

# DEVELOPMENT OF PULSED DETONATION MICRO THRUSTER USING LOW TEMPERATURE CO-FIRED CERAMIC TAPE TECHNOLOGIES

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**Abstract:** A miniature pulsed detonation thruster was developed using low temperature co-fired ceramic tape technology. The detonation chamber size was  $\sim 36 \text{ mm}^3$ . Spark electrodes and ion probes were screen printed and embedded in the LTCC microthruster. The channel and via holes were fabricated using laser cutting techniques. Preliminary characterizations show that the peak thrust generated by the microthruster reaches 80 mN when operating at 20 Hz using stoichiometric ethylene/oxygen. Test results also show that the thruster was able to stably provide 15  $\mu\text{N}\cdot\text{s}$  impulse bits at operating frequencies lower than 80 Hz. However, pulsing frequencies as high as 120 Hz has been achieved.

**Keywords:** microthruster, microcombustion, pulsed detonation engine, LTCC microfluidic device

## INTRODUCTION

With the decreasing size and increasing functions of microsattellites, the development of micro propulsion units that are capable of providing very precise thrust and impulses while consuming little power become imminent. Microthrusters for a 100 kg microsattellite should reliably provide thrust output on the order of a few milli-Newtons, and precise impulse bit on the order of  $\mu\text{N}\cdot\text{s}$ . In addition to the challenges in performance, the overall dimension and weight of the propulsion unit have to be compact enough to be integrated into the microspacecraft, and the electric power drawn from the system should be as small as possible since the electric power in a microsattellite is often very limited. Chemical microthrusters are advantageous from the power consumption perspective comparing to electrical microthrusters. However, the miniaturization and system integration of most chemical microthrusters are often more difficult than their electrical counterparts. As has been pointed out in several recent review articles, the volume and weight of many chemical micro propulsion and power systems are attributed to the flow regulating devices instead of the thruster or reactor alone. In this paper, we presented the development of a chemical microthruster based on valveless pulsed detonation. The fabrication of the microthruster is realized by applying a newly developed low temperature co-fired ceramic tape technology that are able to integrate electrical and optical components.

Detonation is, in principle, a more efficient means of converting chemical energy stored in the fuel into kinetic and thermal energy [1-4]. There are therefore already tremendous interests at macro-scale to develop propulsion devices based on detonative combustion. These devices have detonation tubes with diameters on the order of centimeters or larger, and are generally called pulsed detonation engines (PDE) or pulsed detonation thrusters (PDT). Roy et al. [5] installed a mechanical valve at the inlet section of the combustion

chamber to prevent the intermittently block the inlet gas during the combustion phase in the detonation tube. The valve is closed during the ignition and detonation transmission stages, and is open for purging and gas filling. Schauer et al. [6] had developed a PDE with four detonation tubes by modifying the valve system of a 4-cylinder engine to synchronize the mixture filling and ignition. Single tube operation, double tube operation with 180 degree phase difference and 4-tube operation with 90 degree phase shift were achieved. The research shows that utilizing multi-tube operation can increase the operating frequency of a PDE.

Pulsed detonation engines can also be operated without an inlet valve. The working principle of these valveless designs is based on gas dynamics in the detonation tube. As the pressure in the detonation tube during the detonation transmission phase becomes larger than the inlet pressure of the reactant mixture, the inflow will be blocked. With a suitable inlet design that effectively prevents the detonation wave from propagating back into the feeding lines, pulsed detonation can be achieved without an inlet valve. The pressure in the tube decreases as the burned gas discharging from the tube through the exit nozzle. The reactant mixture is able to refill the tube when the tube pressure is lower than the inlet pressure.

Brophy et al. [7, 8] developed a valveless PDT and tested with both gaseous (methane, ethylene) and liquid (JP-10) fuels. The PDT generates detonation by direct initiation, and a divergent tube was utilized to transmit the reaction wave into the main thrust chamber. In their research using ethylene as the fuel [8], a semi-valveless design, a valveless design for oxidizer inlet and a control valve at the fuel inlet, was applied to achieve more precise control of the fuel quantity. They also implemented absorption spectroscopy to monitor the detonation propagation. The size of combustion chamber is however relatively large; the tube was 10.16 cm in diameter and 58.5 cm in length. The maximum operation frequency was 55

Hz. Flow dynamics of the valveless operation were revealed by Ma et al. [9, 10] using numerical simulations. They concluded that flow rates in the detonation tube as well as the initiator section are essential for successful valveless operation.

