Journal of Mechanical Science and Technology (KSME Int. J.), Vol. 20, No. 1, pp. 85~93, 2006

Rapid Prototyping and Testing of 3D Micro Rockets Using Mechanical Micro Machining

Won-Shik Chu
School of Mechanical and Aerospace Engineering, Seoul National University,
Shinlim-Dong San 56-1, Kwanak-Gu, Seoul 151-742, Korea
Chang-Il Beak
Doowon Heavy industrial Co., Ltd., Sachon, Gyeongnam 664-811, Korea
Sung-Hoon Ahn*
School of Mechanical and Aerospace Engineering, Seoul National University,
Shinlim-Dong San 56-1, Kwanak-Gu, Seoul 151-742, Korea
Tae-Hwan Cho
School of Mechanical and Aerospace Engineering, Gyeong Sang National University,
Jinju, Gyeongnam 660-701, Korea

The trend of miniaturization has been applied to the research of rockets to develop prototypes of micro rockets. In this paper, the development of a web-integrated prototyping system for three-dimensional micro rockets, and the results of combustion tests are discussed. The body of rocket was made of 6061 aluminum cylinder by lathe process. The three-dimensional micro nozzles were fabricated on the same aluminum by using micro endmills with $\phi 100\ \mu m \sim \phi 500\ \mu m$ diameter. Two types of micro nozzle were fabricated and compared for performance. The total mass of the rockets was 7.32 g and that of propellant (gun powder) was 0.65 g. The thrust-to-weight ratio was between 1.58 and 1.74, and the flight test with 45 degree launch angle from the ground resulted in 46 m~53 m of horizontal flight distance. In addition, ABS housing for the micro machined rocket was fabricated using Fused Deposition Modeling (FDM). A web-based design, fabrication, and test system for micro nozzles was proposed to integrate the distributed hardware resources. Test data was sent to the designer via the same web server for the faster feedback to the rocket designer.

Key Words : Micro Rocket, Micro Machining, Rapid Prototyping, Web-based

Nomenclature

μ : Mach angle
θ : Angle of flow velocity from the x axis
ν : Prandtl-Meyer function
m_r : Mass of rocket
m_p : Mass of propellant
$\dot{m}$: Mass flow rate
I_t : Total impulse
I_{sp} : Specific impulse
$F_{\max}$: Max thrust
T_{be} : Effective burning Time
F_{eff} : Effective thrust

1. Introduction

The trend of miniaturization has been expanded to many micro aerospace applications that provide high efficiency. For example AeroVironment commercialized Micro Air Vehicle (MAV) with support of DARPA (Defense Advanced Research Projects Agency). Researchers at Stanford

---

* Corresponding Author,
E-mail : ahnsh@snu.ac.kr
TEL : +82-2-880-7110; **FAX** : +82-2-883-0179
School of Mechanical and Aerospace Engineering, Seoul National University, Shinlim-Dong San 56-1, Kwanak-Gu, Seoul 151-742, Korea. (Manuscript **Received** May 25, 2005; **Revised** December 3, 2005)

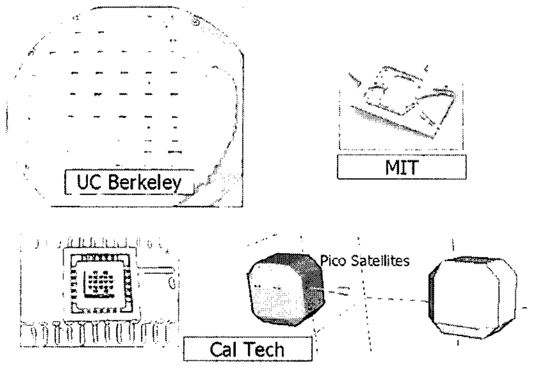


Fig. 1 MEMS-based micro rockets developed by previous researchers

University tried micro helicopter and meso-scale burner array (Liu et al., 2004). Applying MEMS (Micro Electro-Mechanical Systems) technology, micro rockets were developed (Figure 1). One of the main advantages of the micro rockets, theoretically, was to achieve higher thrust-to-weight ratio compared with macro-scale rockets (London et al., 2001). The rocket tested at UC Berkeley used solid propellant (Hydroxyl-Terminated Polybutadiene, HTPB) (Teasdale, 2000) while the one from MIT used oxygen and ethanol (Leo, 2001). TRW and California Institute of Technology developed a micro rocket array on an IC chip that can precisely control the position of Pico Satellites in the space (Lewis et al., 2000). Rossi et al. developed a model for solid propellant micro thruster based on unsteady derivation of the thermodynamic equations (Rossi et al., 2000) and another one-dimensional model based on a lumped parameter (Orieux et al. 2000). They also presented fabrication and assembly of small-scale thrusters (Rossi et al., 2001). Mukerjee et al. tested micro-attitude control thrusters using a vaporization chamber (Mukerjee et al., 2000). Ye et al. examined a vaporizing water micro-thruster with a heating resistor (Ye et al., 2001).

