Design and development of a low power laboratory resistojet

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Design and Development of a Low Power Laboratory Resistojet

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Keywords: Small satellite, resistojet, space thruster

Abstract

Resistojet thrusters are categorized as one of electro-thermal engines which are capable of operating both at high and low power levels based on their design and the mission imposed requirements. High power resistojets operate at a power level of 0.5 - 1.5 kW and a specific impulse of 300 – 350 s using Hydrazine or Ammonia as propellant. The development of such engines commenced in early 1960's. However, with respect to the growing interest for the smaller satellites, low power systems are currently of more interest as they can operate at a power level of below 100 W producing thrust up to 100 mN with a specific impulse of up to 100 s based on the choice of propellant. The propellant can be almost any compressed- or liquefied-gas as long as it is compatible with the high-temperature operating condition. Resistojets operating at low power and using liquid propellants have become attractive propulsion options for small satellites. Therefore, for the first time in west Asia and Iran, a laboratory model resistojet has been designed and developed to operate at low power levels of 15 – 50 W using a liquefied-gas as propellant.

The paper describes the design and development of a butane resistojet of nominal power level of 15 – 50 W, producing near 50 mN of thrust at a specific impulse slightly below 70 seconds. The butane is stored in liquid form in the tank and converts to gas as it emerges. Then, it is heated to a maximum temperature of 350°C while flowing through heaters inside the thruster. It is finally accelerated inside a micro-machined steel convergent-divergent nozzle with a 0.4 mm throat and approximately 250:1 area ratio. The thrust measurement tests were carried out on a cantilever beam test stand measuring the thrust using a high-precision load-cell inside a 1 × 2.5 m vacuum chamber at a pressure of near 3 Pascal.

Introduction

Resistojets are one of electrothermal thrusters which operate by passing the propellant in gaseous state around an electrical heater and increasing the temperature of propellant, then using a conventional convergent-divergent nozzle to accelerate the propellant to supersonic speed and produce thrust.\(^1\) The heating process can be made possible using direct contact between the heating element and the propellant or indirectly, when thruster case is heated by the surrounding elements (the case could be heated radiatively from the outside). The heating of propellant reduces the gas flow rate at a given upstream pressure and a given nozzle area, thus leading to the familiar increase in specific impulse in relation with \(\sqrt{T}\).\(^1\)

This is the main idea behind a resistojet which gives it advantage over a cold gas thruster as it can yield to a higher specific impulse compared to a cold gas thruster using the same propellant and on the same upstream condition through the same nozzle. Equation 1 and 2 show the relationship between specific impulse and temperature. However, as inferred from Equation 1, thrust is independent of temperature at given upstream pressure and constant nozzle geometry.

\[
F = \dot{m}v, \quad v \propto \sqrt{T}, \quad \dot{m} \propto \frac{1}{\sqrt{T}}
\]

\[
I_{sp} = \frac{F}{mg} = \propto \sqrt{T}
\]

