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Development of CAMUI Hybrid Rocket to Create a Market for Small Rocket Experiments

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ABSTRACT

By introducing various innovative ideas, the difficult-to-develop small hybrid-type rocket is successfully developed. The main purpose is to drastically reduce the cost of rocket experiments and thus attract potential users such as metrological and microgravity researchers. A key idea is a new fuel grain design to accelerate the gasification rate of solid fuel. The new fuel grain design, designated as CAMUI as an abbreviation of “Cascaded Multistage Impinging-jet”, is that the gas flow repeatedly collides with the solid fuel surface to accelerate the heat transfer to the fuel. To install a regenerative cooling system using cryogenic liquid oxygen as coolant in a small launcher, the authors devised a valveless supply system (with no valves in the liquid oxygen flow line). Four serial successful launch verification tests by 10 kg vehicle equipped with a 50 kgf thrust CAMUI motor have shown the feasibility of the motor system. The meteorological observation model of 400 kgf class motor is under development and the development of microgravity experiment class of 1.5 to 2 tonf motor will follow subsequently. The authors plan to complete the development of the 400 kgf class motor for meteorological observation model by the end of FY2005.

1. INTRODUCTION

A joint research team of universities and private companies in Hokkaido, Japan has been organized to develop a small-scale reusable launch system based on hybrid rocket. The main purpose is to drastically reduce the cost of sounding rocket experiments and thus create and expand a market for small rocket experiments by attracting potential users who hope to use rocket experiments but cannot afford heavy prices of conventional small sounding rockets.

The reason for the expensive cost of rocket experiments is the high cost of small rockets. The small rockets used for ballistic launch experiments are all solid rockets that use explosives for their propellant. This is because the weak points with liquid rockets, such as their complex structure and heavy weight, become more prominent in smaller rockets. The structure of solid rocket is quite simple: It is basically a cylinder full of explosives with a nozzle and stabilizing fins mounted on its body. Both material costs and manufacturing costs are inexpensive. Nonetheless, the price of a small rocket is expensive. This is because it uses explosives for propellant. The management cost of the explosives absorbs the major cost of a solid rocket. If we can develop a small rocket free from explosives, we can drastically reduce the cost of rocket experiments and thus attract potential users. From this viewpoint, our group is proceeding with research and development of hybrid rockets using a combination of liquid and solid for propellant.

Figure 1 shows the basic concept of a typical hybrid rocket. Generally, in hybrid rockets, solid side contributes as the fuel. A typical design of the solid fuel is a cylinder with a central port in which oxidizer and combustion gas flow. Since hybrid rocket does not use explosives, a large reduction in manufacturing and operation costs becomes possible. In addition, since no liquid fuel is necessary, there is no need to handle dangerous materials. The idea of the hybrid rocket is old, dating back to the 1930s [1]. However, the crucial problem of solid fuel, slow combustion due to the low regression rate, has remained unresolved, and no hybrid rocket has been in practical use as a small rocket launcher. While velocity of 9.8m/s is lost per second to the earth's' gravity, the problem of slow combustion is decisive.

2. CAMUI HYBRID ROCKET

To enhance the regression of the burning surface and speed up the combustion of solid fuel that is essential for its practical use in a small launcher, the authors devised a new combustion method [2,3]. By separating conventional cylinder-shape solid fuel with a central port into multiple cylinder blocks, the fore-ends of all cylinder blocks burn concurrently. ”CAMUI” was named by abbreviating this new method “Cascaded Multistage Impinging-jet.”

