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VAPORIZING LIQUID MICROTHRUSTER TESTING UNDER PULSED MODE OPERATION

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ABSTRACT

Microthrusters are special category of propulsion device used to propel micro sized satellites. It is designed as per the mission requirements. There are various kinds of propulsion requirements such as continuous mode operation for orbit transfer (from one planet to another), orbit shift or adjustment for asteroid mining, pulsed mode operation for attitude control of satellites, and gravitation or solar drag compensation in orbit. Continuous mode operation is a high propellant consuming operation and designed cautiously to reach the destination with onboard available propellant. While pulsed mode operation is widely used for LEO (Low earth orbit) applications, where gravitation drag, atmospheric drag and solar drags are dominating. This paper focuses on the pulsed mode operation of vaporization liquid microthruster in vacuum operating condition. The pulsed mode operation involves timely thrust generation for the fine tuning of the positioning of the microsatellites. The operational timing in this mode of operation ranges from milliseconds to a few seconds at maximum. The operating time is decided based on the adjustment requirement for the positioning of the microsatellites. Vaporizing liquid microthrusters use green propellant to produce thrust. Tests are conducted under vacuum condition to simulate the actual space conditions and corresponding results are plotted. Results has shown a maximum thrust value of 290 µN at 1 sec of valve operating time, 335 µN at 2 seconds, 413 µN at 3 seconds, 524 µN at 4 seconds and 590 µN at 5 seconds of valve operating time for 200°C of a constant VLM temperature respectively. The effect of the dibble volume has also been discussed for the vaporization liquid microthruster using di-ionized water as liquid propellant.

Keywords: Vaporizing Liquid Microthruster (VLM), Green propellant, Vacuum testing, Pulsed-mode operation, 3D printed microthruster.

NONMENCLATURE

Abbreviations	
VLM	Vaporization Liquid Microthruster
LEO	Low Earth Orbit
CAD	Computer aided Design
PHT	Pre Heated Temperature
SLM	Selective Laser Melting
Symbols	
µN	Micro Newton
°C	Celsius
Kg	Kilogram
W	Watts
mNs	Milli Newton Seconds
µN	Micro Newton Seconds
ml	Milli liter
µl/s	Micro liter per second

1.1 Introduction

Satellites, space probes and other space shuttles are used to collect information from beyond our planet and to provide telecommunications beacons and relay stations to satisfy a myriad of scientific, security and commercial functions. Figure 1 shows the increasing trend of launches in microsatellite category worldwide.

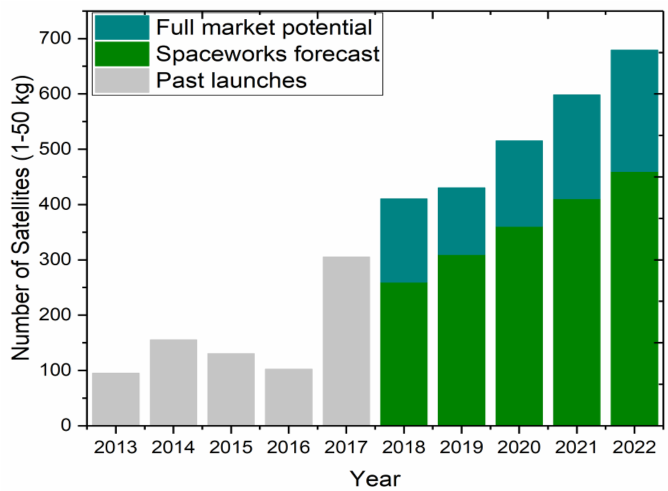

Fig 1 Microsatellite launches history and forecast survey (1-50kg) [3]

All these satellites and space probes require space shuttles to launch them into space. This process is expensive and therefore there is a preference to launch small satellites often in batches to satisfy the specific mission requirements. National agencies such as defence organisations and weather bureaus are also keen to send probes and small satellites into space. The focus of these missions is on Pico, Nano, and Micro sized satellites which usually range from 1 kg to 100 kg [1, 2].

