Preliminary Study of Micro Cold Gas Thruster

Seonghwan Moon, Hwayoung Oh, and Hwanil Huh
Department of Aerospace Engineering, Chungnam National University
#220 Gung-Dong, Daejeon, 305-764 Republic of Korea
hwanil@cnu.ac.kr

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Abstract

Miniaturization of subsystems including propulsion systems is recent trends in spacecraft technology. Small space vehicle propulsion is not only a technological challenge of a scaling system down, but also a combination of fundamental flow/combustion constraints.

In this paper, physical constraints of micronozzle for cold gas micro-thruster are reviewed and discussed. Method to measure small thrust are also described.

Introduction

Micro-thrusters have received significant attraction because of their simplicity. Application of micro-thrusters are for primary propulsion and attitude control of micro-spacecraft.

In an attempt to standardize the definition of microspacecraft, the Air Force Research Laboratory(AFRL) has proposed the standard detailed in Table 1.

Table 1. Small satellite classification standard

Total spacecraft mass	Description
100-1000kg	Small satellite
10-100kg	Micro satellite
1-10kg	Nano satellite
0.1-1kg	Pico satellite
10-100g	Femto satellite
1-10g	Atto satellite
0.1-1g	Zepto satellite

To miniaturize propulsion subsystems, cold-gas, chemical thrusters are scalable and have been under study at the micro-scale. Table 2 summarizes a list of meso- and micro- scale chemical thruster under development.

Table 2. Meso and micro scale chemical thrusters under development

Type	Reference
Solid micro rocket	1), 10), 11)
Monopropellant micro rocket	12), 13)
Bipropellant micro rocket	14)
Cold-gas micro thruster	15)
Thermal transpiration based micropropulsion	16)

Micromachining technology enables the fabrication of new class of devices. This new type of micro devices has an interest in the growing tendency of miniaturization of every system. Indeed, scaling down the dimensions of the system needs a high power-density energy source.

Combustion is one simple way to obtain large quantities of energy from a small volume. Typical *solid propellant has an energy density of around 5J/*㎣. Commercial lithium batteries have an energy density of only 0.3 J/㎣1). The stored energy density *of hydrocarbon fuels is two orders of magnitude* greater than current battery2) (Fig. 1).

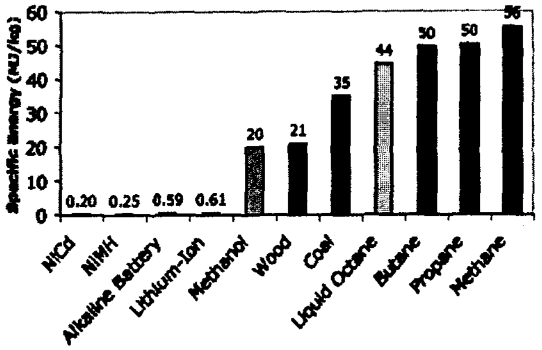

Fig. 1 Energy density

Hydrocarbon fuels as a high energy density fuel have been extensively studied and proven to be an efficient means of energy transform at the macroscopic scale. If the chemical energy can be converted efficiently to useful energy, a microscale combustion device may be very competitive with commercial batteries. Furthermore, with the recently increasing space activities (e.g. micro-satellite) and unmanned aerial vehicles (UAV), demand for high power-density energy sources are also increasing.

Among the propulsion systems frequently used in spacecraft, chemical systems have the lowest complexity and cost. They can provide highly repeatable, extremely small impulse bit (I_{bit}) for accurate orbit maintenance and attitude control.

The micronozzle is an essential component of many propulsion systems, and its success will lead the way for more advanced chemical systems. Thus, with many of the technologies currently under investigation, the micronozzle, which is the heart of the cold-gas system, is chosen as the focus of research..

Scaling Issues of Micronozzle

The effects of scaling-down on combustion in chemical microthrusters have been studied by Bruno3) . Fernandes-Pello4) analyzed the effects of miniaturization on the liquid mechanics, heat transfer and combustion characteristics involved in micropower generating devices.