Figure 2 shows the combustion-chamber concept for CAMUI hybrid rocket. Liquid oxidizer injected into the combustion chamber collides with the fore-end of the first stage of fuel blocks to generate combustion gas. The gas flows downstream through two ports in the first block and, then, collides with the fore-end of the second block. The aim of this mechanism is to accelerate heat transfer to the solid fuel using the impinging jet. By the method CAMUI adopted, one can increase the thrust density (i.e., thrust per unit volume of the combustion chamber) without limit theoretically by segmenting the fuel block into a number of thin blocks. In practice, the mechanical strength of the blocks and pressure loss present an upper limit. In the authors’ experience, it is possible to increase the thrust density (i.e., thrust per unit volume of the combustion chamber) to at least three times more than the conventional type. Thus, the downsizing and increasing thrust of hybrid rocket to solid-rocket levels become possible.

To use the hybrid rocket as a small launcher, the small body must incorporate the liquid-oxygen supply system besides the increase of thrust density. Liquid oxygen is nonexplosive and nonhazardous, and, furthermore, one can expect to obtain high specific impulse from it. However, it is not easy to embed the supply system for liquid oxygen, a cryogenic liquid, into a small body. Take a valve for example: a cryogenic valve is larger than a common valve. Moreover, differing

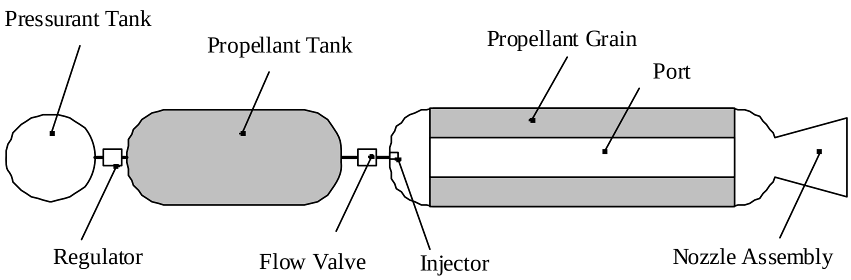

Fig. 1: Basic concept of conventional hybrid rocket.

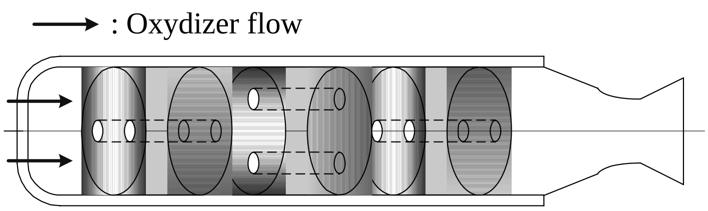

Fig. 2: Basic concept of CAMUI combustion chamber.

from the conventional type, the combustion chamber's sidewall is under heavy thermal attack from the flame in the CAMUI system and thus requires cooling. In short, one has to embed a supply system equipped with a regenerative cooling system using cryogenic liquid in a small body.

As a result of our deliberation on downsizing the valve and simplifying the regenerative cooling line, the authors devised a valveless supply system (with no valves in the liquid oxygen flow line). Fig. 3 illustrates the concept. The liquid-oxygen tank is a coaxial cylinder wrapping around the combustion chamber. The space between the liquid-oxygen tank's inner sidewall and the combustion chamber's outer sidewall is the flow channel of liquid oxygen. Liquid oxygen flows through the orifice at the bottom of the tank, and then goes upward while cooling the chamber's' sidewall, before being injected into the chamber by an injector. There are no valves in the flow path from the liquid-oxygen tank to the combustion chamber. The regenerative cooling path is also very simple. Since the top of the liquid oxygen is under the injector, unless the high-pressure helium flows into the tank to pressurize liquid oxygen, the supply of liquid oxygen to the combustion chamber does not start. A three-way valve connects the pressurizing helium tank to the liquid oxygen tank. Before supplying the liquid oxygen, the valve prevents pressure rising in the liquid oxygen tank by releasing gasified oxygen into the combustion chamber.