The development of micro electro mechanical systems (MEMS) has opened a new window to miniaturize satellites, reduce launch cost and complexity and achieve higher flexibility of operation [6]. Furthermore, it also satisfies the requirement of lightweight material selection and high degree of integration between various components so as to achieve variable thrust options. For this range of microsatellites, new propulsion systems are required and categorised as micro-propulsion systems, which are able to deliver precise thrust, impulse, thrusting time and velocity increment (ΔV) while meeting stringent mass, power and size limitations. The thrust requirement of this category of micro satellites ranges from micro-newton to few milli-newtons for precise attitude control and other operations. The details about the thrust requirement of attitude control is mentioned in Table 1.

Table 1 Representative Thrust Requirement of Attitude Control [4,5]

Dead band angle (deg)	0.1	0.1	180	180
Time interval (s)	20	100	60	300
Microspacecraft				

Mass (Kg)	Cubical dimension (m)	Lower impulse (μNs)		Higher impulse (mNs)	
1	0.10	2.9	0.58	1.8	0.35
10	0.22	64	13	38	7.7
50	0.37	540	110	320	65

Vaporization liquid microthruster is one of the most recent advancement in microthruster family which uses green propellant such as water to produce thrust. It has various merits over other micro propulsion system such as design simplicity, low leakage concerns, can be operated in continuous or pulsed mode, and can be on and off as per mission requirement without failure. There has been a limited work reported on VLM tested under vacuum operating condition and the details presented here is tested under vacuum operating condition. It will be helpful to the research community working in the field of clean technology development for space application.

1.2 Design, material selection and fabrication of microthrusters using additive manufacturing

3D printing is selected as the preferred fabrication method due to its advantage over conventional manufacturing process such as less expensive, quick production, material variety option and single step manufacturing.

The Renishaw printer has been selected to 3D print the microthruster and it uses the Selective Laser Melting (SLM) 3D printing technology. The SLM technology melts and fuses metallic powders with a powerful laser beam. Once a layer of solid metal is created, the tray holding the 3D print is lowered and powder is layered on top. The sintering with the laser resumes for a new layer. Layer after layer the object is 3D printed, until completion. Many sets of 3D parts were printed but could not successfully obtain desired dimensional accuracy.

The Renishaw AM 400 industrial 3D printer has various option to change its parameters like laser power, support structure and angle of orientation. After multiple trial and error, a proper combination of these parameters was found to achieve high dimensional accuracy of the small feature of the 3D printed parts. The combination found has been reported as 200W of laser power, fine support structure and 45 deg up in Y- axis and again 45 deg roll in Z- axis orientation. In this setting, only one point is sintering at a time as one layer and it has shown the key role to achieve high dimensional accuracy of the printed parts. An optical microscope is used to measure the dimension of the fabricated part. Figure 2 shows the details of 3D printed parts measurement. It has been found that with the decrease in the feature dimensions, the deviation in the obtained geometry to the CAD geometry has increased and vice versa as shown in Table 2.

Table 2 Fabricated Microthruster Dimensions vs CAD Design

Dimension	Measured average (µm)	CAD design (µm)	Deviation (%)
Chamber width	6005.83	6000	0.097
Chamber length	12741.98	12740.59	0.011
Half divergence angle	28.24º	28º	0.857

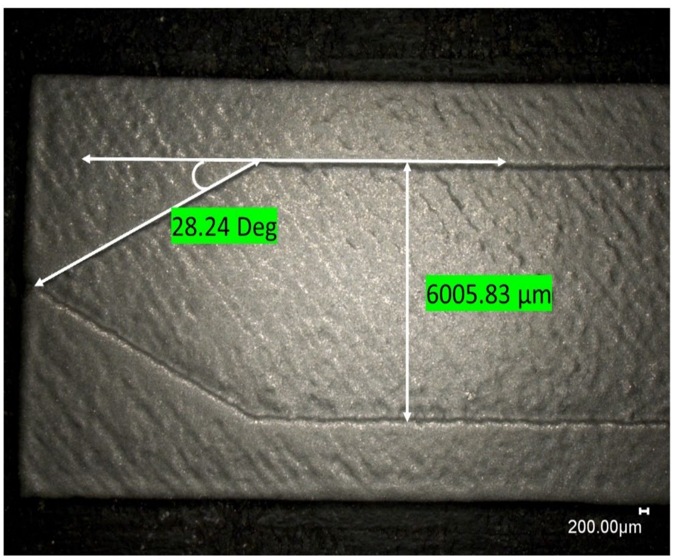

Fig 2 Measured dimensions of the Microthruster

1.3 Experimental setup

To simulate an actual space environment, a vacuum chamber is fabricated using stainless steel (body) and acrylic (top cover). The volume of chamber is selected based on the range of the flow rate to be tested in the vacuum chamber.

