Experimental Study on Water Production by Hydrogen Reduction of Lunar Soil Simulant in a Fixed Bed Reactor

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ABSTRACT

Oxygen is most essential for life support and spacecraft propulsion if man intends to live on the moon. A vital source of oxygen is water. In this study, water production from lunar soil simulant is experimentally investigated employing the hydrogen reduction. The reaction temperature of 1,000 and smaller particle are recommended for the production of water from lunar soil with the 10-15 min processing time.

Keywords: moon, water production, hydrogen reduction, lunar soil simulant

1. INTRODUCTION

In the near future, man will be able to live on the moon. However, he cannot live without water and oxygen. Human habitation on the moon will then require the use of locally derived materials since transportation from the earth costs much time, money and labor. Oxygen is most essential for life support and spacecraft propulsion. Water is a source of oxygen. Hence, production of water from lunar soil is a primary concern.

Over 20 processes of oxygen production on the moon have been proposed.[1] Among these processes, oxygen production employing hydrogen reduction is the most feasible process.[2] In this process, ilmenite contained in lunar soil is reduced with hydrogen producing water (1). Oxygen is subsequently produced by electrolysis (2). Hydrogen produced in reaction (2) can be recycled in reaction (1).

$$FeTiO_3(s) + H_2(g) \quad Fe(s) + TiO_2(s) + H_2O(g) \qquad (1)$$

$$H_2O \quad H_2 + 1/2O_2 \qquad (2)$$

The reaction (1) is endothermic with 11 kJ/mol under 1,000 . Since the free energy formation in this reaction is relatively low, ilmenite can be easily reduced.

Understanding the hydrogen reduction mechanism of ilmenite is important for the mission of utilizing lunar soil. The purpose of this work is to discuss the possibility and the mechanism of water production.

2. EXPERIMENTAL

2.1 Apparatus

The schematic diagram of the experimental apparatus is shown in Fig.1. The apparatus consists of a reactor, a furnace, and a measurement line including a moisture meter, gas flow meters, pressure gauges, thermocouples, A/D converter, and a personal computer for data acquisition.

The schematic diagram of the reactor is shown in Fig. 2. A reactor is made of Inconel-600, and consists of an inner tube of 30 mm i.d. and 275 mm

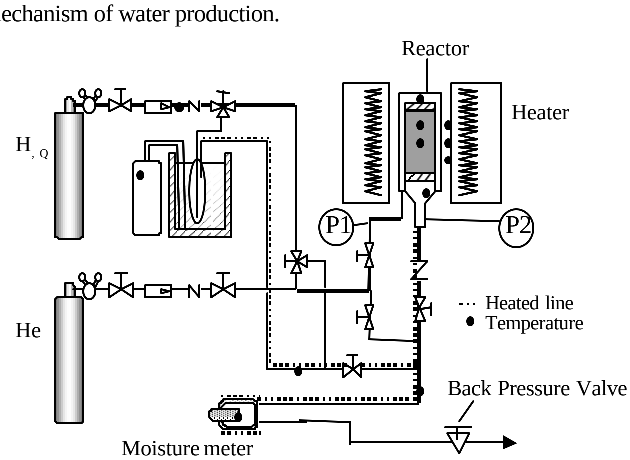


Fig. 1 The schematic diagram of the experimental apparatus.

long and an outer tube. Lunar soil simulant is held in the upper part of the inner tube by placing ceramic screen filters with 10 ì m openings and glass wool on the top and bottom ends of lunar soil simulant.

Hydrogen gas flows up through a preheating gap between the inner and the outer tubes, and reacts with lunar soil simulant. Hydrogen gas with produced water is sent to the moisture probe after the outlet. Water production rate, inlet and outlet pressure, sample temperature, hydrogen mass flow rate are monitored every 0.5 s.

Experiments were conducted with varying of the reaction temperature, the inlet pressure, and the particle size. Experimental conditions are listed in Table 1.

2.2 Lunar Soil Simulant

The sample used in the experiments is lunar soil simulant with similar chemical and mechanical properties of lunar soil. Lunar soil simulant is made by Shimizu Corp., Tokyo, Jap an. The chemical composition of the sample is shown in Table 2. Lunar soil simulant has the mean particle size of 70 ìm, bulk density of $1.55x10^3$ kg/cm^3, specific gravity of 2.94. In the experiments, the original sample is referred to as "Entire". Sieved sample used are below 75 ìm ("Under75") and over 75 ìm ("Over75").

2.3 Analysis

Chemical analysis was carried out to examine the compositions of the non-reduced, the partially reduced, and the nearly complete reduced sample. Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) were carried out to investigate the reaction mechanism.

3. RESULTS AND DISCUSSION

3.1 Water Production Rate and Cumulative Water Production

3.1.1 Effect of Temperature

Effect of temperature on the water production rate is shown in Fig. 3. Higher temperature leads to higher water production rate up to 1,000 . Effect of temperatures on the cumulative produced water is shown in Fig. 4. Larger amount of water is produced at higher temperature up to 1,000 . Cumulative water production at 1,050 is smaller than that of 1,000 . Partial sintering or melting

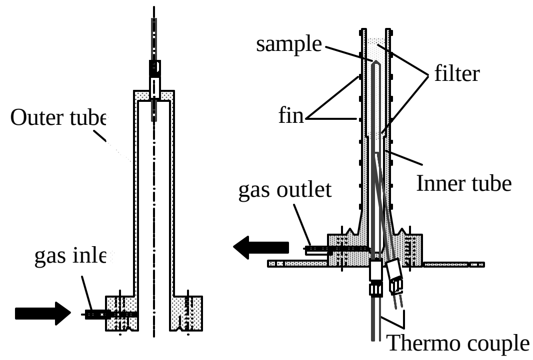


Fig. 2 The schematic diagram of the reactor.