Figure 4 shows the steps to start the motor: Before ignition, gasified oxygen in the liquid-oxygen tank is released into the combustion chamber to fill the chamber. This allows easy ignition by applying electricity and heating the nichrome wire attached to the fore-end face of the first block. Just after the moment of ignition, there is little thrust because the oxygen is supplied only by natural gasification. Just after confirmation of the ignition, the three-way valve switches to close the path releasing gasified oxygen into the combustion chamber and, simultaneously, to open the line connecting the high-pressure helium tank with the liquid oxygen tank to start supplying liquid oxygen. In the actual lift off launch procedure, the timing of this operation corresponds to the time of liftoff. Thus, we call the three-way valve the launch valve. By switching the valve, the thrust suddenly increases to normal combustion mode.

3. LAUNCH VERIFICATION TEST

To confirm that the valveless supply system operates normally under a launch environment, the authors conducted a launch-verification test. Figure 5 shows the flight model motor for the launch experiment. The combustion chamber is 50 mm in inner diameter and 350 mm in length. It mounts seven 35-mm high acrylic blocks and the total acrylic fuel weight is 450 g. The liquid oxygen tank is a coaxial cylinder wrapping the combustion chamber. The engine's' basic structure is almost the same as that Fig. 3 shows. Because of the safety reasons at the launch site, the maximum altitude should be less than 1 km. To fulfill this restriction, the amount of liquid oxygen limited the burning duration. By 500 g amount of liquid oxygen the motor produces thrust about 3.5 seconds.

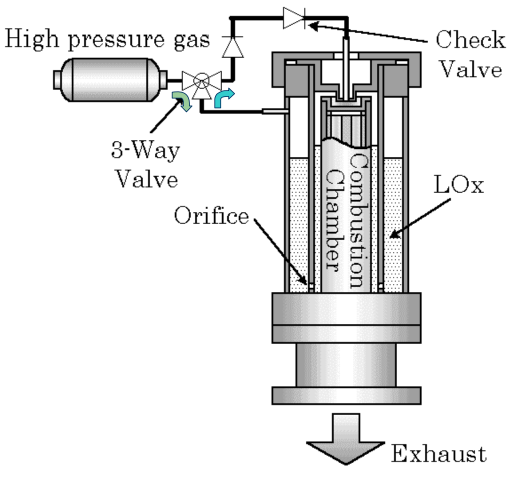

Fig. 3: Valveless LOX feed system.

(a) LOX filling (b) Ignition (c) LOX supply start (d) Steady combustion

Fig. 4: Steps to start the motor.

Before the launch experiment, static firing tests were made to obtain the thrust history the motor generates. Figure 6 shows pressure histories of the liquid oxygen tank (upstream of the throttling nozzle), upstream of the injector (downstream of the throttling nozzle), and the combustion chamber. The pressure difference between the upstream and the downstream of the throttling nozzle gives the flow rate of liquid oxygen. The burnout occurred 4.14 seconds after beginning the pressurization of the liquid oxygen tank. Note that the pressures of the upstream and the downstream of the throttling nozzle coincide with each other at burnout, meaning that all of the liquid oxygen ran out and the flow rate became zero.

Figure 7 shows histories of thrust, and flow rates of liquid oxygen and fuel. The flow rate of fuel means the gasification rate of the fuel, which one can estimate from the chamber pressure and the flow rate of liquid oxygen. Initially the thrust is about 50 kgf and then decreases with time until about 40 kgf at burnout. About 370 g of fuel burned out, which corresponds to about 80% of the initial fuel weight of 450 g. Serial launch experiments were conducted four times in March 2002, January 2003, March 2004, and March 2005 at Taiki, Hokkaido, Japan. All of them were successfully completed.