When it comes to choice of propellant for a resistojet, nearly any gas could be used, although it needs to be compatible with the high-temperature condition of the thruster. Mostly compressed gases are used in resistojets as propellant although recently liquified-gases are also introduced as propellant of choice in low power resistojet systems. Utilization of liquified-gas propellants instead of compressed-gases can significantly diminish propulsion system total mass as they can be stored in low pressure and in liquid form. It also lessens the leakage probability compared to high-pressure gasses in typical resistojet systems. Basically, resistojets can operate in a wide range of input power from less than 50 W up to more than 1.5 kW and they can be classified with respect to their power into high-power resistojets with power levels
of 0.5 – 1.5 kW of power and low-power resistojets with a power of less than 100 W. The most successful application of high-power resistojets has been based on the superheating of catalytically decomposed hydrazine, which has the advantage of commonality with familiar fuel systems used in hydrazine monopropellant applications. The heaters can operate over the wide pressure range encountered with blow-down systems, and their input voltage is low enough to require no special power conditioning, except for current surge protection. Operation can continue in a non-superheated mode in case of heater failure. The plume is not ionized and poses no unusual spacecraft interaction problems. On the other hand, low-power resistojets have recently become of more importance as yearning for low-cost small satellites has rapidly grown. These thrusters are intended to have the simplicity of cold gas propulsion systems while enhancing the poor performance of it. They are capable of performing orbit correction and stationkeeping maneuvers for small satellites as well as attitude control missions. The most outstanding applications of low-power resistojets come back to systems developed by Surrey Satellite Technology LTD (SSTL). SSTL is a leading manufacturer of small satellites and sub-systems in UK. It has built and launched 30 satellites from UoSAT-1 to PICOSAT in 2001. The SSTL low power resistojet has been mounted on several satellites as below:  
- Alsat-1 (2002), UK-DMC, Nigeriasat-1, Bilsat-1 (2003), and Glove-A (2005); all using Butane as propellant.  
SSTL has mentioned that the achieved thruster specific impulse will vary according to propellant, power input, firing duration and thrust levels and the values achieved during their test have included 55s with xenon, 99s with nitrogen and up to 100s with Butane while the thruster can be operated at up to 500°C. Based on the aforementioned discussions and with the intention of prospective application in a small-satellite, a laboratory-model low power resistojet has been designed and developed for the first time in west Asia (Iran) and successfully tested in vacuum condition. The thruster utilizes Butane as propellant which is a liquefied gas stored in liquid form in the tank. The thruster is designed to produce near 50mN of thrust at a power range of 15 – 50W and a specific impulse of less than 80s. The design and development of the thruster is described in the present paper.

**Resistojet System Background**

Table 1 indicates a list of some of the most important resistojets ever flown including the most recent low power resistojet systems as well as their launch year, performance parameters and the satellite they were used on.

<table>
<thead>
<tr>
<th>Year</th>
<th>Satellite</th>
<th>Propellant</th>
<th>Watt</th>
<th>mN</th>
<th>Isp (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1965</td>
<td>Vela</td>
<td>Nitrogen</td>
<td>-</td>
<td>92</td>
<td>187</td>
</tr>
<tr>
<td>1965</td>
<td>US Navy Sat</td>
<td>Ammonia</td>
<td>30</td>
<td>89</td>
<td>-</td>
</tr>
<tr>
<td>1967</td>
<td>Adv. Vela</td>
<td>Nitrogen</td>
<td>30</td>
<td>89</td>
<td>132</td>
</tr>
<tr>
<td>1971</td>
<td>US Navy Sat</td>
<td>Ammonia</td>
<td>3</td>
<td>44</td>
<td>356</td>
</tr>
<tr>
<td>1981</td>
<td>Meteor 3-1</td>
<td>Ammonia</td>
<td>450</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1988</td>
<td>Gstar-3</td>
<td>Hydrazine</td>
<td>600</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1997</td>
<td>Iridium</td>
<td>Hydrazine</td>
<td>500</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>Satellite</th>
<th>Propellant</th>
<th>Watt</th>
<th>mN</th>
<th>Isp (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>UoSAT-12</td>
<td>Nitrous oxide</td>
<td>100</td>
<td>125</td>
<td>127</td>
</tr>
<tr>
<td>2002</td>
<td>Alsat-1</td>
<td>Butane</td>
<td>2×15</td>
<td>50</td>
<td>80</td>
</tr>
<tr>
<td>2003</td>
<td>UK-DMC</td>
<td>Butane</td>
<td>2×15</td>
<td>50</td>
<td>80</td>
</tr>
<tr>
<td>2003</td>
<td>UK-DMC</td>
<td>Water</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2003</td>
<td>NigeriaSat-1</td>
<td>Butane</td>
<td>2×15</td>
<td>50</td>
<td>80</td>
</tr>
<tr>
<td>2003</td>
<td>BilSat-1</td>
<td>Butane</td>
<td>2×15</td>
<td>50</td>
<td>80</td>
</tr>
<tr>
<td>2005</td>
<td>DMC+4</td>
<td>Xenon</td>
<td>2×30</td>
<td>18</td>
<td>48</td>
</tr>
<tr>
<td>2005</td>
<td>GSTB-v2</td>
<td>Butane</td>
<td>2×15</td>
<td>50</td>
<td>80</td>
</tr>
<tr>
<td>2008</td>
<td>Rapideye</td>
<td>Xenon</td>
<td>2×30</td>
<td>18</td>
<td>48</td>
</tr>
<tr>
<td>2009</td>
<td>N2</td>
<td>Xenon</td>
<td>2×30</td>
<td>18</td>
<td>48</td>
</tr>
<tr>
<td>2009</td>
<td>Proba-2</td>
<td>Xenon</td>
<td>2×30</td>
<td>18</td>
<td>48</td>
</tr>
</tbody>
</table>