All the electrical feed-throughs and connectors for communication between the ambient and vacuum chamber are selected based on the vacuum standards to provide a leak proof environment inside the vacuum chamber. The Syringe pump is placed inside the vacuum chamber to mimic the actual space operating condition.

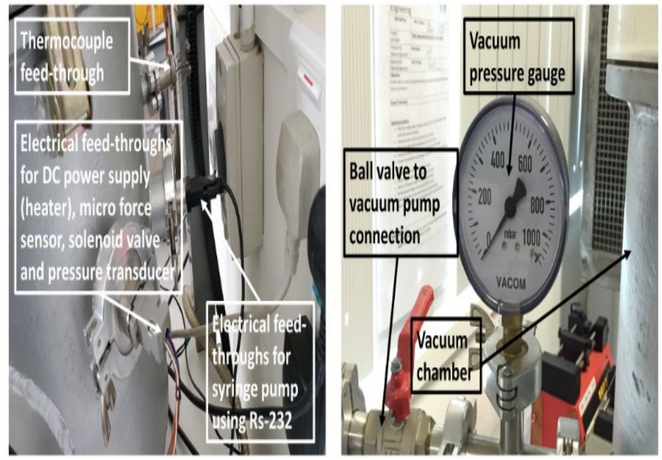

Fig 3 Vacuum gauge, electrical and thermocouple feed-throughs

A detailed actual experimental setup is shown in Figures 3, 4 and 5. This is a vacuum test setup, so each component must be leak proof. For this vacuum testing, whole micro propulsion system is placed inside the vacuum chamber. The micro propulsion system consists of a syringe pump, a glass syringe of 10 ml capacity, Teflon tubing, a pressure transducer to measure inline pressure, a T-joint, a lee micro solenoid control valve with submicron filter and the microthruster. A lab view code has been developed to operate and record the data such as pressure, temperature, thrust, valve status.