These micro rocket, however, were fabricated by using semiconductor processes, which typically make 2.5 dimensional or prismatic geometry. One of the issues in the 2.5D nozzles is un-axisymmetric flows, which is difficult to control. The other concerns are fabrication time and cost. Usually MEMS design and fabrication process takes relatively longer time and higher cost than mechanical machining for prototyping of the early design.

For the miniaturized geometry with minimum feature of 100 μm ~ 1 mm, mechanical micro machining provides less fabrication time, cost and higher accessibility compared with MEMS process.

In this paper, a design and prototyping system for three dimensional micro rockets and test results of the fabricated rockets are discussed. In order to integrate data for the distributed fabrication and testing of the micro rockets, a web-based system was proposed.

2. Design of micro rocket

Different from general micro machining (Ahn et al, 2005), the geometry of micro nozzle requires special design and fabrication system. To integrate the design tool and remote fabrication facility, the web-based communication was necessary in this study. Previous work shows that, in terms of accessibility, web-based systems were quite effective (Ahn et al., 2002 ; Lee et al., 2005 ; Yang et al., 2004).

The main parts of a micro rocket are divided into a nozzle, a combustion chamber, and a housing. The most critical design in a micro rocket is the geometry of micro size nozzle. Of available design methods, the method of characteristics (Anderson, 1990) was applied in this study.

2.1 Method of characteristics

The flow motion of two-dimensional inviscid irrotational flow is governed by (Anderson, 1990)

$$\left(\begin{array}{l} (u^2-a^2)\dfrac{\partial u}{\partial u}+uv\left(\dfrac{\partial u}{\partial y}+\dfrac{\partial v}{\partial x}\right)+(v^2-a^2)\dfrac{\partial v}{\partial y}=0 \\ \dfrac{\partial v}{\partial x}-\dfrac{\partial u}{\partial y}=0 \end{array}\right) \quad (1)$$

when

$$\frac{u^2+v^2}{a^2}-1=\frac{V^2}{a^2}-1=M^2-1>0,\ \text{i.e.}\ M>1 \quad (2)$$

there are two real characteristics through each point of the flow field

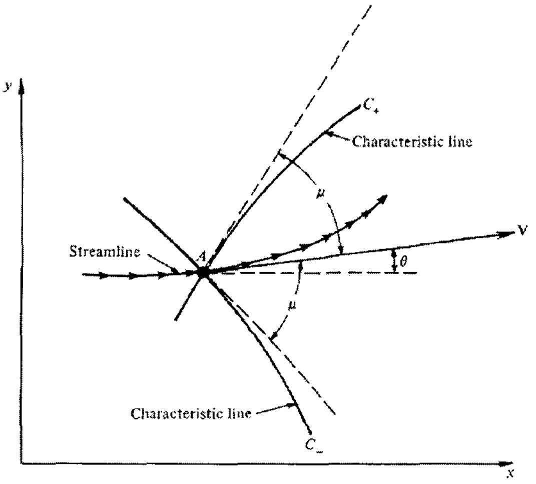


Fig. 2 Illustration of characteristic lines

$$\left(\frac{dy}{dx}\right)_{char}=\tan(\theta\mp\mu) \tag{3}$$

when μ is the Mach angle, and θ is the angle of flow velocity from the x axis (Figure 2).

The characteristic line satisfy compatibility equations

$$\theta+\nu(M)=const=K_- \quad \text{(along the } C_- \text{ characteristic)} \tag{4}$$

$$\theta-\nu(M)=const=K_+ \quad \text{(along the } C_+ \text{ characteristic)} \tag{5}$$

where ν is the Prandtl-Meyer function.

The last step is to find flow field condition of next point from the known flow field conditions at two points (Figure 3)

$$\theta_1+\nu_1=(K_-)_1 \tag{6}$$

$$\theta_2-\nu_2=(K_-)_2 \tag{7}$$

At point 3 using eqs. (4), (5)

