Research paper

Thermite as a chemical heat source for the science payload

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387

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Abstract

The neutral wind in ionosphere region has been the target on the earth environmental research. Chemical tracer releases represent the most widely used technique for in situ neutral wind measurements. The wind velocity is measured optically from the ground and lithium vapor is generally employed as the tracer. The science payload for the research is required that lithium is converted from a solid phase into vapor which is injected into the space throughout the sounding rocket experiment. The payload therefore should be loaded with thermite as the heat source for vaporizing lithium. Thermite is known as a powder mixture of a metal and a metal oxide without binder that undergoes the redox reaction with high heat energy release. That is why thermite is selected as the chemical heat source for the payload. The rocket-borne Lithium Ejection System (LES) is a chemical release device that has been developed for the Japanese space research program.

The ignition and combustion characteristics of thermite were studied to develop the device. Thermite usually consists of iron oxide and aluminum and burns comparable to explosives. Therefore the combustion properties for the device should be improved. This paper will discuss the composition and the reaction properties of thermite. Finally, the design of the device was confirmed by the full scale ground test.

Keywords : thermite, condesed phase reaction, redox reaction

1. Introduction

The environment of the thermosphere and ionosphere region is still the target for the scientific researches. The neutral wind in the region is a physical process. The wind at the altitude from 100 km to 300 km is usually observed with the optical techniques using chemical releases. Many kinds of metal vapor releases have been used in sounding rocket experiments as tracers of the neutral or ion motions in the thermosphere and ionosphere, including sodium, lithium, barium, and strontium[1)-4)]. Some of the earliest experiments involved the use of lithium vapor as a neutral tracer[5)-8)]. Both sodium and lithium trail releases were used in the early days of sounding rocket experiments in the 1960's. Both types of releases require solar illumination to make them visible. There has been renewed interest in the lithium release technique in the last few years as a way to extend thermosphere wind profile measurements. Lithium is a solid at room temperature, so a gas phase release requires rapid vaporization of the metal to make a cloud at an intended altitude. The release canister is designed to produce a high -heat chemical reaction without gaseous products. The lithium canister in the early experiments had a mixture of thermite, usually iron oxide and aluminum, and lithium flakes or pellets. However, since the system did not satisfy the safety requirements of the Japanese sounding rocket, the mechanical design should be varied considering the burning characteristics of thermite.

Thermite is currently categorized as a non-explosive although the reaction is vigorous and generates high temperature products[9)–12)]. A popular composition for thermite is a mixture of ferric oxide (FO) and aluminum (Al) :

$$Fe_2O_3+2Al \rightarrow Al_2O_3+2Fe \quad (1)$$

Generally, this reaction product, iron, is in the form of high temperature liquid. Since most of the chemical heat of thermite reaction is accumulated in the condensed phase products, their temperature will increase to values up to 3000 K[13)]. The initiation of thermite reaction requires making hot spot by a chemical reaction because Al usually is activated chemically at above the melting temperature, 933 K[14), 15)].

In our concept, thermite for the payload can be ignited by pyrotechnics and burned at a sufficiently high temperature to vaporize the lithium. Due to the chemical property of lithium, thermite should be loaded independently in the canister at least.

The Lithium Ejection System (LES) described here is an updated payload canister design created to support the space research program in Japan. This paper introduces LES design and discusses the optimization of thermite composition.

2. Objective

The objective of this research is the optimization of thermite composition for the science payload. Since the boiling temperature of lithium in an atmospheric pressure is 1623 K, the requirement of the reaction products temperature should be at least 1700 K. The duration of the capability is defined more than 15 seconds based on the scientific requirement for the Japanese experiment. Moreover, the mechanical design of the chemical release device should be updated to satisfy the safety standard for the Japanese sounding rocket. The composition and reaction properties of thermite should also be investigated for the design. The burn rate characteristics of thermite and the temperature of the reaction products were evaluated experimentally. The composition of thermite and the metal particle size were chosen as parameters for the investigation of the burning characteristics. Based on the information from these results, the ground test was conducted to confirm the design of the chemical release device.