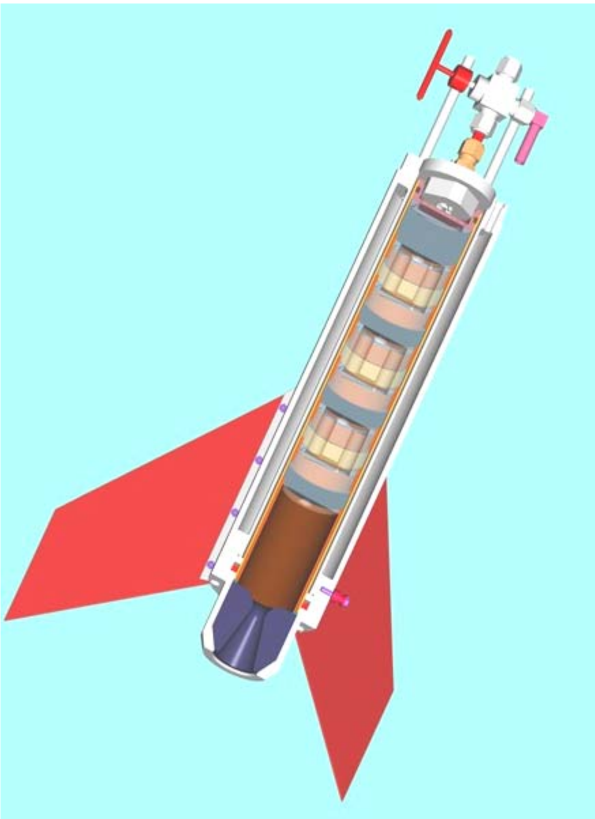

Fig. 5: 50 kgf class flight model motor.

4. CURRENT STATUS

The authors are now proceeding with development of a larger-size CAMUI hybrid rocket for practical use as a small launcher for meteorological observations and microgravity experiments. Table 1 summarizes basic data of experimental small CAMUI launchers. Initial weight and the weight at recovery are about 60 kg and 30 kg respectively with the meteorological observation model, and about 300 kg and 150 kg with the microgravity experiment model. The inner diameter of the combustion chamber is 145 mm for the meteorological observation model and 280 mm for the microgravity experiment model, generating 400 kgf and 1.5 tonf thrusts respectively. Both of them use polyethylene as solid fuel.

Serial static firing tests of 400 kgf class motor have just begun. Figure 8 shows the LOX feed system of the test motor. The pressure difference between the LOX tank (P1) and the downstream of the orifice (P2) gives the LOX flow rate. Figures 9 and 10 show an example of the test data,

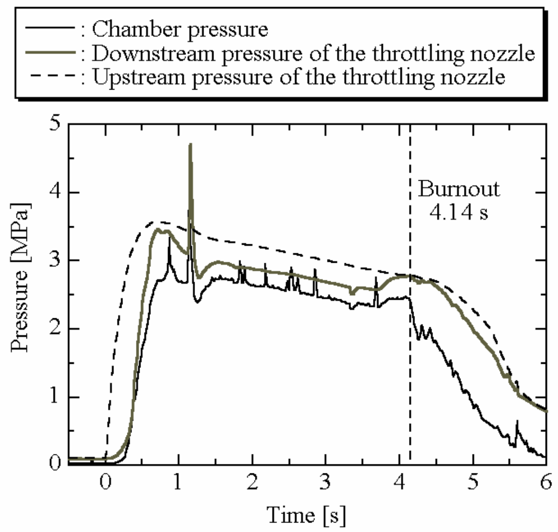

Fig. 6: Pressure histories.

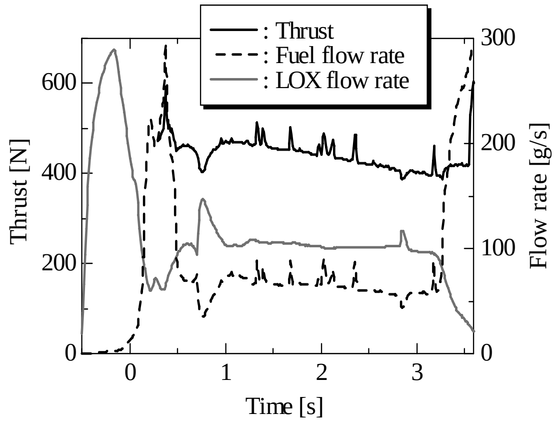

Fig. 7: Histories of thrust and flow rates.

histories of thrust and pressure in Fig. 9 and histories of LOX and fuel flow rates in Fig. 10. Fuel flow rate is calculated from histories of pressure and LOX flow rate by the reconstruction method [4]. Figure 10 shows the validity of the method, showing good agreement of thrust histories obtained by a thrustmeter and the reconstruction method.