$$\theta_3+\nu_3=(K_-)_3=(K_-)_1 \tag{8}$$

$$\theta_3-\nu_3=(K_+)_3=(K_+)_2 \tag{9}$$

Solving Eqs. (8) and (9), we obtain θ and ν_3 from known values of K_+ and K_-

$$\theta_3=\frac{1}{2}\left[(K_-)_1+(K_+)_2\right] \tag{10}$$

$$\nu_3=\frac{1}{2}\left[(K_-)_1-(K_+)_2\right] \tag{11}$$

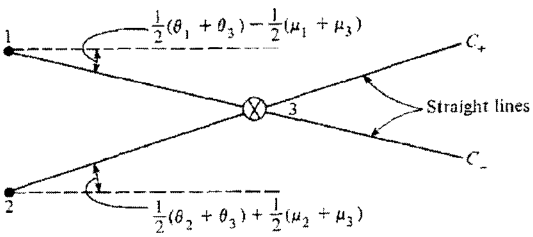


Fig. 3 Approximation of characteristics by straight lines

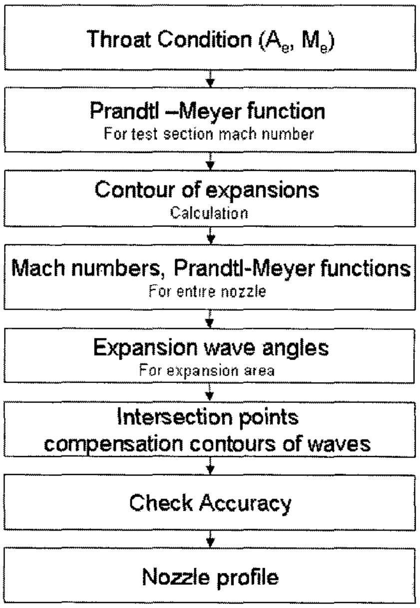


Fig. 4 The procedure of finding nozzle profile

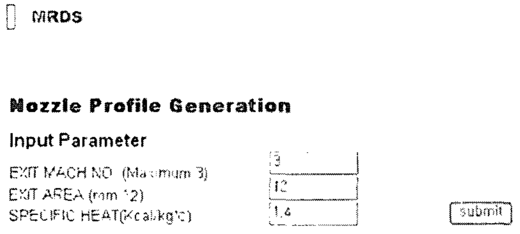
Repeating this step, points covering entire flow field can be calculated.

The procedure of finding nozzle profile is as follows (Figure 4) (Cho, 1975)

In this analysis two-dimensional flow model was applied for axisymmetric nozzle flow from the micro nozzle. In addition, the perfect gas condition was assumed. However, for the micro-scale nozzle flow studied in this study, these discrepancies may be neglected since we are looking at the first approximation probably provides enough information.

2.2 Web-based design

A FORTRAN code was implemented to solve the equations for method of characteristics. The



Nozzle Profile Generation

Input Parameter

EXIT MACH NO (Maximum 3) 3
EXIT AREA (mm^2) 12
SPECIFIC HEAT(Kcal/kg°c) 1.4

Fig. 5 Nozzle profile design using the Internet-based system

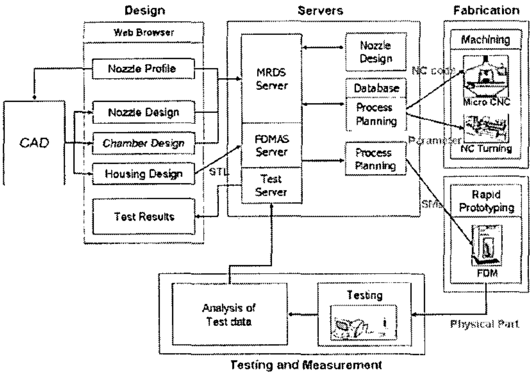


Fig. 6 Communication of the prototyping system

design tool was modified and integrated with a web-based interface (http ://fab.snu.ac.kr/mrds).

As shown in Figure 5, a nozzle designer inputs exit Mach number, exit area, and specific heat of the gas using the web-based tool. The input parameters are sent to the Micro Rocket Design Service (MRDS) server via the internet (Figure 6).

The calculated nozzle profile is fed back to the designer as a text file. For manufacturing, the designer has two options, 1) use the Computer Numerical Control (CNC) code generator provided in this service from the web server, or 2) read the text data into a commercial CAD system to make a three-dimensional nozzle geometry (Figure 7) and to generate a CNC code using any CAM system. Figure 8 shows a cross-sectional view of the micro nozzle with parameters for micro machining. Roughing and finishing tool paths are generated automatically in the server, and the mechanical micro machining process may fabricate micro nozzles in a rapid manner.