The relatively low thrust density is one of the major shortcomings of pulsed detonation engines. Pulsed detonation is able to provide relatively high peak thrust, but the average thrust is low due to the intermittent operation. Increasing the pulsing frequency can increase the thrust density; however, the frequency is usually limited by the time required for re-filling the detonation tube with fresh mixture. Smaller tubes therefore may be advantageous since charging time of the mixture can be reduced. McManus et al. [11] developed a small PDE, which had a 25.4 cm long and 4.74 cm in diameter detonation chamber. The volume of the chamber was 452 cm<sup>3</sup>. The thruster was operated with hydrogen/air mixtures, and can be pulsed at frequencies between 10 and 35 Hz. The maximum average thrust was approximately 12 lb. Kitano et al. [12] developed a even smaller PDE. The detonation chamber of their design was 66 cm in the length and 1.5 cm in inner diameter. The volume of the tube was 116.6 cm<sup>3</sup>. Hydrogen was utilized as the fuel and both air and oxygen had been tested as the oxidizer. Operation frequencies as high as 80 Hz had been achieved.

The micro-scale pulsed detonation thruster developed in the present study is at least three order of magnitude smaller than the PDTs reported in the previous works [11, 12], in terms of chamber volume. Higher operating frequencies can potentially be achieved. The micro-scale PDT will be fabricated using the low temperature co-fired ceramic tape technology, which has been proved to be a effective fabrication process for high temperature chemical reactors [13-15]. We will discuss the design and fabrication process in the next chapter. Procedures and results of thrust measurements will also be presented.

## THRUSTER DESIGN AND FABRICATION

### Design

The size for combustion based miniature devices is generally on the order of 1 mm. The flame quenching distance, which is the gap width that the flame can successfully propagate, primarily limits the smallest dimension for the reacting chamber. However, the size of the reacting feeding channels can be as small as tens of micrometers. It would be very challenging for most micro-fabrication processes to be cover dimensions ranging from tens of microns to a few millimeters. The selection of substrate materials is also a problem for these combustion based micro-devices due to the high temperature (1500 K or above) involved. Recently, co-fired ceramic tape has been demonstrated to be a promising material for this kind of devices [13-15]. Electrical elements can be inherently integrated into

LTCC. Our previous works has also shown that optical windows can also be co-fired or bonded after firing.

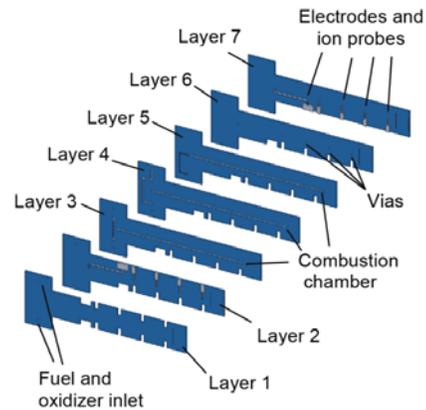


Fig. 1: Exploded view of the thruster structure.

Since LTCC tape technology is essentially a 2-D fabrication technique, the three dimensional structure has to be decomposed into 2-D slices from the beginning. Fig. 1 shows the exploded view of the 2-D layers of the micro PDT developed in the present study. The width of the detonation channel in the PDT is 1.14 mm wide before co-firing, and the height is 0.49 mm, which is the stacked thickness of the 6 sheets of LTCC tapes utilized. The length of the channel is 100.2 mm. It is known that LTCC shrinks after co-firing. The shrinkage ratio is 13.9 % along both X and Y directions, and 14.6 % in Z direction for the LTCC tape, so the width and the height of the channel become 0.98 mm and 0.42 mm respectively after sintering. The length of the channel after sintering is 86.3 mm which is slightly longer than the induction distance required for detonation wave of stoichiometric ethylene/oxygen mixture to develop in a smooth channel [16]. The final volume of chamber is ~ 36 mm<sup>3</sup>, which is 3 orders of magnitude smaller than the smallest pulsed detonation thruster reported in the literature.

