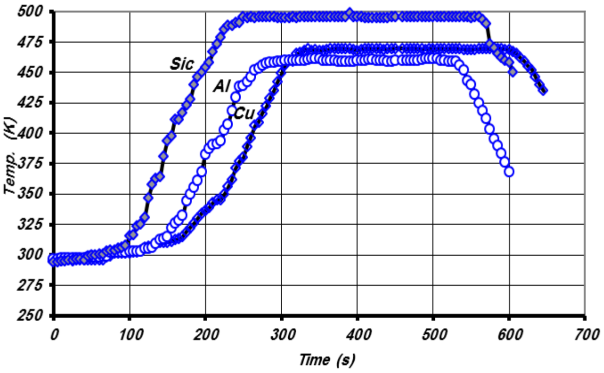


Fig.(9). Comparison of bed materials wall temperatures.

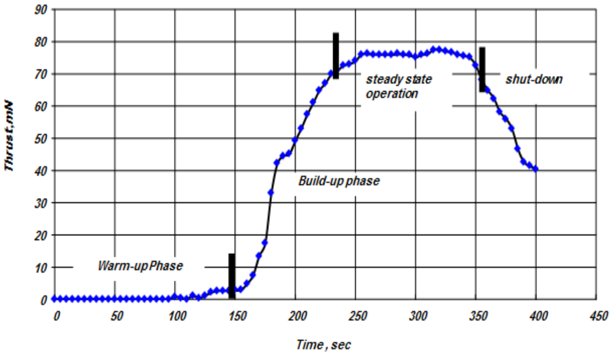


Fig. (10). Thrust to time curve.

Table (4). Summary of the tests observation.

Material	**Advantages**	**Disadvantages**
Aluminum	- High temperature achieved, - Low weight.	▪ Poor packing density after operation, ▪ Change of properties.
Silicon carbide	-Fast start-up, -No material degradation.	▪ Less temperature achieved than another material (stainless steel).
Copper	- Very fast start-up, -Heavy material.	▪ Poor packing density after operation.
Sand	-High heat capacity.	▪ Slow start-up, ▪ Material degradation, ▪ Some sintering to heater, ▪ Poor packing density after operation.
Copper/sand	-None	▪ Slow start-up, ▪ Poor packing density after operation,
Stainless steel	-High temperature achieved, -No material degradation.	▪ Slow start up, ▪ Heavy material, ▪ Change of proprieties after operation, ▪ Slow shut down.

complete thermal equilibrium, no significant variation on H_2O mass flow rate is observed during equilibrium state inside chamber.

To overcome that problem, it is carried out more easily by regulating gas pressure feed system during thruster operation to reach steady feeding of the H_2O inside chamber.

Figures (12-13) illustrate the measured new behavior of thruster (thrust and temperature) for a wide range of operating time.

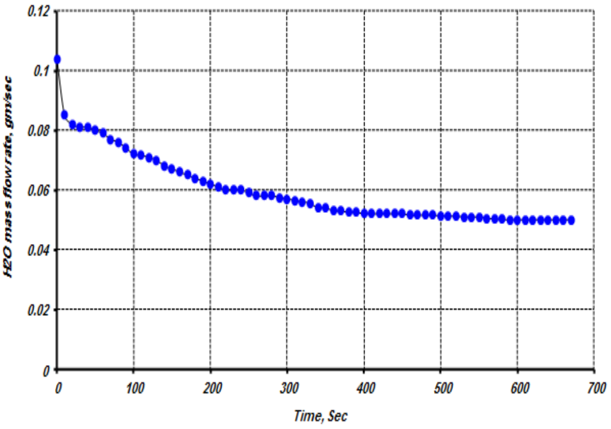


Fig. (11). H_2O mass flow rate with operating time.

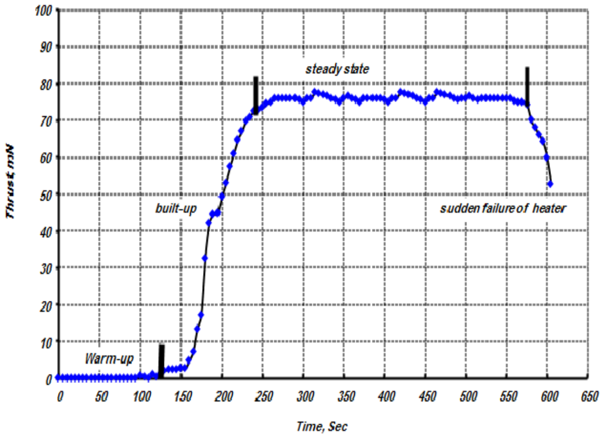


Fig. (12). Thrust to time curve SiC) thruster with H_2O controllable.