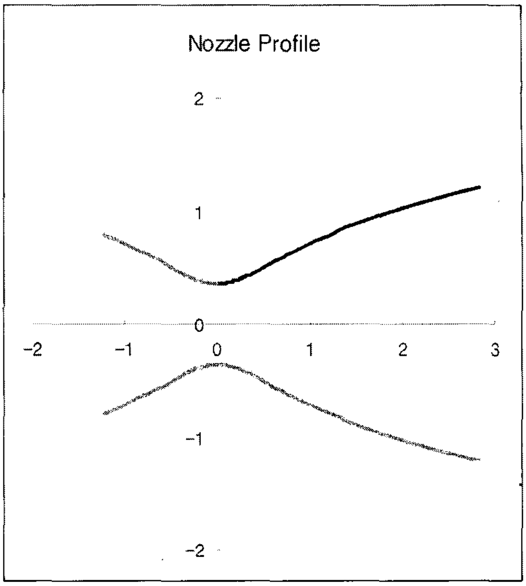
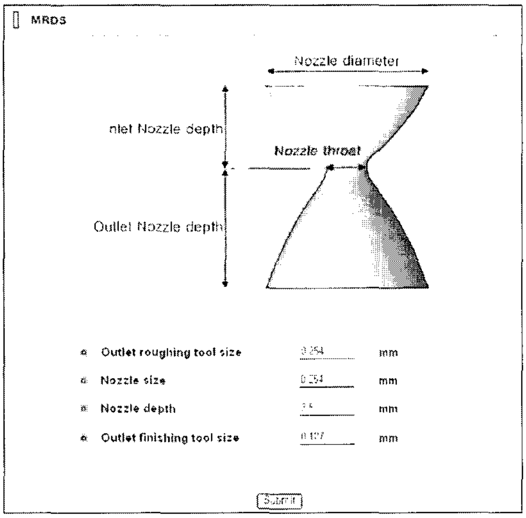


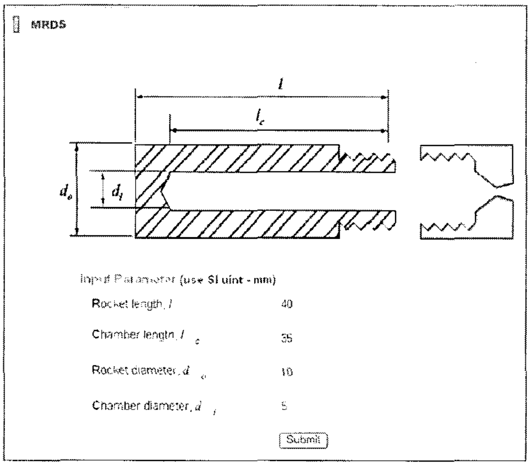
Fig. 7 Nozzle profile from the web-based design tool to be 3D modeled in a commercial CAD



Outlet roughing tool size 0.254 mm
Nozzle size 0.254 mm
Nozzle depth [illegible] mm
Outlet finishing tool size 0.127 mm

Fig. 8 Homepage for web-based micro nozzle fabrication

The combustion chamber is designed as Figure 9. Geometric parameters were typed by the designer and transmitted to the manufacturer. Finally, as shown in Figure 6, the geometry of the plastic housing is designed using a commercial CAD and submitted to the FDMAS (Fused Deposition Modeling Advisory Service) (Beak et al., 2002) as an STL (Stereolithography) format.



Input Parameter (use SI uint - mm)

Rocket length, l 40

Chamber length, l_c 35

Rocket diameter, d_o 10

Chamber diameter, d_i 5

Fig. 9 Design tool for combustion chambers

3. Fabrication Process

Prototypes of micro nozzles were fabricated using the web-based system. The fundamental process of micro nozzle is mechanical micro machining (Figure 10) using High Speed Steel (HSS) tool shown in Figure 11. The smallest tool diameters used in this study were 100 μm~500 μm for flat endmill (roughing), and 200 μm for ball end mill (finishing). Aluminum 6061 T6 rod was used as the nozzle material. The 3-axis micro stage (the precision is 1 μm) and high speed spindle (max. spindle speed is 42,000 rpm) was used to fabricate the rocket nozzle.

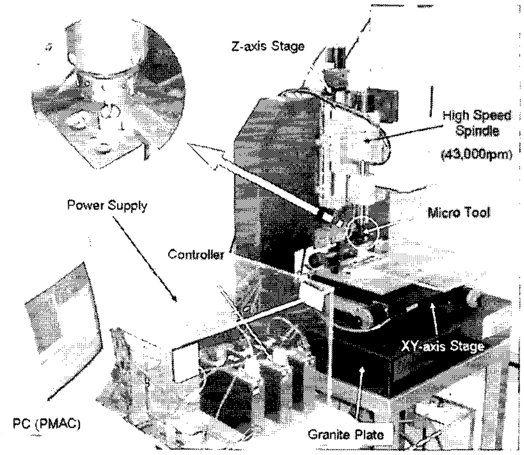
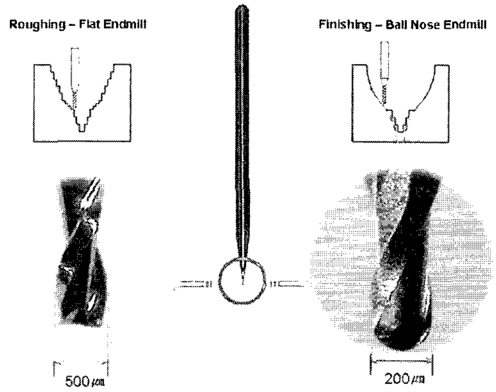


Fig. 10 The 3-axis stage for micro machining used in this study

The total machining time for the rocket nozzle was about two hour and 30 minutes. To reduce thermal effect (Zverev et al., 2003) on the spindle unit, 23000 rpm was used. The feed rate was 20 mm/min. Figure 12 shows the throat of machined nozzle.