**The most recent low power resistojets**

Basically, resistojets are among simple propulsion systems and they mainly consist of resistojet thruster and propellant tank. Figure 1 shows a simple schematic of a resistojet. If the propellant is stored at a high pressure, then a propellant feeding system is needed to reduce its pressure to the desired pressure to enter the thruster nozzle. However, to elaborate a resistojet system several different elements can be mentioned:

- Propellant tank
- Propellant tank heater
- Fill and drain valve
- Filter
- Temperature transducer

![Fig. 1 Simple schematic of a resistojet system.](image-url)
• Solenoid valve
• Pressure regulator (if applicable)
• Resistojet
  o Heater
  o Filter
  o Nozzle

Other measurement sensors like flow-meters and pressure transducer may also be used in experiments to observe akin parameters.

Considering the choice of propellant for a low power resistojet, several parameters like specific impulse, storage pressure, state, and specific heat are of paramount importance. Table 2 summarizes the most essential factors of these propellants which need to be considered in each design alongside with other parameters like contamination, toxicity, etc.

Table 2 Low power resistojet propellant characteristics. (5-7)

<table>
<thead>
<tr>
<th>Propellant</th>
<th>P</th>
<th>ρ</th>
<th>Isp^*</th>
<th>Isp^+</th>
<th>Cp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressed gases</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrogen</td>
<td>200</td>
<td>218</td>
<td>76</td>
<td>129</td>
<td>1.0</td>
</tr>
<tr>
<td>Xenon (needs thermal control)</td>
<td>69</td>
<td>1570</td>
<td>31</td>
<td>52</td>
<td>0.16</td>
</tr>
<tr>
<td>Butane (C_{4}H_{10})</td>
<td>2.1</td>
<td>530</td>
<td>70</td>
<td>103</td>
<td>2.0</td>
</tr>
<tr>
<td>Propane (C_{3}H_{8})</td>
<td>8.4</td>
<td>430</td>
<td>76</td>
<td>166</td>
<td>2.0</td>
</tr>
<tr>
<td>Nitrous Oxide (N_{2}O)</td>
<td>51</td>
<td>740</td>
<td>66</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ammonia (NH_{3})</td>
<td>8.6</td>
<td>610</td>
<td>105</td>
<td>187</td>
<td>2.2</td>
</tr>
<tr>
<td>Carbon dioxide (CO_{2})</td>
<td>57.3</td>
<td>760</td>
<td>65</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Liquified gases</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes
1) Isp^* denotes theoretical I_{sp} (s) at 20°C for Polyflex thruster used on SNAP-1 with throat 0.42mm and expansion ratio 208:1.
2) Isp^+ denotes theoretical I_{sp} (s) at 500°C for infinite nozzle expansion.
3) P denotes storage pressure in bar and ρ denotes storage density in kg.m^{-3}, both at 20°C.
4) C_p denotes specific heat at 100°C and 1 bar.
5) ρ denoted storage density.

**Propulsion System Design**

The designed and developed resistojet thruster consists of various elements which are elaborated individually. Figure 2 depicts a schematic of the low power laboratory resistojet system designed and developed. However, at this stage of research, the focus has been placed on design and development of resistojet thruster rather than relevant elements of a resistojet propulsion system. Thus, most of the elements including tank and valves have been selected from the very available parts around.

