# Magnesium energy cycle system for the power product

**Yasutaka Sakurai**[1], **Takashi Yabe**[2], **Kazunari Ikuta**[3],
**Manabu Ishioka**[1], **Yoichi Ogata**[1], **and Yuji Sato**[2]

[1]*Department of Mechanical Science and Engineering (Yabe Lab), Tokyo Institute of Technology,*
*2-12-1 Ookayama, Meguro-ku, Tokyo-to 152-8550, Japan*
[2]*Integrated Research Institution, Tokyo Institute of Technology, 2-12-1 Ookayama,*
*Meguro-ku, Tokyo-to 152-8550, Japan*
[3]*Entropia Laser Initiative, Tokyo Institute of Technology, 2-12-1 Ookayama,*
*Meguro-ku, Tokyo-to 152-8550, Japan*

The energy storage of solar radiation with magnesium as an energy reservoir is proposed for renewable energy cycle. Magnesium reaction with water generating hydrogen and residual MgO is used to retrieve energy. Solar pumped laser is used to reduce MgO back to magnesium. This unique reduction process is possible because highly concentrating power density of laser radiation realizes non-equilibrium states of magnesium and oxygen dissociation from MgO and quickly separates each other for avoiding recombination to MgO. The proposed energy cycle consists of three key technologies: power generation by magnesium combustion, reduction of magnesium oxide, MgO, the combustion residue, and solar pumped laser that drives the MgO reduction process. This paper describes the experimental investigation of Mg combustion engine characterization.

*OCIS codes:* 000.2700, 000.4930, 160.3900.

A major part of energy at the present day comes from fossil fuel such as petroleum oil, coal, natural gas, and so on. Especially, petroleum accounts for 52% of total supply of primary energy in Japan. However, fossil fuel will definitely be depleted in future. Carbon dioxide ($CO_2$) gas emitted by combustion of petroleum causes global warming and it is said that seawater surface will rise by 7 m before 2100[1]. For this reason, it is imperative that we need to develop clean energy resource replacing fossil fuel.

Generally speaking, natural energy resources such as solar power, wind power, and geothermal heat power, are unsteady and depend on weather and climate. Although hydrogen-based storage has been proposed, the storage density is very low, the cycle still depends on carbon dioxide, and the production of methanol is not efficient[2]. Therefore we suggest a new clean energy cycle using magnesium (Mg)[3,4].

Mg is the 8th most abundant element on the earth and the 2nd most abundant metallic element in the ocean. Mg generates hydrogen ($H_2$) in the reaction with $H_2O$ at 873 K and emits no carbon dioxide. Produced heat and $H_2$ generate electric power and thrust power using a turbine, piston engine, and fuel cell. MgO, which is the residue after Mg combustion, can be reproduced to Mg using sunlight laser. Once energy is stored in Mg, the cycle does not depend on weather, climate, and hours of daylight.

We have succeeded in a laser oscillation at wavelength of 1.06 $\mu$m, gathering ray of sunlight to Cr-Nd YAG ceramics using Fresnel lens and secondary collecting optics[5]. The MgO is efficiently reduced using laser ablation generated by focused laser[6]. In this paper, magnesium injection cycle (MAGIC) engine that utilizes the Mg reaction with $H_2O$ to generate power is described. Choosing proper conditions on Mg and $H_2O$ mixing ratio and the shape of Mg, the rate of heat release and $H_2$ generation can be controlled.

In this section, we describe an engine mode where the rate of Mg reaction with water is rather moderate so that hydrogen is generated without reacting with oxygen. Figure 1 shows the schematics of the experimental setup. Mg plates of 0.3- and 0.6-mm thickness are placed inside reaction chamber. Hydrogen generated is measured by flow meter. The volume of the reaction chamber is 2 L. Water is introduced in the chamber from an upper lid and the speed of water supply can be varied. The Mg is heated by ohmic heating and starts burning with oxygen inside the chamber. When the temperature inside chamber is raised over 873 K[7], Mg is ignited and starts reacting with water. By choosing proper rates of water supply, temperatures of Mg and water can be kept over 873 K and hence additional heating from outside is not required. The reaction of Mg and $H_2O$ generates $H_2$ as shown by reaction (1). The reaction of Mg and $H_2O$ is self-sustained reaction since the reaction is exothermic. In this moderate reaction, the temperature of $H_2$ is kept low and hence $H_2$ does not react with oxygen

$$\mathrm{Mg} + \mathrm{H_2O} \rightarrow \mathrm{H_2} + \mathrm{MgO} + 359.68\,\mathrm{kJ}. \qquad (1)$$