For the combustion chamber, Aluminum 6061 T6 rod with 12 mm diameter and 40 mm length was machined to have 5 mm diameter and 35 mm deep blind hole as shown in Figure 9. A drill of 5 mm was used with a CNC lathe to fabricate the hole.

For the solid propellant, a gun powder for firework (Hunan Provincial Fine Crackers & Fireworks) was used. Gun powders usually have



(a) Flat endmill for roughing (b) Ball nose endmill for finishing

Fig. 11 Micro endmills used in this study

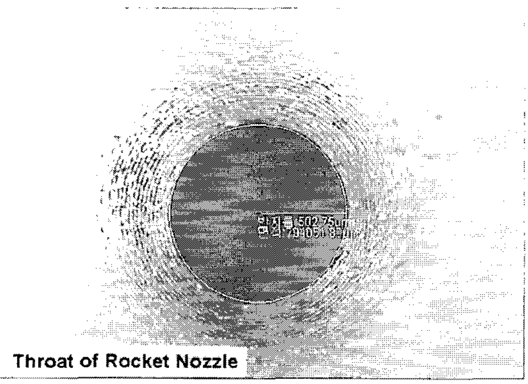


Fig. 12 Measurement of throat geometry for the fabricated rocket nozzle (Radius: 502.75 μm)

rapid explosion, thus more effective at high altitude or at the space environment than ground level (London et al., 2001). To prevent an accidental disassembly of the nozzle and the combustion chamber during combustion test, mechanical fastening by threads was applied.

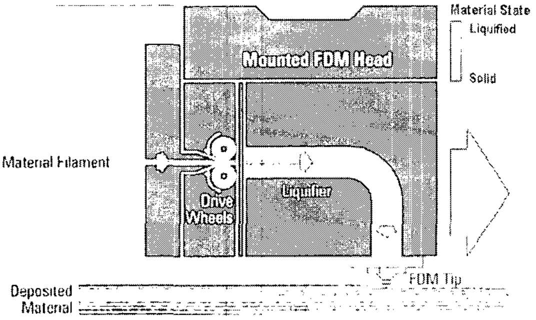
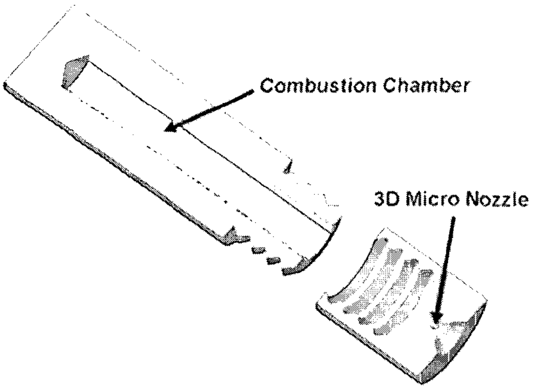
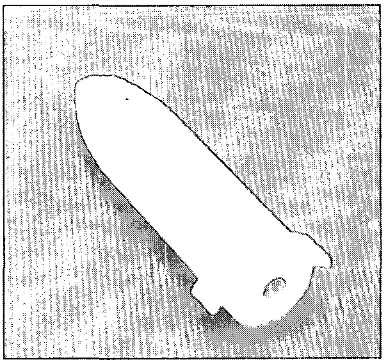


Fig. 13 Schematic process of Fused Deposition Modeling (FDM)



(a) Aluminum nozzle and chamber



(b) Housing made from FDM

Fig. 14 Machined parts and assembled rocket motor with ABS housing made from FDM

In case where the housing of micro rocket is necessary, plastic housing was prototyped by Fused Deposition Modeling (FDM) technology. FDM is a rapid prototyping technology (Figure 13) that can fabricate prototypes using plastic materials. The FDM machine deposits about 300 μm thin semi-molten filament of ABS or Polycarbonate in the way determined by Quickslice software (FDM, 1998). Figure 14 shows an assembly of micro machined parts and housing made from FDM.

4. Thrust Tests and Results

Among prototypes, two types were tested to measure thrust properties. The nozzle with 1 mm throat diameter was referred to Type 1 while the nozzle with 0.5 mm throat diameter was referred to Type 2 (Table 1).

The combustion chamber was filled with the gun powders. The nozzle was fastened to the motor case by the threads. Igniting gun powders from the same manufacturer were filled space inside of the nozzle, and a wick was connected to the ignition gun powders. The assembled rocket was supported by plastic foam. Then nozzle was faced upward and was fixed on a digital scale that may measure up to 0.001 g resolution.

A digital camcorder was used to record the experimental process during the combustion tests. As intended, the combustion generated a three-dimensional exhausted gas (Figure 15).