![Resistojet system plan designed for experimental tests.](image)

Based on the aforementioned data presented in Table 2 and in the light of the many benefits of liquified gases compared to compressed gasses like ease of storage at low pressure and lower system mass; a liquified gas was selected as propellant of choice. Among available liquified gases, butane was chosen to be utilized in the resistojet with respect to ease of access, ease of storage, flight heritage, low storage pressure and no need for a pressure regulator, and non-toxicity. Figure 3 shows butane vapor pressure behavior versus temperature. Based on the curve, butane vapor pressure at 21°C is 2.5 bar and its pressure increases as temperature rises. Therefore, 2.5 bar has been chosen as the system operating pressure for butane at 21±10 °C. Subsequently, the propellant which is stored at 2.5 bar in the tank can be directly fed into the thruster without any special pressure considerations.

The critical temperature of butane where it cannot be in liquid gas any more is near 156°C which is adequately high and no serious concern exists related to the operating temperature of the system mounted in a satellite in space environment. Another temperature constraint concerning butane is the cocking temperature where it decomposes and carbon which is a product of this decomposition can block the throat. It has been reported that butane can successfully operate at temperatures up to 500°C without cocking. (8-10)
An off-the-shelf butane tank, which has been designed for commercial use, was initially used for the resistojet system with a volume of 1 liter. However, an engineering model stainless-steel tank with a volume of 2.5 liter has been designed and developed in the next step. Figure 4 shows a 3D-model of the tank.

**Fill and drain valve**
A manual valve has been utilized to fill and drain the propellant tank.

**Filter**
Three filters have been employed in the system. First one is a coarse filter before tank to prevent entrance of particles when filling the tank. Second one is a 20 µm filter to stop the propellant to emerge in liquid form from the tank, in any probable condition. And last is a 10 µm brass filter used inside the resistojet and exactly before the nozzle to protect the throat from getting blocked by any particle.

**Heater**
Except from the heating elements inside the resistojet which are an inseparable part of a resistojet, heaters are necessary to be mounted on the tank to control the propellant temperature which tends to decrease rapidly while the thruster is working. Heating elements are nichrome electrical resistance heaters which have been used in resistojets for many years including resistojets developed by SSTL. They are designed to both vaporize the liquid butane and heat gaseous butane and they can raise the temperature up to 600ºC.  \(^1\)

**Solenoid valve**
A dual solenoid valve has been used in the system to open and close the propellant flow to the thruster. Figure 5 shows a picture of the solenoid valve.

**Resistojet thruster**
Resistojet thruster body consists of 4 separate parts all made of stainless steel ST-316, which are nozzle, heat exchanging interior and exterior walls, and cap. Figure 6 show a picture of all the parts together but not assembled.
Two sets of nichrome electrical resistance heaters enter the heat exchanging zone through the holes made in the cap and the holes are closely filled and sealed with borosilicate, shown in Fig. 7. Propellant also enters the resistojet through the center hole in the cap.

The heating elements, covered with a layer of fiberglass for electrical isolation, are then tightly wound around the interior wall of heat exchanging zone in a way that 50 cm of each heater is wound around a length of 33 mm. Figure 8 indicates a designed model of the heaters wound together with the practical model developed.

Two sets of heaters are designed with two intentions. One can be the primary winding while the other is the back-up. On the other hand, they both can be used simultaneously in an operating mode when more power is desired.

In next stage, different parts of the thruster have been assembled together and the 10µm filter has been placed right before the nozzle entrance. The remaining unsealed areas between the different parts have been fully sealed using silicon-based high-temperature RTV gasket-maker while assembling. The sealant can resist up to 500ºC which is quite less than the maximum temperature that the resistojet is going to operate at. Moreover, the sealant has been successfully tested for outgassing in vacuum condition. Figure 9 shows different stages of assembling the thruster in the order of operation.
Thruster nozzle is a conical convergent-divergent nozzle with 0.42±0.2 mm throat diameter, 6.2±0.2 mm output diameter, and an area ratio of near 250:1. The angle of divergence in the nozzle is 26º. The thruster is designed to operate at power levels of 15 – 50 W, producing near 50 mN of thrust at a specific impulse of slightly less than 70 s.

Experimental Facility

Before presenting the test results of the resistojet, it is necessary to mention the utilized experimental facilities. The thruster functional tests have been performed in a vacuum chamber using several sensors and a Loadcell which briefly explained below.