3. Outline of lithium ejection system

Figure 1 illustrates the design of LES. Main components are the steel canister, exhaust tube, safe and arm device and the pyrotechnics for ignition.

Thermite is loaded into the canister with a certain level of pressure. The canister has an inner tube as a holder for the chemical tracer metal. Accordingly, both materials can be loaded separately. The diameter of the canister was 160 mm and the height was 120 mm. The dimension of the inner tube was 60 mm in diameter and 100 mm in length and the tube with small holes can be loaded with more than 120 g of lithium.

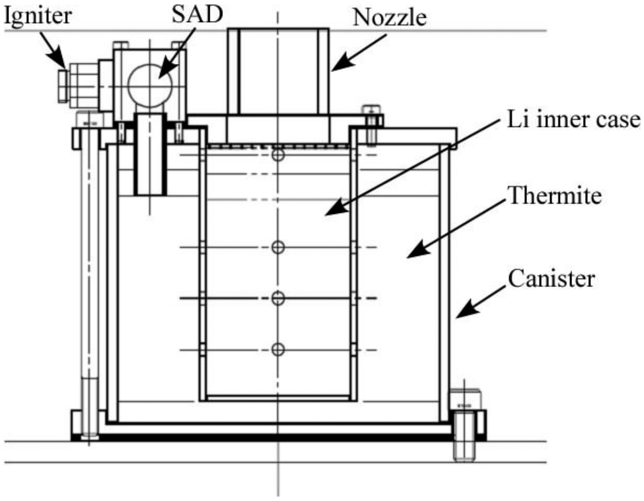

Figure 1 Mechanical design of LES.

The device required a high temperature chemical heat source to vaporize the metals. Thermite reaction is basically a gas-less chemical reaction which generates hot condensed phase products having the potential to vaporize some light metals. The thermite used in the payload canister has to produce sufficient heat to vaporize all of lithium. The hot liquid product passes through the holes of the inner tube into the case and contacts with lithium directly. Then, the lithium vapor is generated effectively without chemical reactions and is ejected from the payload through the exhaust tube without delay. An important difference between the current device design and that used in earlier experiments is that the lithium is loaded into the canister separately rather than being mixed with the thermite. This both enhances the ground safety for handling and storing the devices throughout the rocket launch operation and produces flexibility in replacing the lithium with other chemical tracers. Based on the safety requirement, the Safe and Arm Device (SAD) was equipped to prevent the hazardous situation caused by unexpected firing of the pyrotechnics.

4. Thermite composition study for LES

4.1 Sample composition

For the composition design of the thermite, the mixture ratio between FO and Al, and the particle diameter of metals were employed as parameters. Thermite sample composition is listed in Table 1.

The mass ratio of 10.0 for FO was constant for all samples. MMR was defined as the metal mass ratio of the mixture ; e.g., MMR = 2.00 means that the composition of the sample is FO / Al = 10.0 / 2.0 in mass ratio. Since the particle diameter may have an impact on the burn rate of thermite, three different Al particle diameters, 10, 25 and 45 μm, were prepared for these tests. Moreover, an alloy of Al and Mg (MgAl), known as magnalium, was also used as a metal component, and their particle size was 45 μm in diameter. Magnalium is widely used in pyrotechnics and the ignition temperature of the alloy is lower than that of Al particle because MgAl has a lower melting

Table 1 Composition of the thermite samples

MMR (Al / MgAl)	Al (F/10 μm)	Al (M/20 μm)	Al (C/45 μm)	MgAl (45 μm) Mixture Ratio [%]
2.00 (2.00/0)	F200	M200	C200	0
2.50 (2.00/0)	F250	–	–	0
3.00 (2.00/0)	F300	–	–	0
3.38 (2.99/0)	F338	–	–	0
2.00 (1.00 / 1.00)	F200MA	M200MA	C200MA	50
2.50 (1.25 / 1.25)	F250MA	–	–	50
3.00 (1.50 / 1.50)	F300MA	–	–	50
3.38 (1.69 / 1.69)	F338MA	–	–	50

MMR : Metal Mass Ratio
F : Fine, M : Middle, C : Coarse

temperature of 723 K[16]. It is expected that MgAl improves the ignition characteristics of thermite composed of FO/Al. For example, the F300 and M200MA sample correspond to FO/ Al (10 μm)/ MgAl = 10/3/0 and FO / Al (25 μm) /MgAl = 10/1/1in mass ratio, respectively.