The authors plan to complete the development of the meteorological observation model by the end of FY2005 and, subsequently, the development of a microgravity experiment model will follow in three years. The launch cost will be one to two million yens for the meteorological observation model and less than five million yens for the microgravity experiment model.

5. CONCLUSIONS

Serious cost reduction is possible by developing a small rocket that does not use explosives for propellants. By introducing CAMUI grain design and the valveless liquid oxygen feeding system, the difficult-to-develop small hybrid-type sounding rocket is successfully developed. The hybrid rocket breaks the limits of conventional solid-propellant small rockets and can respond to a variety of needs of weather observation, microgravity experiments, etc., with low launch costs.

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Table 1: Basic data of experimental small launchers.

	CAMUI-400 kgf	CAMUI-1.5 tonf
Propellants	Polyethylene/LOX	
Specific impulse [s]	279	
Thrust [kgf]	400	1500
Diameter [mm]	~240 mm	~400 mm
Payload weight [kg]	4.0	10~15
Total weight [kg]	60	300
Propellant weight [kg]	30	150
Maximum altitude [km]	60	110
Application	Meteorological observation	3 min. Micro-gravity experiment

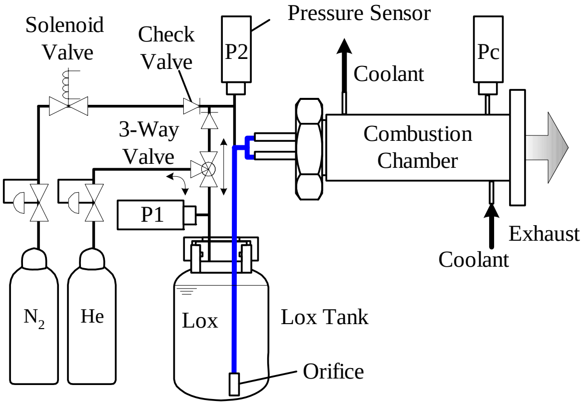

Fig. 8: LOX feed system of the 400 kgf class static firing test motor.

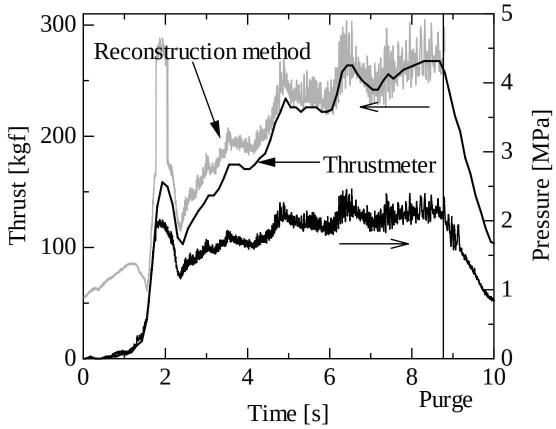

Fig. 9: Histories of pressure and thrust.

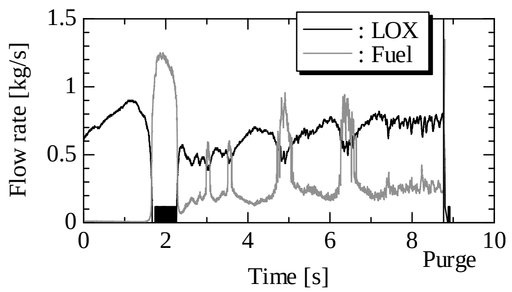

Fig. 10: Histories of LOX and fuel flow rates.