Vacuum chamber

Resistojet tests have been performed inside a big-size cylindrical 1 × 2.5 m vacuum chamber at a pressure of near 3 Pa. Vacuum pressure increased to 100 Pa during the thruster operation and remained constant. The chamber uses a rotary pump together with a diffusion pump to maintain this pressure and has several feedthroughs for electrical connections. Figure 10 and 11 show vacuum chamber and feedthrough.

Flow meter

A flow meter was supposed to be utilized to observe the gas flow. However, it could not be available for the tests and it will be used to test the engineering model in near future. The flow meter is a micro-bridge mass flow sensor that operates on the theory that gas flow across the surface of a sensing element causes heat transfer. Then, output voltage varies in proportion to the mass of the gas flowing through a given sensor's inlet and outlet ports. It can measure mass flow from 0 to 5 SLPM. Figure 12 shows a picture of this flow meter.

Fig. 12 Photograph of the flow meter.

Thermocouple

A k-type thermocouple capable of measuring temperature from -20 to +1000°C with 0.3 s response time was chosen to monitor the temperature of propellant tank, thruster case, and exhaust flow to assist in extracting their behavior. An indicator is also used in conjunction with the thermocouples to show the values. Figure 13 shows a picture of the thermocouple and indicator.

Fig. 13 Photograph of the thermocouple and indicator.
**Pressure transducer**
A pressure transducer with a range of 0 – 25 bar with a resolution of ±0.5% has been used to measure the pressure of the propellant tank. Figure 14 depicts a picture of it.

Fig. 14 Photograph of the pressure transducer.

**Loadcell and data acquisition system**
A high-precision sensor with high signal-to-noise ratio, capable of measurement of force and torque in 6-axis has been utilized to record the resistojet thrust during operational tests in vacuum chamber. Table 3 indicates sensing ranges and relevant resolutions for the sensor. In addition, relevant data acquisition devices have been used to analyze and record the sensor data. Figure 15 shows a picture of the sensor and its data acquisition system.

Table 3 Sensing range and resolution of the 6-axis force and torque sensor.

<table>
<thead>
<tr>
<th>Axes</th>
<th>Sensing ranges</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_x$, $F_y$ ($\pm$N)</td>
<td>0.5 - 36</td>
<td>1/128</td>
</tr>
<tr>
<td>$F_z$ ($\pm$N)</td>
<td>0.5 - 36</td>
<td>1/128</td>
</tr>
<tr>
<td>$T_x$, $T_y$ ($\pm$Nmm)</td>
<td>0.5 - 500</td>
<td>1/10</td>
</tr>
<tr>
<td>$T_z$ ($\pm$Nmm)</td>
<td>0.5 - 500</td>
<td>1/10</td>
</tr>
</tbody>
</table>

Fig. 15 Photograph of the 6-axis force and torque sensor.

**Microbalance**
A RADWAG microbalance with weight measurement range between maximum 310 g and minimum 10 mg and an accuracy of 0.1 mg has been employed to measure the difference in the weight of tank before and after a certain number of pulses. It can be used to calculate the thruster mass flow rate. Figure 16 shows a picture of the microbalance.

Fig. 16 Photograph of the microbalance weighing a butane tank.

**Oscilloscope, power supply, and multi-meter**
A 100 W GW-Instek power supply, a two-channel digital Agilent oscilloscope, and a FLUKE multi-meter were used wherever needed.

**Thrust Measurement Mechanism**
Resistojet thrust has been measured inside the vacuum chamber using a direct measurement method. That is, the resistojet exhaust flow exerts force and torque to a 50 cm cantilever beam placed several millimeters away from the nozzle outlet and this force and torque can be measured using the 6-axis sensor positioned at the beam root. Finally employing the data acquisition system, output is transmitted to a PC to be monitored, recorded, and interpreted by LabVIEW.