A RS232C interface of the precision balance with PC was used to collect test data. Average thrust data of three repetitions were shown in

Table 1 Specification of the micro rocket

	Type 1	Type 2
Mass of Rocket (m_r)	7.32 g	7.32 g
Mass of Propellant (m_p)	0.65 g	0.65 g
Minimum Diameter of Nozzle	1 mm	0.5 mm
Dimensions of Combustion Chamber	35×ϕ5 mm	35×ϕ5 mm
Dimensions of Motor Case	40×ϕ10 mm	40×ϕ10 mm
Propellant	gun powder	gun powder
Flight Distance, D	49~50 m	46~53 m

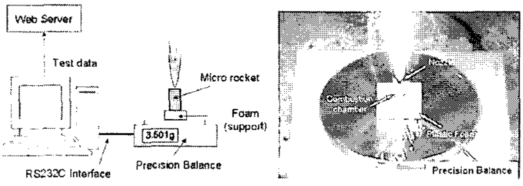


Fig. 15 Exhaust gas from the micro nozzle

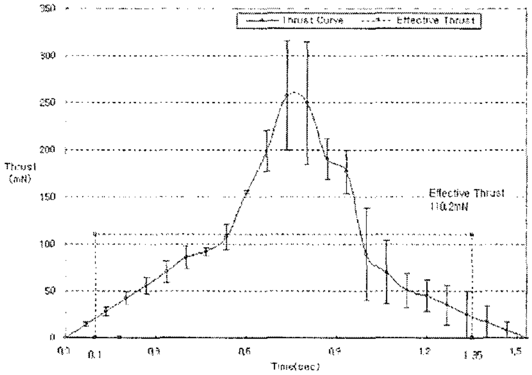


Fig. 16 Thrust characteristics of the micro rocket (Type 1, throat$=\phi1$ mm)

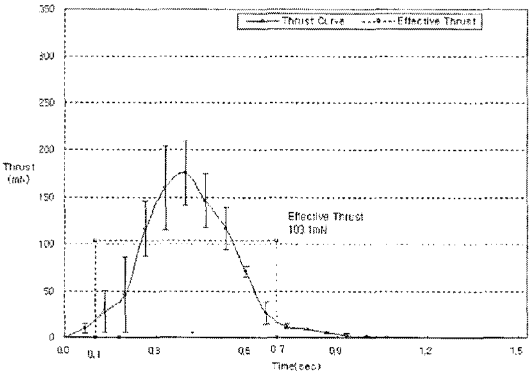


Fig. 17 Thrust characteristics of the micro rocket (Type 2, throat$=\phi0.5$ mm)

Table 2 Test results of the micro rockets

		Type 1	Type 2
Total Impulse, I_t		137.9 mN·sec	61.9 mN·sec
Specific Impulse, I_{sp}		21.6 sec	9.7 sec
Max Thrust, $F_{\max}$		257.9 mN	175.5 mN
Effective Burning Time, T_{be}		1.25 sec	0.6 sec
Effective Thrust, F_{eff}		110.2 mN	103.1 mN
Mass Flow Rate, $\dot{m}$		0.52 g/sec	1.08 g/sec
Thrust-to-Weight Ratio	Initial value	1.41	1.32
	Last value	1.53	1.44

Figures 16 and 17.

For Type 1, total impulse was 137.9 mN·sec, and specific impulse, I_{sp}, was 21.6 sec by Eq. (12) (Bu et al., 2002)

$$I_{sp}=\frac{\int Fdt}{m_p g} \tag{12}$$

When m_p is the mass of propellant.

Although the burning time, t_b, was about 1.5 sec the effective burning time may be defined as the time from when thrust was observed obviously till it diminished (Hess and Mounford, 1964).

In this case, t_{be} was defined by the time when 10 percent of the maximum thrust was reached (between 0.1 sec and 1.35 sec from Figure 16). From Eq. (13), the mass flow rate was 0.52 g/sec (Bu et al., 2002).

$$\dot{m}=\frac{m_{fuel}}{t_{tb}} \tag{13}$$

The effective thrust was 110.2 mN from Eq. (14)

$$F_{eff}=I_{sp}\dot{m}g \tag{14}$$

The thrust-to-weight ratio was as follows

$$\begin{aligned} &\mathit{Initial}:\ \frac{F_{eff}}{(m_p+m_r)\,g}=1.41 \\ &\mathit{Final}:\ \frac{F_{eff}}{(m_r)\,g}=1.53 \end{aligned} \tag{15}$$

Table 2 shows the results for Type 2 rocket.

4.1 Flight test

Since the thrust-to-weight ratios were greater then 1, the rockets could be launched vertically.