For Mg of 50.0×50.0×0.3 (mm) size, hydrogen generation lasted for 40 minutes from 100-g Mg. Figure 2 shows the time evolution of consumed Mg with 0.3-mm

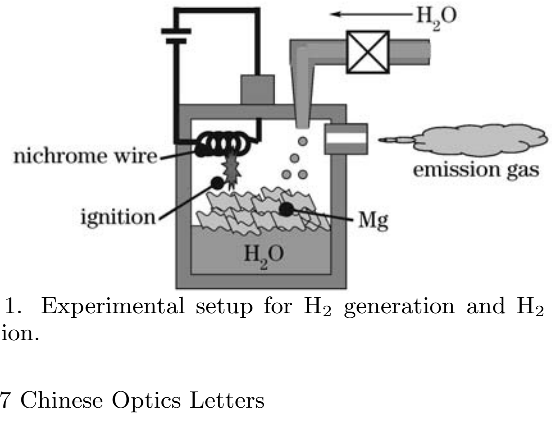

Fig. 1. Experimental setup for $H_2$ generation and $H_2$ combustion.

1671-7694/2007/S1S102-03

thickness, changing the amount of water supply from 10 to 30 ml/min. The reaction becomes faster as the speed of water supply increases. Furthermore, Fig. 2 shows that the reaction speed depends on the thickness of Mg (for the case of 20-ml/min water supply). It can be seen that the thicker Mg plate reduces the reaction speed.

When water is placed inside chamber and the size of Mg is reduced, the reaction proceeds very rapidly and raises the temperature inside chamber over the hydrogen igniting point (873 K). At the outlet of the nozzle, hydrogen then reacts with oxygen to produce water and excess heat by the reaction,

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + 241.83\ \mathrm{kJ}. \qquad (2)$$

The thrust is obtained by $H_2$ combustion because those two reactions proceed at the same time.

In the experiments of MAGIC engine, Mg of 5.0×0.5×0.3 (mm) in average is used. The volume of the reaction chamber is 300 ml and diameter of nozzle is 4.0 mm. Because of large surface area for small size of Mg, the reaction proceeds very fast and finishes in a few seconds, and the speed of exhaust gas is 150 m/s. This gas flow is used to drive a turbine of 100-mm diameter with 8 fins of 30×40×1 (mm) size. In this experiment, we have achieved 8000 rpm as shown in Fig. 3. Instantaneous thrust was deduced from Fig. 4. Emitted materials (propellant) from a nozzle are supposed to be $H_2$, $H_2O$, and MgO. Figure 5 shows the time variation of the torque when the amount of $H_2O$ is kept constantly at 80 ml, and the mass of Mg is changed from 5 to 20 g. The Mg is heated by ohmic heating of nichrome wire and the thrust becomes maximum around 4.0 s. Maximum torque obtained depends on the amount of Mg and its maximum of 0.127 N·m was realized with 20-g Mg.

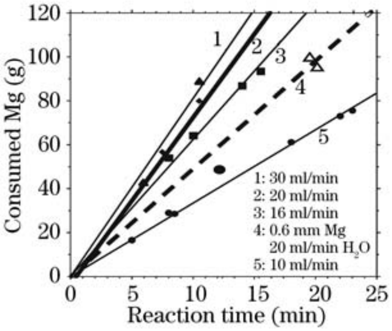

Fig. 2. Reaction time versus consumed Mg in $H_2$ generation experiment with the water supply from 10 to 30 ml/min. Thickness of Mg is 0.3 mm except for the curve 4.

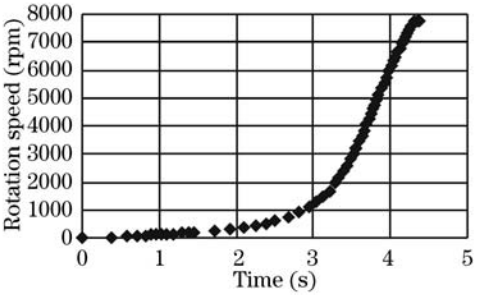

Fig. 3. Rotation speed versus time for 20-g Mg.

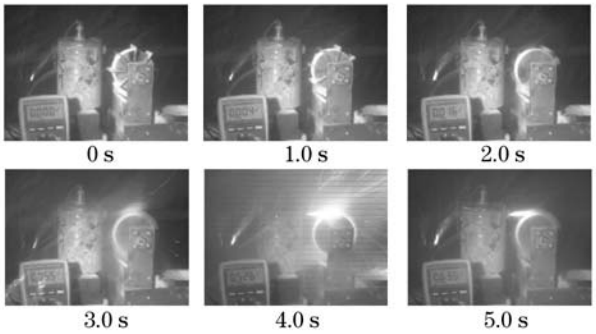

Fig. 4. Rotation of the turbine and emission gases.