The details of thrust measurement mechanism are elaborated in Ref. 12. Another measurement mechanism similarly can be used to measure thrust using the strain caused by the thruster exhaust plume on the cantilever beam.13

The 6-axis sensor employed is capable of measuring both force and torque caused by the resistojet exhaust plume on the cantilever beam. The expected thrust (near 50 mN or 0.05 N) is quite near the resolution of sensor for force measurement (7.8 mN) which is not appropriate. However, the expected torque using a 50-cm beam is 0.025 Nm which adequately far from the resolution of the sensor for torque measurement (0.0001 Nm) and can be absolutely justifying to choose to utilize the 6-axis sensor measuring the torque caused by the thruster rather than the force.
Before testing the thruster, it has been initially numerically simulated using CFD method. Simulation of the flow inside the thruster has been accomplished utilizing the commercial software FLUENT 6.3 and an axisymmetric grid generated by the commercial software GAMBIT. In this simulation, Butane was selected as the propellant and also to approach the real environment condition, length of computational space was considered 50 times of nozzle characteristic length. The grid has been optimized and refined during the run wherever needed so that the results are independent of grid. As a result of the compressibility effects, an implicit, density-based method has been chosen which discretized the flow equations using Roe-FDS flux type and turbulence terms were solved using K-Є standard method with standard wall functions. Simulation has been done for different heat flows from the walls of heat exchanging zone to model various input power of 0 – 60 W. The results of the simulation which are elaborated in Ref. 12 show that the thruster produces approximately 48 mN of thrust independent of input power while its specific impulse increases from 66 to 99 s when power rises from 0 to 60 W and mass flow decreases from 0.074 to 0.048 g/s respectively.2) The results of the simulations are in good agreement with the experimental results of the SSTL low power resistojet.11,14) Benefiting from the experience of previous vacuum functional testing of electric thrusters in Iran15,16) (PPT), the laboratory model resistojet thruster has been successfully tested in vacuum to prove its performance. During the operational tests, tank temperature, thruster case temperature (as an indicator of flow before nozzle), and exhaust flow temperature has been monitored and recorded to study the behavior of the resistojet. Additionally, torque produced by the thruster on the cantilever beam has been recorded to extract the thrust. Moreover, tank weight, before and after the tests, has been measured to calculate the thruster mass flow and specific impulse. Figure 17 shows a picture of the resistojet thruster mounted on the test stand inside the vacuum chamber.

Prior to each test, resistojet heaters have been on for a duration of 8.5 min, then solenoid valve has opened the propellant line and thruster has been operating for 5 min (300 s).

After error analysis and filtering the noise caused by the vacuum chamber operation, one of torque curves extracted from the thruster test at 30 W is shown in Fig. 18. Using a 50 cm beam, the thrust is 2 times of the torque. The average thrust of the resistojet in 300 s of operation is 44.5 mN which shows acceptable compliance with both the results of the numerical simulation2) and the experimental results of SSTL resistojet11). The temperature behaviors captured by thermocouples are discussed in Ref. 12.

We were unable to calculate the exact mass flow rate and specific impulse because we were facing minor leakage in some connections that could not be eliminated in preliminary tests.
Future Works

The development of an engineering model of this resistojet thruster is in final steps. During the development of the engineering model, there have been serious efforts to eliminate all the problems and obstacles faced with the laboratory model including leakage which prevented us from exact measurement of specific impulse.

Conclusion

A laboratory low power resistojet has been designed and developed for the first time in west Asia and Iran. The resistojet thruster utilizes a liquified gas (butane) as propellant because it is a non-toxic propellant that can be stored in liquid form and at low pressure in the tank, thus needs no pressure regulator compared to other compressed gases and liquified gases. The thruster nozzle has 0.42 mm throat diameter with an area ratio of near 250:1. The thruster has been successfully tested in a big-size cylindrical 1 × 2.5 m vacuum chamber at 100 Pa, producing near 50 mN of thrust at 15 – 50 W. The results are in good agreement with the earlier models developed by SSTL. Thrust measurement mechanism consists of a cantilever beam facing the thruster exhaust plume, which transmits the thrust to a high-precision 6-axis torque sensor. A microbalance was utilized to measure the change in tank weight before and after a certain time of operational test to calculate the mass flow rate and specific impulse. Following the successful tests of the laboratory model, development of an engineering model resistojet initiated and is in final stages.

References