Micronozzles suffer high viscous losses due to the low Reynolds number. The conventional design approach for nozzles of macroscale rocket motor assumes a thin boundary layer. Also, estimated performance loss due to viscous boundary layer is less than 1%. However, in a micronozzle, viscous effects will be very influential5).

Surtherland and Maes recognize the utility of achieving a small $I_{bit,}$ as well as low thrust, with a cold gas system. However, for "mechanical and reliability factors", they suggest that nozzles having throat diameter less than 250 microns are undesirable6). Afterwards several studies have been conducted to address the low Reynolds number regime for supersonic nozzles, for chemical nozzles and for low-density hypersonic nozzles.

The science of nozzle flow is advanced when Rothe made electron beam measurements of the viscous flow within the nozzle. These nozzles have 2.5 mm and 5.0 mm throat diameter and are run at chamber pressures of 0.15 psia6). This study has shown that the inviscid core is very small at throat Reynolds number of 500. The inviscid core disappears and the flow becomes fully viscous as the Reynolds number approaches 3005).

Recently a number of experimental and numerical investigations have various flow and performance aspects of microfabricated two-dimensional micronozzles. In general, the performance of circular cross-section nozzles is higher than the non-circular ones. This is due to higher friction and heat transfer losses for non-circular nozzles. Zakirov7) explains the reasons as follows: Formation of boundary layer at the flat end wall leads to higher friction losses since increases in boundary-layer thickness is not compensated by flow channel expansion in that direction. For non-circular nozzle, cross-sectional perimeter-to-area ratio is always higher than that of for circular one. This suggests higher nozzle wall surface area in contact per same volume of fluid flow, for non-circular nozzle, and results in higher friction and heat transfer losses. Therefore, we adopt circular axisymmetric micronozzles instead of 2-D micronozzles.

Design of Cold Gas Microthruster

In cold gas micropropulsion, thrust is produced by ejecting mass (i.e. gas) at high speeds through the nozzle. The thrust is determined by Newton's second law of motion under the assumption of constant gas property. Thrust is

$$F = \dot{m}c \qquad (1)$$

Using the definition of thrust coefficient, thrust can be expressed by eqn.(2).

$$F = \lambda C_F P_C A_t \tag{2}$$

$$\lambda = \frac{1+\cos\alpha}{2} \tag{3}$$

$$C_F = \sqrt{\frac{2\gamma^2}{\gamma-1}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}\left[1-\left(\frac{P_e}{P_C}\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{4}$$

Thrust chamber pressure can be varied from 2 to 20 bar. To investigate scale down effects, we change the nozzle throat diameter: 2.0, 1.0, 0.5 and 0.25mm. Predicted thrusts are presented in Table 1. And mechanical design of cold gas micronozzle is given in Fig. 3.

Table 3. Predicted thrust(gas: N_2)

Nozzle throat diameter [mm]	Pc [bar]		
	2.0	10.0	20.0
	Thrust [N]		
0.25	0.0075	0.0615	0.1343
0.5	0.03	0.246	0.5374
1.0	0.1201	0.9839	2.1494
2.0	0.4805	3.9357	8.5976

Thrust Measurement Method

The mechanical methods of low thrust measurements are categorized in Table 2[8].

The ideal thrust measurement systems have an infinite stiffness. However, the difficulty when designing low thrust and dynamic measurement system is the dilemma met between sensitivity and band width. To obtain a high natural frequency system, one must stiffen the mechanical part that causes a decrease in thrust measurement sensitivity.

With strain gage sensors and signal conditioning circuitry, thrust measurement system is designed and will be fabricated. Strain gage sensor has been employed for thrust measurement because of its simplicity, cost effectiveness, linearity, repeatability and good stability[6]. However, the deflection-thrust relation is affected by the temperature of the elastic member. Also, the thrust signal can be easily disturbed even by small facility induced vibration. So natural frequency is measured and then its bandwidth is eliminated for measuring thrust. And each column forms full bridge which compensates the thermal effects. Signal conditioning circuitry and low pass filter are shown in Fig. 4. And a schematic diagram of the thrust measurement system is shown in Fig. 5. It consists of two plate, four columns and eight bars. The critical load P, minimum load required to make columns buckle, can be determined using equation (5).