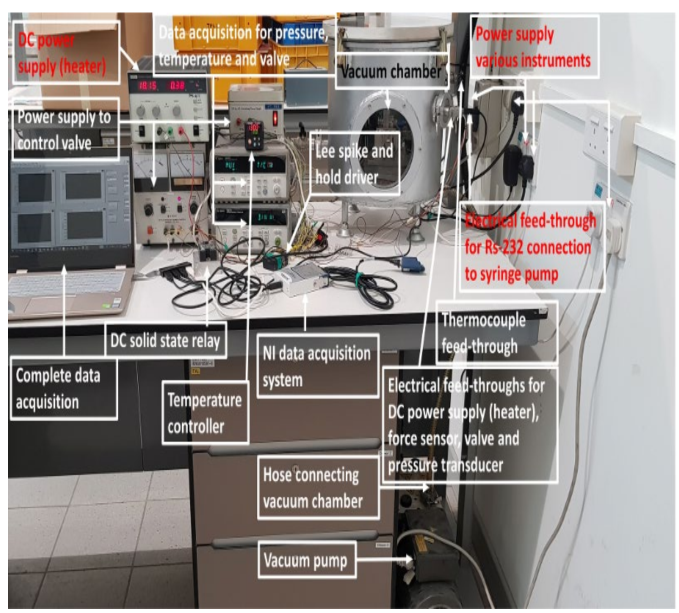

Fig 4 Actual vacuum test setup

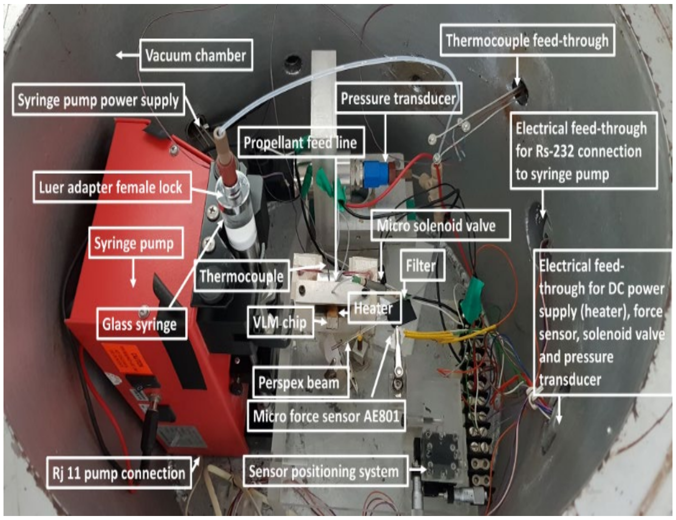

Fig 5 Inside view of vacuum chamber setup

For this microthruster, experimental tests are performed under vacuum conditions for the temperature range of 160 °C to 200 °C with an incremental interval of 10 °C of the VLM temperature and at a propellant flow rate of 1.5 µl/s. Data are recorded for a period of 1 to 5 seconds of valve operation. It is observed that the time taken to reach zero thrust, is in the range of 20-25 seconds after closing the valve. The length of the propellant tubing is reduced for this experiment to reduce the time to reach zero thrust. It also helped to reduce the dribble volume and saved the propellant for useful thrust operation.

1.4 Results and discussion

Real time graphs for thrust, inlet pressure, VLM temperature, valve status, average thrust and total impulse are plotted. Figure 6 shows the real time thrust measurement graph for the fabricated VLM at a PHT temperature of 160 °C at a flow rate of 1.5 µl/s.

Tests are conducted, and real time graphs are plotted for a valve opening time of 1 s, 2 s, 3 s, 4 s and 5 s respectively. The thrust reported at milliseconds of valve operating time are in the range of 100 µN at vacuum operating condition. The reason behind this delay is the time taken to completely vaporize the propellant in the microthruster. The actual thrust is achieved after the valve is closed, therefore only a higher pulsed mode operation time is reported in this experiment at the propellant flow rate of 1.5 µl/s. Results are shown in Figure 7 for 1 second of valve opening time, Figure 8 for 2 seconds, Figure 9 for 3 seconds, Figure 10 for 4 seconds and Figure 11 for 5 seconds of valve opening time respectively. A maximum thrust value of 290 µN at 200°C of a constant VLM temperature is reported at 1 sec of valve operation, 335 µN at 2 seconds, 413 µN at 3 seconds, 524 µN at 4 seconds and 590 µN at 5 seconds for a constant VLM temperature of 200°C respectively.