In the PDT design, spark ignition electrodes and four pairs of ion probes are also integrated. The electrodes of the igniter and probes locate on the top and bottom surfaces of the channel, which correspond to Layer 1 and Layer 7 in Fig. 1. Oxidizer was injected at one end of the detonation chamber, while fuel was injected perpendicularly into the detonation chamber from the sides. The inlet design effectively prevents back-firing and flame stabilization at the mixing point.

### Fabrication

The major steps of the fabrication procedure include pre-lamination, via and channel cutting, metal wire patterning, stacking and second lamination, dicing and co-firing. The flow chart of the procedure is shown in Fig. 2.

The thickness of LTCC green tape (Electrosience 41020) is ~ 125 μm. In order to obtain the required thickness for fabricating the reaction channel, several

sheets of green tapes have to be stacked and laminated using hot press into a thicker block. The lamination pressure and temperature are 3000 psi and 70 °C respectively for 10 min.

The number of layers in each block is however limited by the capability of the cutting tool utilized for the channel and via hole fabrication step. We presently use CO<sub>2</sub> laser cutter (GCC LaserPro Mercury II) to cut the channels and via holes. Although the 60 W laser can cut through over 10 layers of LTCC tapes; but the dimension control becomes difficult when high laser power is applied. The LTCC tape can be uncontrollably burned. The non-uniform cross-sectional power distribution of the laser beam also causes side-walls to become slanted. The angle was approximately 30° from the vertical axis.

Three layers of green LTCC sheets were laminated into a block in the present study to compromise with the limitations. The thermal effects on LTCC also have to be taken into account when designing the laser cut path; otherwise, there will be significantly dimensional error and distortion of the channel shape. The laser power used to cut the LTCC blocks is 13.2 W with the focusing head travelling at 80 mm/s. The resolution is set at 1000 PPI.

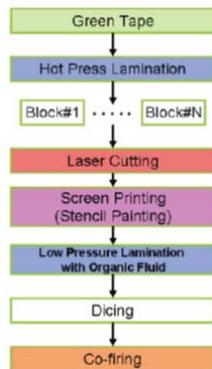


Fig. 2: Fabrication flow chart of LTCC pulsed detonation thruster.

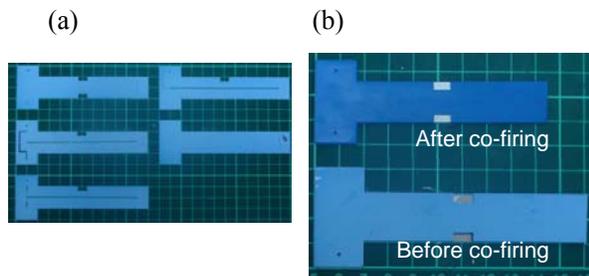


Fig. 3: (a) The major green tape blocks for fabricating the micro PDT, and (b) The micro PDT before and after co-firing..

Fig. 3(a) shows the LTCC blocks after via holes and channels have been cut. Sliver paste was then screen printed on the blocks to form electrical wirings. The blocks are stacks together after the screen printing process. A second lamination step should be carried before co-firing; however, the internal channels make

high pressure lamination unfeasible because the cavity could collapse under the high pressing force. Consequently, a low pressure lamination approach involving the coating of organic solvent between the blocks was applied. The organic solvent is essentially a mixture of 85% honey and 15 % water in weight. After uniformly coat the block surfaces with the solvent, the blocks are stacked together, and the whole stack was again hot pressed with a much lower pressure at 500 psi and 70 °C for 3 min.

The final step of the fabrication procedure is the co-firing process. Common co-firing temperature curve for LTCC materials consists of two stages. The temperature is first increased slowly to and hold at 450 °C for a while before being further increased rapidly to the final sintering temperature at 850 °C . The temperature dwell at 450 °C is for the burning out of organic compounds in the LTCC tape. Since extra organic solvent has been added to the PDT stack during the second lamination, the dwelling time at 450 °C was extended in the present study. The rate of the first temperature rise is also reduced to avoid rapid gasification of the organic solvent, which may delaminate the stack. After the sintering process, the LTCC PDT was naturally cooled to room temperature. Fig. 3(b) shows the micro PDT before and after co-firing.