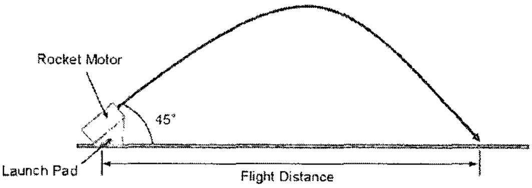
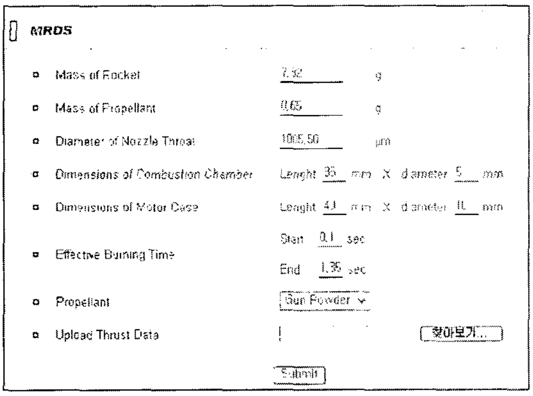


Fig. 18 Set up for launch tests. The flight distance was measured from the horizontal distance of micro rocket launched at 45° from the ground

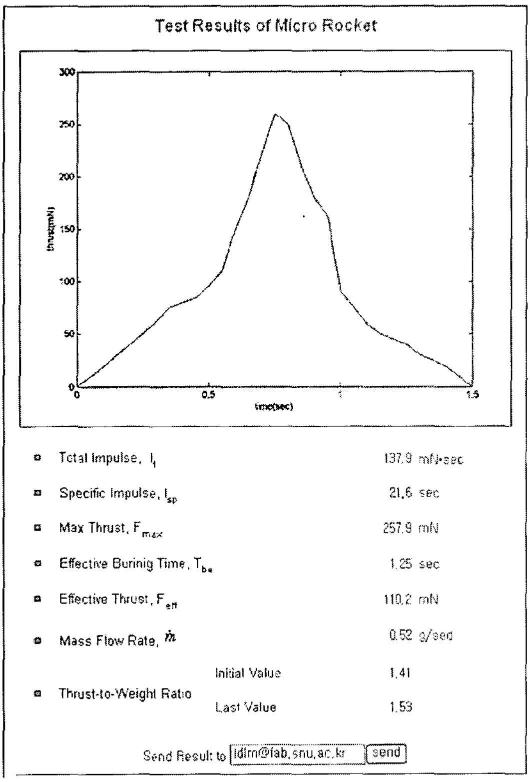
For simplicity of measurement, however, 45° launch was tested (Figure 18). Type 1 rocket showed flight distance between 49 m~50 m.

Type 2 rocket compared with Type 1 had higher specific impulse and maximum thrust. However, effective thrust was similar for both types. In terms of actual flight distance, both types showed similar results.



Mass of Rocket	7.32 g
Mass of Propellant	0.65 g
Diameter of Nozzle Throat	1005.50 μm
Dimensions of Combustion Chamber	Lenght 35 mm X diameter 5 mm
Dimensions of Motor Case	Lenght 43 mm X diameter 11 mm
Effective Buring Time	Start 0.1 sec End 1.35 sec
Propellant	Gun Powder
Upload Thrust Data	

Fig. 19 Input parameters for uploading test results of micro rocket



Total Impulse, I_t		137.9 mN•sec
Specific Impulse, I_{sp}		21.6 sec
Max Thrust, F_{max}		257.9 mN
Effective Burinig Time, T_{be}		1.25 sec
Effective Thrust, F_{eff}		110.2 mN
Mass Flow Rate, $\dot{m}$		0.52 g/sec
Thrust-to-Weight Ratio	Initial Value	1.41
	Last Value	1.53

Send Result to idlm@fab.snu.ac.kr

Fig. 20 Test results of micro rocket calculated from the web server using data in Figure 19

The combustion test and flight test required specially handled procedure and isolated location because of safety issues. Often times the designer of the rocket and the people testing combustion are different and located in different town. Thus, the web-based integration helped prompt turnover of design-fabrication-testing routines. The test results from Eqs. (12) ~ (15) were calculated at the web server using the raw test data (Figure 19). This information was fed back to the original designer of the prototype rocket via the Internet (Figures 6 and 20).

5. Conclusions

By using mechanical micro machining, several prototypes of micro rockets were fabricated, and two types of them were tested. From the thrust test and flight test, the capability of the micro rocket was examined. With throat diameter in hundreds micro meter range, the solid propellant successfully produced thrust that resulted in thrust to weight ratio larger than one. Compared with MEMS-based 2.5D rockets, the total time from design to testing was very little. One of the advantages in this system was the characteristics of mechanical micro machining system which provided fast processing time and high accuracy. The other advantage, from the point of system integration, was that the web-based design and fabrication system offered rapidly processed information sharing among remote design, fabrication and testing sites, resulting in efficient experimentation.

For the future work, numerical prediction of the thrust and other characteristics of micro rocket as well as experimental study of better nozzle geometry in micro scale can be valuable areas of study.