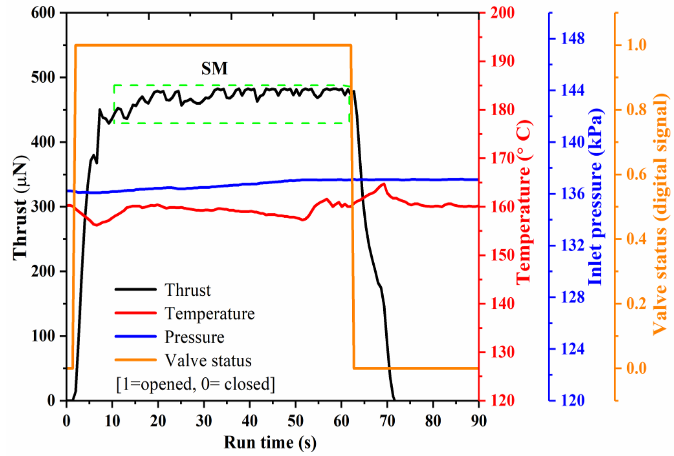

Fig 6 Thrust at a PHT of 160 °C for a flow rate of 1.5 µl/s

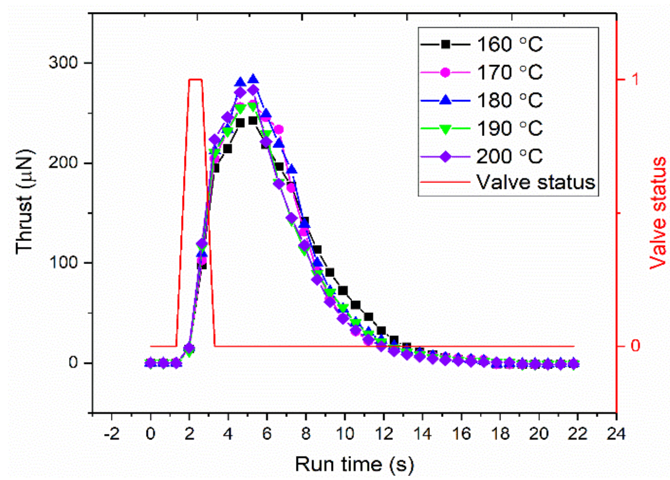

Fig 7 Thrust obtained in a pulsed mode operation for 1 s at a flow rate of 1.5 µl/s

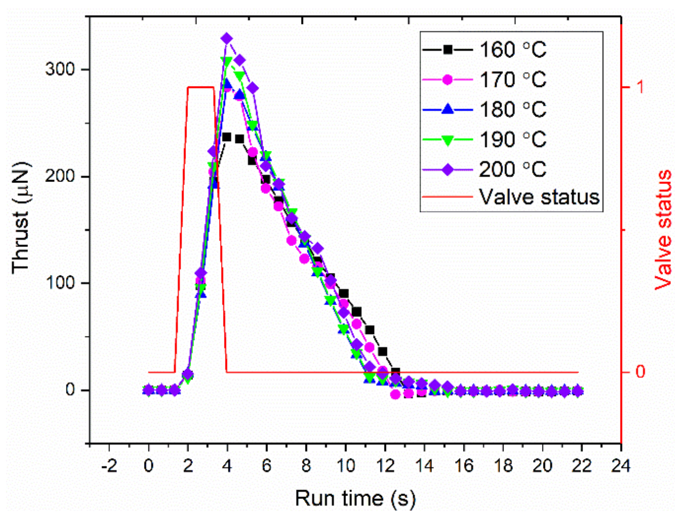

Fig 8 Thrust obtained in a pulsed mode operation for 2 s at a flow rate of 1.5 µl/s

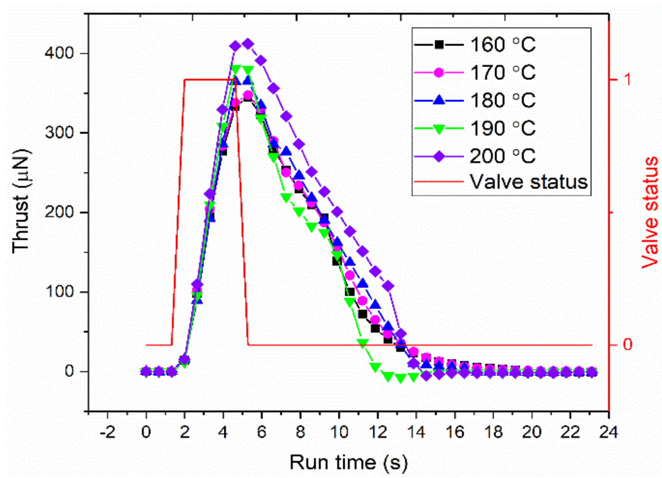

Fig 9 Thrust obtained in a pulsed mode operation for 3 s at a flow rate of 1.5 µl/s