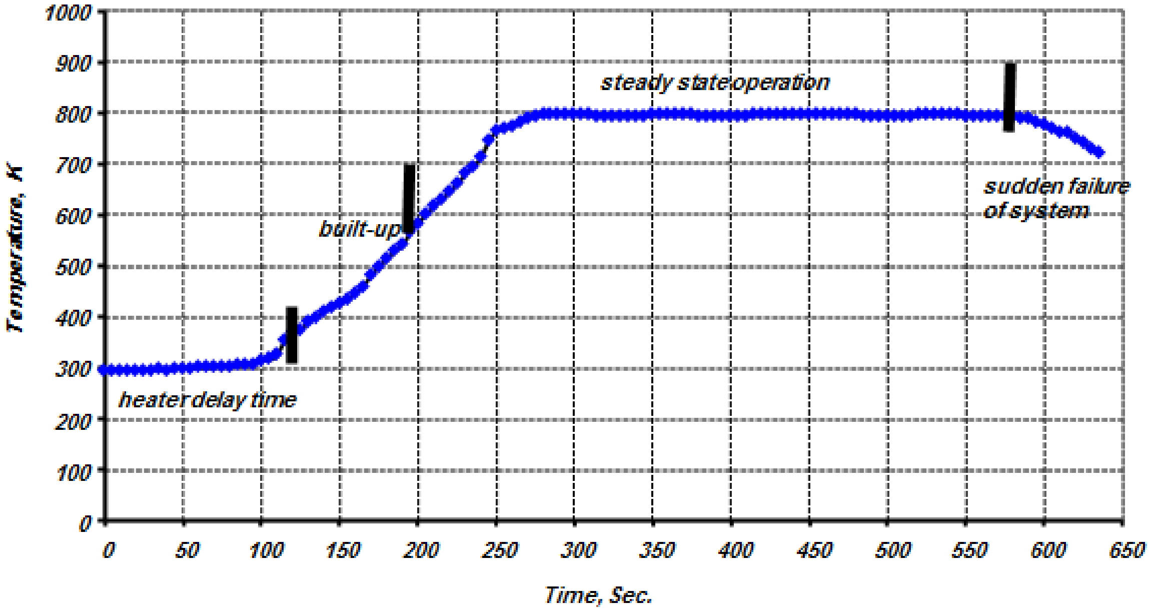


Fig. (13). (SiC) bed material temperatures versus operating time.

The steady state thrust values reach the same thrust at the same power, the time needed to reach complete thermal equilibrium starting from cold conditions is decreased by 15%, Silicon carbide bed material warm-up reaches after 125 s and build-up phase takes less than 100 s. The unexpected decay in thrust at 575 s is attributed to a sudden failure of the heater.

The (SiC) as packed bed material is approved as shown during experimental tests; it is accepted as suitable media inside chamber for Resisto-jet thruster. Conversely, commercial heater has unreliable lifetime (15-30 min); experiment needs a more consistent heater.

CONCLUSIONS

Non-Conventional propulsion offers available alternative to conventional propulsion, which produces high temperature combustion gases being harmful to small satellite subsystems. The selection of non-conventional propulsion type (Resisto-jet thruster) has substantial impact on the small satellite to satisfy launch correction and station keeping missions.

The Resisto-jet thruster is the simplest electro-thermal thruster. Typically, the working fluid (H_2O, N_2O, Air, Argon, H_2, Air.) is heated by satellite electric power and offers great overall benefits as compared to chemical thrusters. Clean exhaust, acceptable performance, low flame temperature, restart capability and acceptable consumed power with low thrust make this type of thrusters a suitable candidate for launch correction and station keeping with small satellites.

A Resisto-jet thruster capable of operation on H_2O propellant is designed and constructed in the form of a laboratory model and tested to investigate its operational characteristics experimentally and theoretically.

The best performance is achieved with the Silicon carbide that is why it can be considered as the best candidate bed material. The heater cartridge must be designed with high reliability (long-life), variable power input and satisfies redundancy option.

The maximum demonstrated thrust reaches $\approx$5 mN at power 200 W using H_2O working fluid with $\approx$0.06 gm/s mass flow rate.

The H_2O as working fluid with (SiC) bed material Resisto-jet thruster model described here has been demonstrated to operable over a range of thruster levels from 50-200 mN and at input electric power levels from 100-300 W to get specific impulse from 150-200 s.

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