Acknowledgments

This research was supported by Brain Korea 21 project, Institute of Advanced Machlvery and Design of Seoul Netional University, Research

Center for Aircraft Parts Technology of Gyeongsang National University and Korea Research Foundation (KRF- 2004-041-D00066).

References

Ahn, S. H., Bharadwaj, B., Khalid, H., Liou, S. Y. and Wright, P. K., 2002, "Web-based Design and Manufacturing Systems for Automobile Components : Architectures and Usability Studies," *International Journal of Computer Integrated Manufacturing*, Vol. 15, No. 6, pp. 555~563.

Ahn, S. H., Chu, W. S., Kim, D. S. and Jun, C. S., 2005, "MIMS : Web-based Micro Machining Service," *International Journal of Computer Integrated Manufacturing*, Vol. 18, No. 4, pp. 251~259.

Anderson, J. D., 1990, *Modern Compressible Flow : with Historical Perspective*, 2nd ed., McGraw-Hill Publishing Company, New York.

Beak, C. I., Chu, W. S. and Ahn, S. H., 2002, "FDMAS-an Internet based Advisory Service for Fused Deposition Modeling," *Korean Society of Mechanical Engineers*, conference.

Bu, J. H., Yu, S. S., Lee, K. Y., Jung, D. H. and Hwang, J. S., 2002, *Jet-propelled engine*, Chung Mun Gak, pp. 397~401.

Cho, T. H., 1975, *Design of supersonic wind tunnel nozzle using the method of characteristics, Technical Paper*, Agency for Defense Development, Korea.

FDM, 1998, FDM® System Documentation, Stratasys, Inc.

Hess, W. and Munford, N. V. S., 1964, *Jet Propulsion for Aerospace Applications*, Pitman Publishing Co., pp. 454~465.

Lee, K. H., Kim, H. S. and Kwak, Y. K., 2005, "Mobility Improvement of an Internet-Based Robot System Using the Position Prediction Simulator," *International Journal of Precision Engineering and Manufacturing*, Vol. 6, No. 3, pp. 29~36.

Leo, A., 2001, Pocket Rocket Pack a Punch. An Enterprise MIT Technology Review 104.

Lewis, D. H., Janson, S. W., Cohen, R. B. and Antonsson, E. K., 2000, "Digital Micropropulsion," *Sensors and Actuators*, Vol. 80, pp. 143~154.

Liu, H. C., Lee, S., Kang, S. K., Edwards, C. F. and Prinz, F. B., 2004, "RP of Si_3N_4 Burner Arrays Via Assembly Mould SDM," *Rapid Prototyping Journal*, Vol. 10, No. 4, pp. 239~246.

London, A. P., Ayon, A. A., Epstein, A. H., Spearing, S. M., Harrison, T., Peles, Y. and Kerrebrock, J. L., 2001, "Microfabrication of a High Pressure Bipropellant Rocket Engine," *Sensors and Actuators*, Vol. 92, No. A, pp. 351~357.

Mukerjee, E. V., Wallace, A. P., Yan, K. Y., Howard, D. W., Smith, R. L. and Collins, S. D., 2000, "Vaporizing Liquid Microthruster," *Sensors and Actuators*, Vol. 83, pp. 231~236.

Orieux, S., Rossi, C. and Esteve, D., 2000, "Compact Model based on a Lumped Parameter Approach for the Prediction of solid Propellant Micro-rocket Performance," *Sensors and Actuators*, Vol. 101, No. A, pp. 383~391.

Rossi, C., Conto, T. D., Esteve, D. and Larangot, B., 2001, "Design, Fabrication and Modeling of MEMS-based Microthrusters for Space Application," *Smart Mater. Struct.*, Vol. 10, pp. 1156~1162.

Rossi, C., Rouhani, M. D. and Esteve, D., 2000, "Prediction of the Performance of a Si-micromachined Microthruster by Computing the Subsonic Gas flow Inside the Thruster," *Sensors and Actuators*, Vol. 87, pp. 96~104.

Teasdale, D., 2000, Solid Propellant Micro Rockets, Masters Thesis, University of California at Berkeley.

Yang, Z. J., Peng, Z. J. and Kim, S. S., 2004, "Bearing Load Distribution Studies in a Multi Bearing Rotor System and a Remote Computing Method based on the Internet," *KSME International Journal*, Vol. 18, No. 6, pp. 946~954.

Ye, X. Y., Tang, F., Ding, H. Q. and Zhou, Z. Y., 2001, "Study of a Vaporizing Water Microthruster," *Sensors and Actuators*, Vol. 89, No. A, pp. 159~165.

Zverev, I. A., Eun, I. U., Chung, W. J. and Lee, C. M., 2003, "Thermal Model of High-Speed Spindle Units," *KSME International Journal*, Vol. 17, No. 5, pp. 668~678.