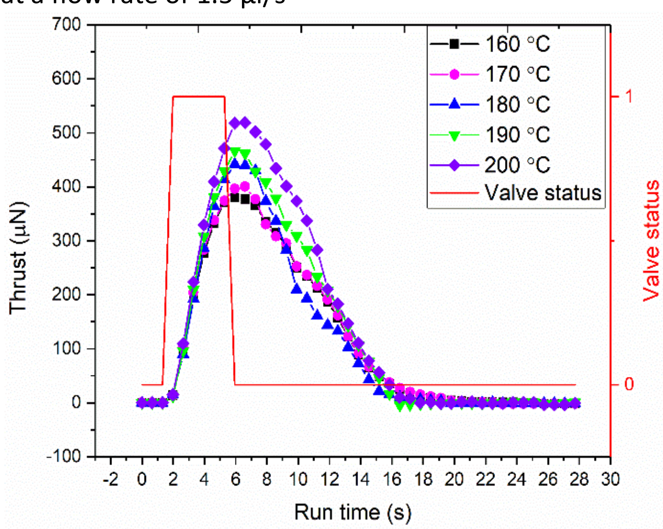

Fig 10 Thrust obtained in a pulsed mode operation for 4 s at a flow rate of 1.5 µl/s

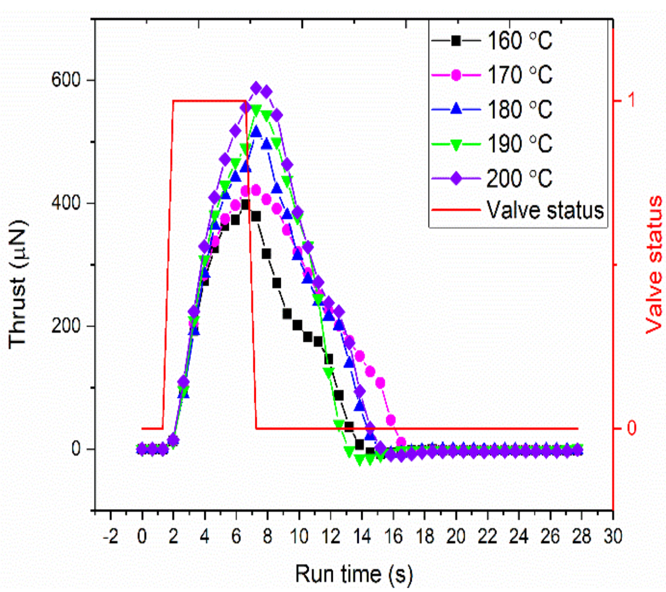

Fig 11 Thrust obtained in a pulsed mode operation for 5 s at a flow rate of 1.5 µl/s

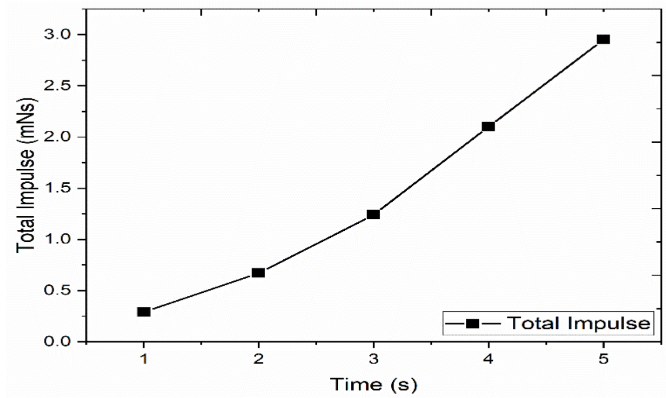

Fig 12 Total impulse at various operating duration

The total impulse is found in the range of 0.3 mNs to 2.9 mNs for a mass flow rate of 1.5 µl/s at 200 °C microthruster temperature. Table 1 shows the total impulse requirement for a range of microsatellite, and the result shown in Fig 12 shows good agreement with 1kg category of microsatellite requirements.

1.5 Effect of dribble volume in VLM

The basic working principle of a liquid fueled propulsion system involves atomization and injection of liquid propellant into the chamber followed by combustion to form hot gas. This hot gas is accelerated through the supersonic nozzle to achieve thrust. The main valve allowing the flow control of the liquid fuel to reach combustion chamber plays a key role. When the main valve was closed, there will be a formation of residual propellant between the valve seat and the exit of injector hole. This residual propellant is called as ’dribble volume’. The residual propellant results in afterburning and that gives a little ’cutoff’ thrust after valve closure [7]. The thrust delivered during this time was usually called as ’cut off impulse’ [8].