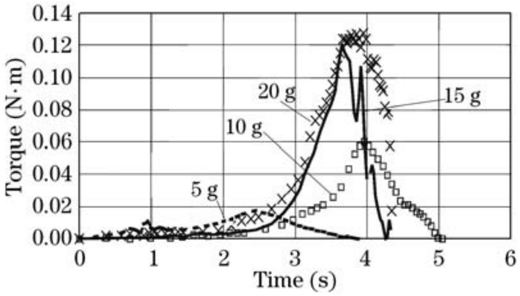

Fig. 5. Time variation of torque for the different masses of Mg from 5 to 20 g.

Figure 6 shows the dependence of torque on Mg and $H_2O$ mixing ratio for 20-g Mg. The water amount was changed from 20 to 100 ml. Torque increases monotonically with water amount until it reaches its maximum and rapidly decreases to zero. Since the total amount of energy produced from Mg-$H_2O$ reaction is determined from the amount of Mg, the increase of water reduces velocity of vapor and momentum increases for the given amount of energy.

The reason of torque increase in proportion to water is analyzed by considering energy balance between laser input and thermodynamic properties of Mg and water (vapor). Let $m_{\mathrm{Mg}}$, $m_{\mathrm{H_2O}}$, and $Q_{(1)}$, $Q_{(2)}$ be the initial masses of Mg and $H_2O$, energies produced by the reactions (1) and (2), respectively. Then from reactions (1) and (2), one can obtain

$$Q_{(1)} = 359.68\ \mathrm{kJ} \times \frac{m_{\mathrm{Mg}}}{24.3}, \qquad (3)$$

$$Q_{(2)} = 241.83\ \mathrm{kJ} \times \frac{m_{\mathrm{H_2}}}{2} = 241.83\ \mathrm{kJ} \times \frac{m_{\mathrm{Mg}}}{24.3}. \qquad (4)$$

If $H_2O$ is steam when Mg reacts with $H_2O$, the energy

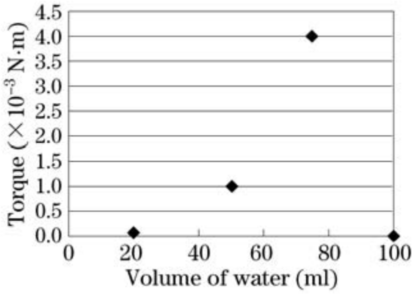

Fig. 6. Relationship between torque and water volume with 20-g Mg.

required to raise the temperature of water inside the chamber up to $T_{\mathrm{in}}$ is given by

$$Q_{\mathrm{w}}^{\mathrm{in}} = \{(373\ \mathrm{K} - T_{\mathrm{initial}}) \times c_{\mathrm{w}} + q^{\mathrm{ev}} + (T_{\mathrm{in}} - 373\ \mathrm{K}) \times c_{\mathrm{vap}}\} \times m_{\mathrm{H_2O}}, \tag{5}$$

where $T_{\mathrm{initial}} = 293$ K is the initial temperature, $c_{\mathrm{w}} = 4.18$ J/(g·K) the specific heat of water, $c_{\mathrm{vap}} = 1.56$ J/(g·K) the isovolumetric specific heat, $q^{\mathrm{ev}} = 2.25$ kJ/g the latent heat of water boiling. Here, we set $T_{\mathrm{in}}$ to the temperature of $H_2$ ignition, 873 K, and $T_{\mathrm{out}}$ to the temperature of experimental result, 1773 K. The energy $Q_{\mathrm{w}}^{\mathrm{out}}$ required for raising the temperature of $H_2O$ emission gas to $T_{\mathrm{out}}$ is expressed by

$$Q_{\mathrm{w}}^{\mathrm{out}} = (T_{\mathrm{out}} - T_{\mathrm{in}}) \times c_{\mathrm{vap}} \times m_{\mathrm{vap}}, \tag{6}$$

where we define $m_{\mathrm{vap}} = m_{\mathrm{H_2O}} - (18/24.3)m_{\mathrm{Mg}}$ because water of $(18/24.3)m_{\mathrm{Mg}}$ is used for reaction (1) and rest of water is evaporated.