4.2 Measurement of burn rate and reaction temperature

Thermite mixture powder was molded in an acrylic tube whose dimension was 19 mmϕ in diameter and 50 mm in length, and the case thickness was 3 mm as shown in Figure 2.

The thermite powder was pressed with a pressure of 15 MPa and the sample density resulted in approximately 1.7 x10^3 kg/m^3. In order to detect the combustion front and measure the burning rate, thermocouples whose wire diameter was 100 μm were embedded in a sample at three locations. The burn rate was evaluated by using the distance between the tip of sensors and the time of the signal rising from each of the sensors. The temperature of the reaction products was measured directly with W-Re thermocouples whose wire diameter was 100 μm. The junction bead of the thermocouple was embedded in the center of the samples. The burning test was conducted three times in air.

5. Results and Discussion

5.1 Burning rate characteristics of thermite

Figure 3 shows the profile of the thermocouple signal throughout the burning test.

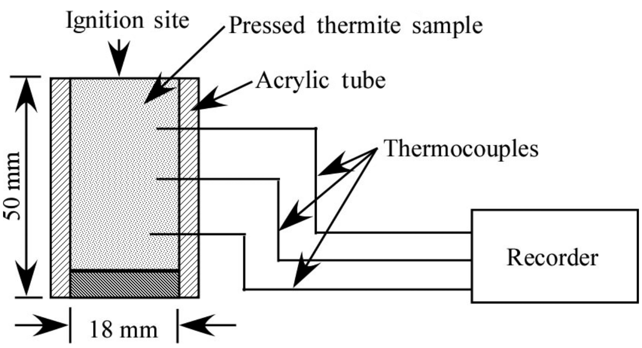

Figure 2 Sample preparation and the setup for the burn rate measurement.

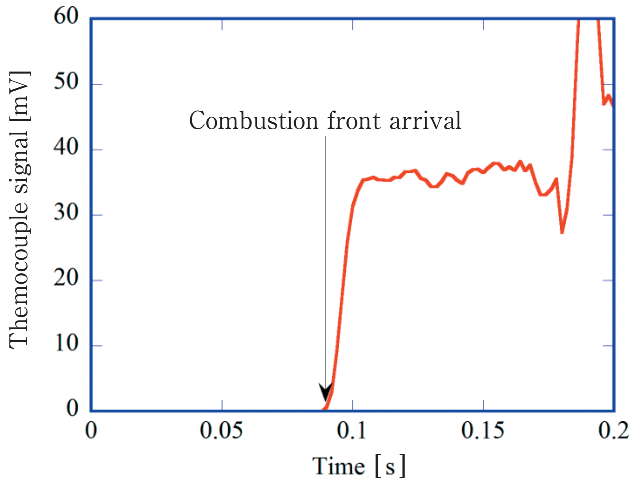

Figure 3 Thermocouple signal profile.

The voltage rose immediately when the reaction front reached the thermocouple bead. For this experiment, the arrival time of the reaction front was defined as the time when the voltage exceeded 1.0 mV. Based on the definition above, the burning rate of thermite was estimated as shown in Figure 4.

The burning rate of the sample F200MA showed the minimum value of 7.9 mm/s. At the other extreme, F338 which is the stoichiometric composition, the burn rate increased to 58.2 mm/s. It was found that there was a wide burning rate range created by small modification of the thermite composition. It is suggested that local exothermic reaction may contribute to the burning rate enhancement. The burning rate data was used to estimate the effect of the particle diameter. In Figure 5, the sample containing fine Al showed the highest value, 18.4 mm/s, and the burning rate decreased with increasing Al particle diameter.