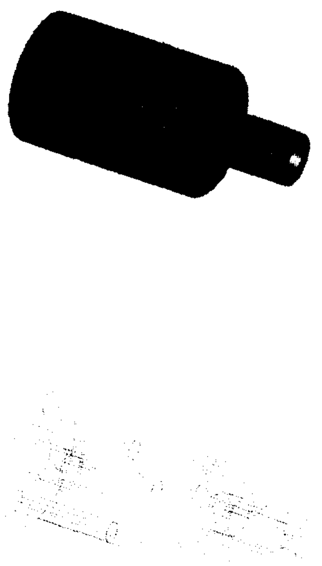

Fig. 3 Cold gas thruster design

$$P = 4\pi^2 EI/L^2 \tag{5}$$

When Thrust measurement system is critically loaded, even a small force in the traverse direction produces a large deflection of the column.

The thrust measurement system has four full bridge. The two gauges which undergo tensile strain form one fair of opposite arms of the bridge and the other two gauges which undergo compressive strain form the other pair of opposite arms of the bridge. The full bridge produces a maximum differential output voltage for a given deflection.

The bridge output is connected to a instrumentation amplifier, namely INA 125. This is a low power, high accuracy instrumentation amplifier with a precision voltage reference. A single external resistor sets any gain from 4 to 10,000. The output of the INA 125 is connected to OP 27. The output are initially nullified by OP 27. The output is connected to low pass filter. And then signal will be connected to computer .

Table 4. Mechanical methods of low-thrust measurement

Measured	Balancing force	Structure	Advantage	Problem
Momentum flux of exhaust plume	gravity (exerted on target)	target	simple	change of exhaust plume
Reaction force	elastic force	elastic member	quick response	thermal effects, Vibration
Reaction force	gravity	balance	without nonlinear relation (no deflection), small thermal effect	friction at fulcrum, slow response
Reaction force	gravity	pendulum	small thermal effect	friction at fulcrum, slow responce

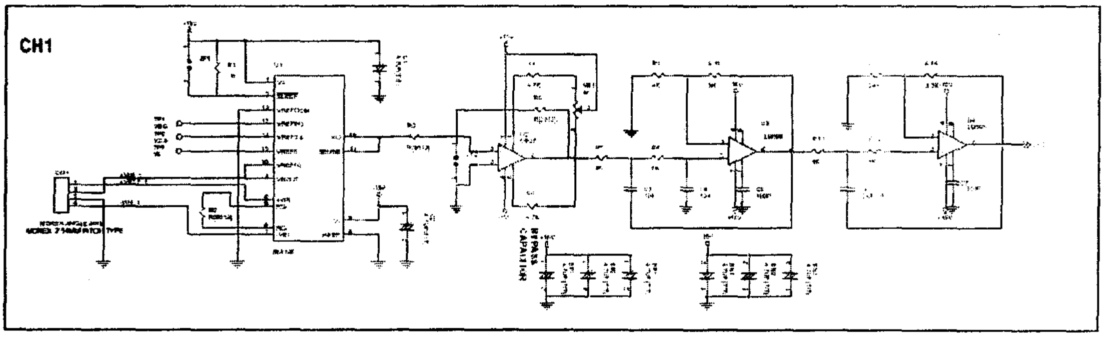

Fig.4 Signal conditioning and low pass filter circuitry.

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Nomenclature

I_{bit}	the minimum impulse obtained once the thruster is given the command to fire
$\dot{m}$	mass flow rate
c	effective exhaust velocity
P_C	chamber pressure
C_F	thrust coefficient
At	nozzle throat area
E	Young's modulus
I	moment of inertia
L	length of the column
α	nozzle divergence half angle
γ	ratio of specific heats
λ	thrust correction factor