The kinetic energy $U_{\mathrm{m}}$ for propellant is derived by subtracting energies required for heating from total reaction energy as

$$\begin{aligned} U_{\mathrm{m}} &= \frac{\left(Q_{(1)} - Q_{\mathrm{w}}^{\mathrm{in}} + Q_{(2)} - Q_{\mathrm{w}}^{\mathrm{out}}\right)}{m} \\ &= E_{\mathrm{m}} - \frac{Q_{\mathrm{w}}^{\mathrm{in}} + Q_{\mathrm{w}}^{\mathrm{out}}}{m}, \end{aligned} \tag{7}$$

where we introduced the specific energy, emission energy per mass,

$$E_{\mathrm{m}} = \left(Q_{(1)} + Q_{(2)}\right)/m, \tag{8}$$

where $m = m_{\mathrm{vap}} + m_{\mathrm{MgO}}$ and $m_{\mathrm{MgO}}$ is the mass of MgO emitted from the nozzle. Using these energies, momentum $M_{\mathrm{p}}$ is expressed as

$$M_{\mathrm{p}} = m v_{\mathrm{vap}} = m\sqrt{2U_{\mathrm{m}}}. \tag{9}$$

Considering $m = (Q_{(1)} + Q_{(2)})/E_{\mathrm{m}}$ and $m_{\mathrm{vap}} = m - m_{\mathrm{MgO}}$

$$\frac{Q_{\mathrm{w}}^{\mathrm{out}}}{m} = (T_{\mathrm{out}} - T_{\mathrm{in}}) \times c_{\mathrm{vap}} \times \left(1 - \frac{m_{\mathrm{MgO}}}{Q_{(1)} + Q_{(2)}} E_{\mathrm{m}}\right), \tag{10}$$

$$\frac{Q_{\mathrm{w}}^{\mathrm{in}}}{m} = A \times \left\{1 - \left(\frac{18}{24.3} m_{\mathrm{Mg}} - m_{\mathrm{MgO}}\right) \frac{E_{\mathrm{m}}}{Q_{(1)} + Q_{(2)}}\right\}, \tag{11}$$

where $A = \{(373\ \mathrm{K} - T_{\mathrm{initial}}) \times c_{\mathrm{w}} + q^{\mathrm{ev}} + (T_{\mathrm{in}} - 373\ \mathrm{K})\} \times c_{\mathrm{vap}}$.

If MgO is not emitted from nozzle ($m_{\mathrm{MgO}} = 0$), $m$ becomes only the mass of vapor and we get a relation

$$M_{\mathrm{p}} = \frac{Q_{(1)} + Q_{(2)}}{E_{\mathrm{m}}} \sqrt{R}, \tag{12}$$

where $R$ is given by

$$R = 2\left\{ \left(1 + A \times \frac{18}{24.3} m_{\mathrm{MgO}}\right) E_{\mathrm{m}} - (T_{\mathrm{out}} - T_{\mathrm{in}}) c_{\mathrm{vap}} - A \right\}. \tag{13}$$

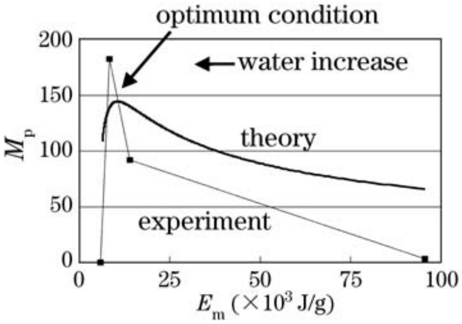

Fig. 7. Specific energy $E_{\mathrm{m}}$ versus gas momentum $M_{\mathrm{p}}$.

Figure 7 shows the relation between specific energy and momentum of vapor. When amount of water is small, the momentum of vapor is low because water sufficient for reaction is not supplied. On the other hand, when the amount of water is too much, vapor decreases because heat generated is used only for increasing the temperature of liquid water. For these reasons, there exists an optimal mass ratio of $H_2O$ to Mg, which is 3.1. Specific energy at this point is 10604 J/g.

In conclusion, the new clean energy cycle is proposed by using the magnesium and solar pumped laser. The combustion system of Mg and $H_2O$ can be used to produce $H_2$ for fuel cell and momentum for turbine driver. $H_2$ generated from the MAGIC engine can be controlled by the amount of Mg and $H_2O$ as well as their mixing ratio. Optimum mass ratio of $H_2O$ to Mg, 3.1 is verified theoretically and experimentally. It will be necessary to investigate emitting process from a heat engine and to explore the phenomenon inside a heat engine and optimizing power.

Y. Sakurai's e-mail address is sakurai@stu.mech.titech.ac.jp.

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