In contract, the dependence on the particle diameter for the burn rate was not observed in the sample containing MgAl. Basically, since thermite reaction occurs in a condensed phase, one of the burn rate controlling factors is the specific surface area. The results showed that the particle diameter affected on the burning rate and the coarse particle would be the rate controlling. The dependence of the particle diameter should be verified by

387

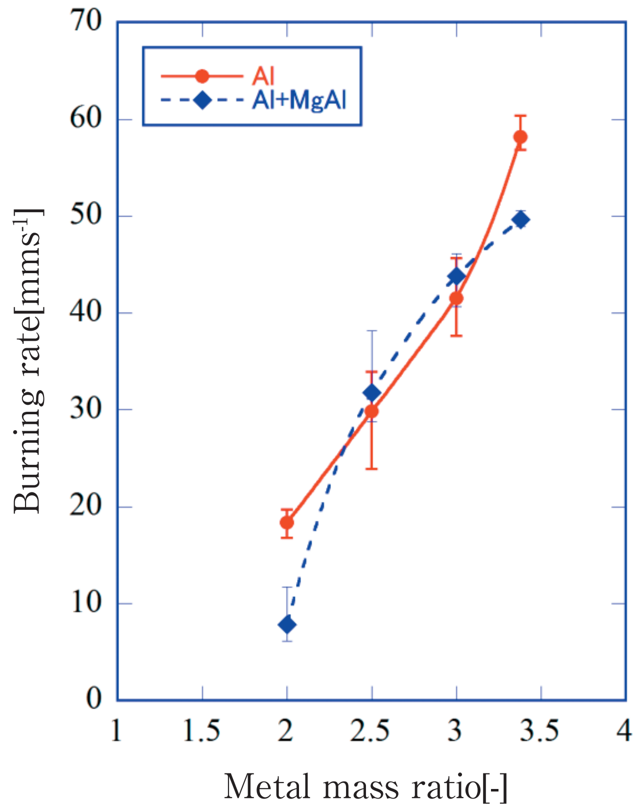

Figure 4 Burning rate characteristics (1).

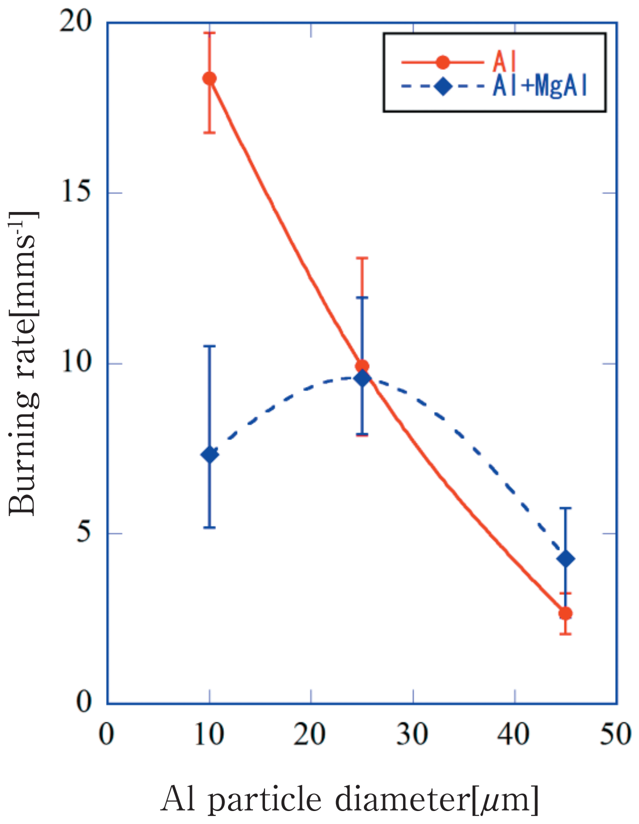

Figure 5 Burning rate characteristics (2).

further experiments using the sample containing fine and coarse of Al particles. It was found that the Al particle size and the mass ratio of Al in thermite are the burning rate controlling parameters.