## PERFORMANCE CHARACTERIZATION

### Test Rig

The experiment setup for thrust test is shown in Fig. 4. Fuel, oxygen and dilute gases are supplied from high-pressure gas cylinders and regulated using mass flow controllers. The ignition frequency of the PDT was controlled through a multi-channel signal synchronizer (Timing Hub, IDT). A pendulum-type thrust stand was used for thrust characterizations. The LTCC PDT is clamped in an aluminum fixture that works as the adapter for connecting gas lines. A miniature force transducer (PCB209C11) was utilized for thrust measurement.

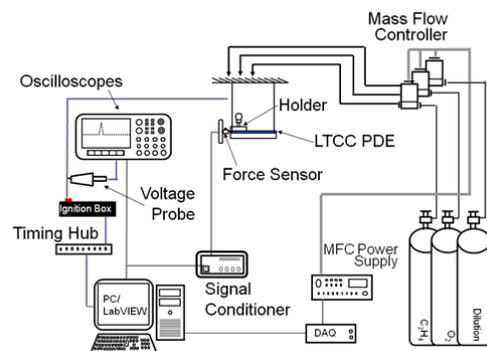


Fig. 4: Thrust test system.

### Thrust Output

Fig. 5 shows the typical thrust evolution of a typical thrust pulse. The mixture was stoichiometric ethylene/oxygen and the pulsing frequency was 20 Hz.

The feeding flow rate was 1200 sccm. The very narrow peak before the main thrust peak was due to the noise from the ignition spark. The maximum thrust was  $\sim 70$  mN, and occurred at  $\sim 300$   $\mu$ s after ignition. The duration of the main thrust peak was  $\sim 500$   $\mu$ s.

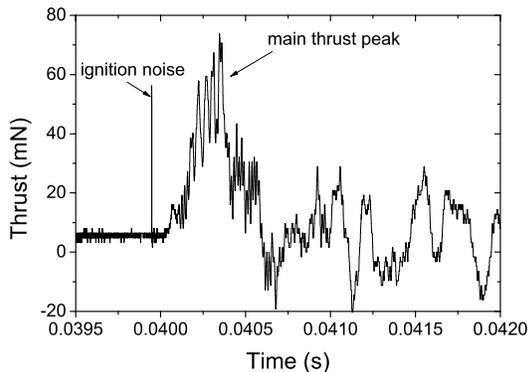


Fig. 5: Thrust evolution of a typical thrust pulse.

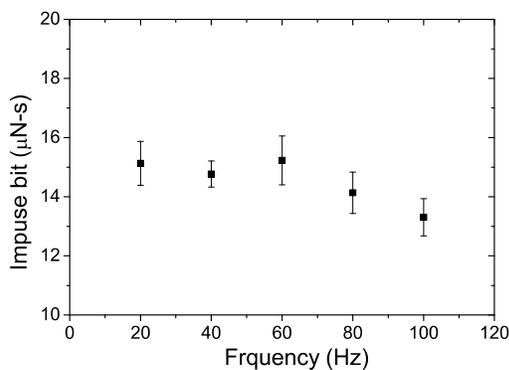


Fig. 6: Average Impulse bit at different pulsing frequencies.

The effect of pulsing frequency on the average impulse bit was revealed in Fig. 6. The mixture utilized for the test was  $C_2H_4/3O_2/0.33N_2$ , and the feeding flow rate was 1300 sccm. The average impulse bit is the mean impulse of 10 pulsing cycles. For frequencies below 80 Hz, it is found that the average impulse was steady at  $\sim 15$   $\mu$ N-s. However, the impulse decreases at higher pulsing rates, which may be due to insufficient time for fresh mixture to refill the chamber. The measurements also showed that the variation of the impulse bit was within  $\pm 1$   $\mu$ N-s. The results also imply that average thrust is proportional to pulsing frequency for cases lower than 80 Hz.

## CONCLUSION

A miniature pulsed detonation thruster has been successfully designed, fabricated and characterized. A valveless inlet was adopted for the PDT to minimize the moving parts, which are generally undesirable in microsystems. The microthruster was fabricated using low temperature co-fired ceramic tape technology. Ignition electrodes and ion probes were embedded in the structure. The fabrication process for including internal channels has also been developed. A pendulum type test stand was implemented to measure

the thrust of the microthruster. Preliminary tests show that the stable impulse bit at  $\sim 15$   $\mu$ N-s are obtained at pulsing frequencies less than 80 Hz. The peak thrust for stoichiometric  $C_2H_4/O_2$  mixture was 70 mN.

## ACKNOWLEDGEMENTS

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