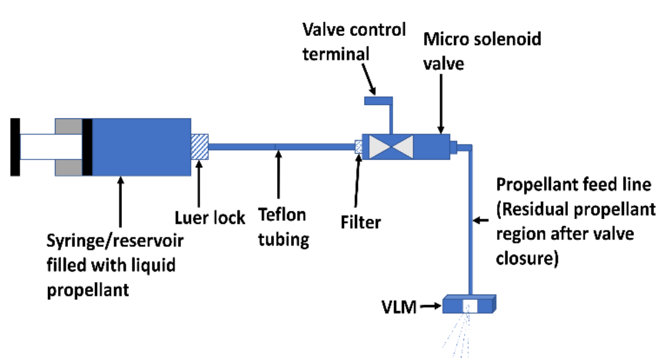

Fig 13 Dribble volume in VLM

The liquid fueled microthruster has to be shut down after firing for the required thrust in a practical application for attitude or orbit control of microspacecraft. The amount of thrust generated is controlled by closing the micro-solenoid valve installed in the propellant feed system. Once the micro solenoid valve is closed, there will be a small amount of liquid propellant trapped in between the micro solenoid valve and the vaporization chamber of the microthruster. This trapped residual liquid propellant is called as 'dribble volume'. Figure 13 shows the schematic view of the propellant feed line between the micro solenoid valve and the microthruster. This micro-solenoid valve could not be mounted near to the VLM due to the thermal behavior of VLM causing premature failure of the micro solenoid valve. In addition, it also creates the backflow during the microthruster operation. In the present study, the propellant feed line length is set as 4 cm. This leads to the generation of 'dribble volume' and therefore microthruster takes certain interval of time for emptying the residual propellants in the tube. The effect of dribble volume can be reduced by installing the micro solenoid valve closest to the VLM vaporization chamber. But there are concerns about back flow and thermal effects of the propellant on the micro solenoid valve as described above. Muller et al reported the same phenomenon for VLM in their study [9]. Figure 14 shows the emptying out process after the valve closure for the present test case.

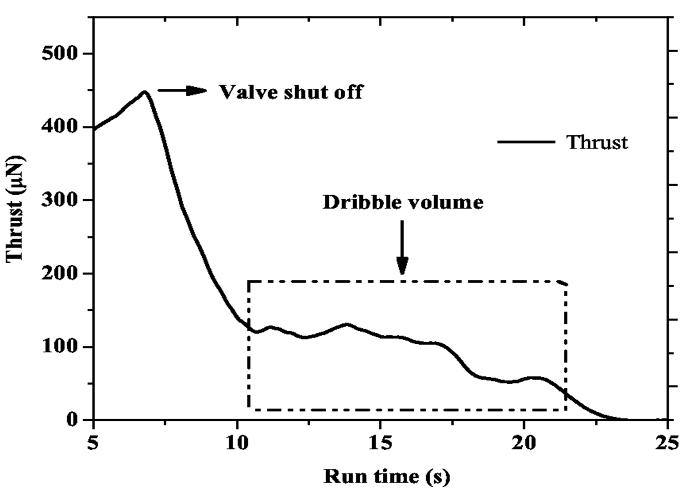

Fig 14 Dribble volume effect

The rise in thrust is approximately for 12 s before reaching thrust level of zero for the propellant flow rate of 1.5 µl/s as shown in the figure 14. This residual thrust leads to a poor impulse bit performance in attitude control of microsatellites.

1.6 Conclusions

A vaporization Liquid microthruster is fabricated using additive manufacturing technique and compared with the CAD design dimension. A very limited work has been published on real time measurement and testing of microthruster in vacuum operating condition. The thruster has been tested in vacuum operating condition to mimic the space operating conditions. Initially it showed a large deviation but after changing few parameters, a high thruster with high measurement accuracy has been fabricated. Pulsed mode operation is used to attitude control of microsatellites in space. This has been investigated and a very good result has been presented. Results show that this technology is promising to fulfill the thrust and total impulse requirement of the microthruster of 1-10 kg category at a propellant mass flow rate of 1.5 µl/s. Dribble volume optimization has also been presented in this study.

1.7 References

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