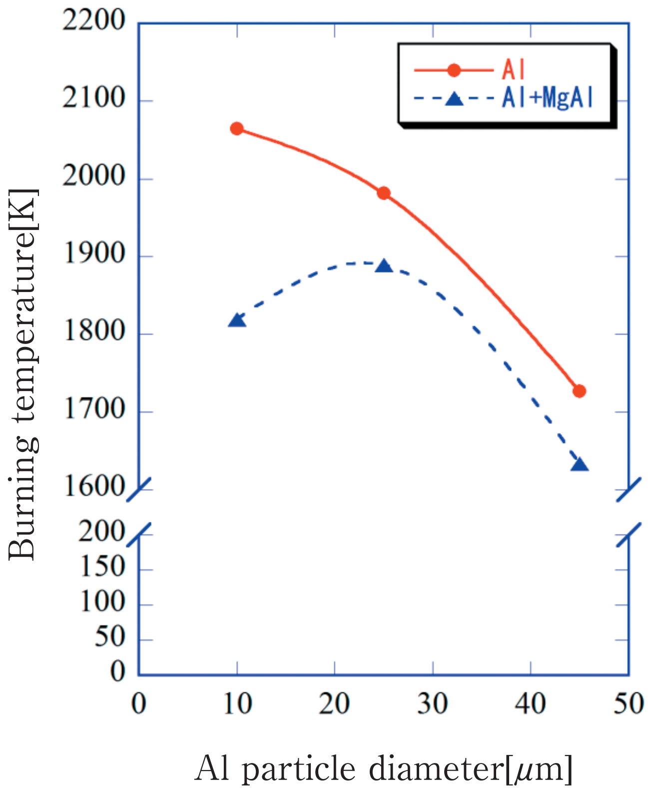

Figure 6 Burning temperature of the combustion products.

5.2 Temperature of the reaction products

The relationship between the temperature of the reaction products and the Al particle diameter is shown in Figure 6.

The temperature for the Al based sample dropped from 2064 K to 1726 K with increasing particle diameter. However, the trend for the sample with MgAl was different, the same as shown in Figure 5, and the maximum value was 1889 K for the particle diameter of 25 μm. In both cases, the results showed that the temperature exceeded the boiling temperature of lithium, 1623 K, for any composition. From the results of the burning rate and temperature measurement, the composition F200MA (MMR = 2.0 with 10 μm of Al and Mg/Al) has the potential to control the burning rate and the products temperature with a small composition change. For LES design, the composition was selected as a candidate considering the system requirements.

6. Ground firing test for the design confirmation

The burning test was conducted to confirm the design of LES. The specifications for the LES including the gas ejection delay and the duration are characterized by the ground test data and are referred to the time-line of events for the rocket launch. Before the burning test, LES run through the vibration test under the simulated flight environment of the sounding rocket.

The best way to understand the properties of LES is to measure the temperature profiles of the exhaust tube surface and the canister. As shown in Figure 7, the thermocouple, T1, was fixed on top of the exhaust tube surface and the temperature profile was measured throughout the test.

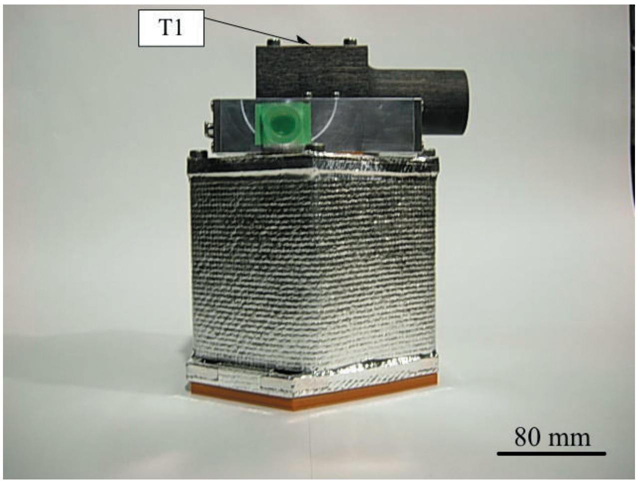

Figure 7 Temperature measurement point.

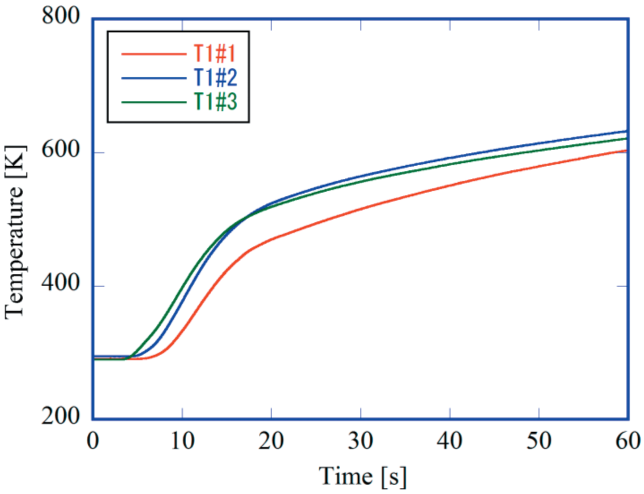

Figure 8 Temperature profile of the exhaust tube.

The lithium vapor ejection delay was estimated by using T1 profile because the temperature gradient changed by the heat input from the vapor. The lithium gas release is caused by the contact with the hot thermite reaction product, therefore the ejection delay is fundamentally involved in the mechanical design.

Three firing tests were successfully conducted as shown in Figure 8.

Two inflexion points observed in the results usually involve the change in state for the heat input from the vapor. The temperature increased rapidly when the vapor ran through the tube. Considering the heat conduction to the tube material, the vapor launch time should be earlier than the calculated results. The delay and the duration could also be estimated by the VTR capture data as shown in Figure 9, which had a recording rate of 30 fps.

The data were compensated with the constant, $\eta = 0.85$. The data from the temperature measurements were compared with the data of the optical method and the result are listed in Table 2.

Although the accuracy of the optical data was dominant over the temperature measurement, the error of the analytical results from the thermocouple was within 10%. As a result, the average ejection delay of the three tests was X + 5.5 s with an error of 1.1 s.

Figure 9 Lithium gas ejection during the ground test.

Table 2 Results of lithium gas ejection delay

	T_{TC} [s]	T_{OPT} [s]	Error
Test#1	6.62	6.3	+5.1 %
Test#2	5.53	5.1	+8.9 %
Test#3	4.51	4.9	−7.9 %

T_{TC} : Data from thermocouple
T_{OPT} : Data from video capture

7. Summary

LES described here was tested successfully in Japan on the flight of sounding rocket S-520 in August 2007. Three lithium releases were carried out during the flight, and the vapor was released at altitudes from 150 km to 250 km. The important parameters for the design were the burning rate and the reaction product temperature. The results showed that the burning rate of thermite was affected by the composition and the particle diameter of Al and the coarse Mg/Al particle suppressed the burning rate of thermite. The temperature of the reaction products is also controlled by the mixture ratio of the thermite. The result of ground test was provided the lithium vapor ejection characteristics; the average exhaust delay of lithium vapor is X + 5.5 s with an error of 1.1 s.

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宇宙科学観測機器用テルミット剤の研究

羽生宏人*，岡田実**，伊藤正則**，野副克彦**，川野達也**，松本伸二**，吉田裕二*

熱圏における中性風は重要な研究対象であり，この観測から地球環境を知る上で重要な情報を得ることができる。中性風のその場観測には化学物質放出手法が広く用いられてきており，特に高高度の風速計測にはリチウムガスを用いることが多い。放出後，化学物質によって散乱する太陽光を地上から観測する方法が一般的である。この研究に用いられる科学観測機器には観測ロケット実験中に速やかにリチウム等の固体物質をガス化する機構を付与することが求められる。従前からガス化の熱源にテルミット剤が採用されている。テルミット剤は金属と金属酸化物の混合物として知られ，酸化還元反応で多量の熱を発生させる材料である。以上の背景に基づいて，ロケット搭載型のリチウム噴射装置を日本の宇宙科学実験用に開発した。

本研究では，装置開発のためにテルミット剤の燃焼特性に関する研究を行った。酸化鉄とアルミニウムで構成されるテルミット剤は一般に激しい反応を示すが，研究によって装置に適した組成を開発した。本稿では主にテルミット剤の組成と反応特性の相関および装置の概要について述べる。

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