Table 1 Experimental Conditions.

Sample Weight [g]	40
Hydrogen Flow Rate [l/min]	4
Reaction Temperature [•]	900, 950, 1000, 1050
Inlet Pressure [kPa]	303, 404, 505
Particle Size [µm]	Entire, Under75, Over75

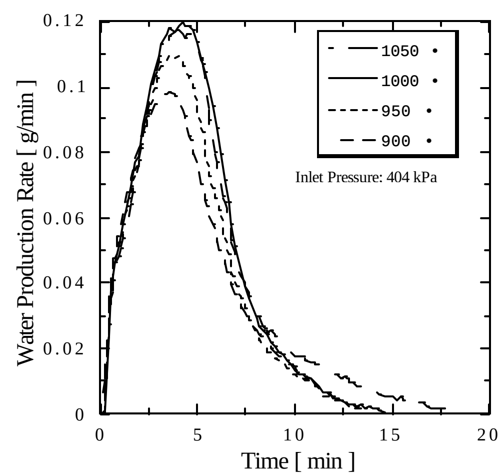


Fig. 3 Effect of temperature on water production rate.

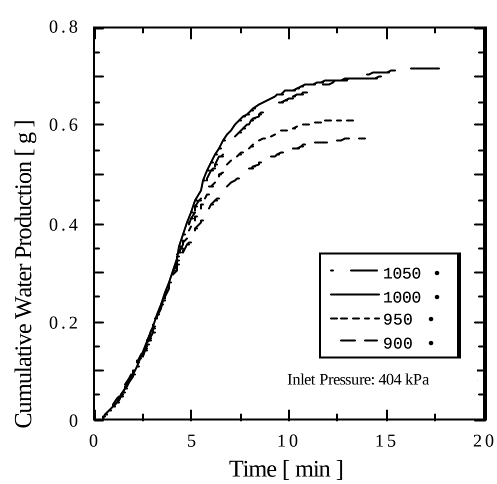


Fig. 4 Effect of temperature on cumulative water production.

occurred at higher reaction temperature, resulting in the unreacted FeO and Fe_2O_3 at the inner part of the particle.

3.1.2 Effect of Inlet Pressure

Effect of inlet pressure on the water production rate is plotted in Fig. 5. Lower pressure leads to higher water production rate because of larger diffusion coefficient. Therefore, mass transfer process inside the particle is considered to be the rate-controlling process.

The amount of cumulative water production is also depends on inlet pressure. Reduction at higher pressure produces the larger amount of cumulative water production. Equilibrium at high pressure enhances hydrogen reduction.

3.1.3 Effect of Particle Size

Effect of particle size on the water production rate is plotted in Fig. 6. Water production rate of "Under75" sample is higher than that of "Over75". The higher rate of "Under75" is due to the following two reasons. The first reason is due to larger surface area. The second reason is due to lower pressure, resulting from larger pressure drop; the average pressure in the reactor with "Under75" is 250 kPa, and that with "Over75" is 300 kPa.

The amount of cumulative water production of "Under75" is larger than that of "Over75". Large size of the particle would not be reduced completely because hydrogen gas cannot reach the inside of the larger particle.

3.2 Chemical Composition

The chemical composition of lunar soil simulant before and after reduction is shown in Table. 2. Ferric oxide (Fe_2O_3) is completely reduced and ferrous oxide (FeO) is slightly reduced by hydrogen. Other components contained in lunar soil simulant is not influenced by hydrogen reduction.

3.3 SEM Analysis

Fig. 7 shows the SEM photographs of the cross section of the particles before and after reduction. The ilmenite (bright parts) has several holes after reduction. This caused by the oxygen release, leaving a product of Fe. At 1,050 , alkali contents (gray parts) melt and block the pores of the particles.

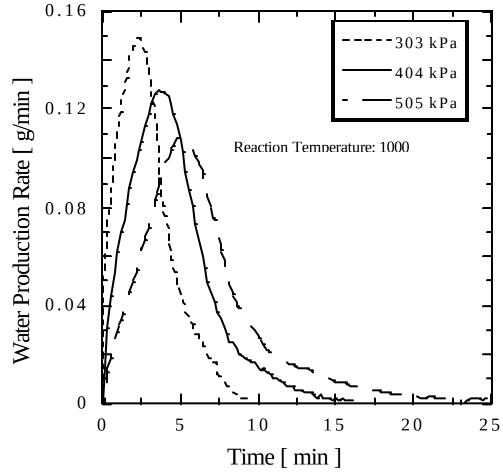


Fig. 5 Effect of inlet pressure on water production rate.

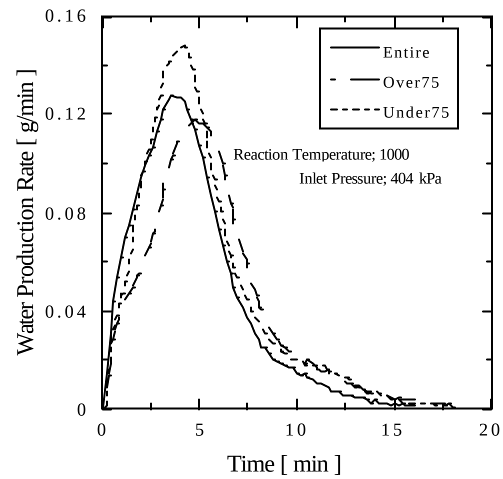
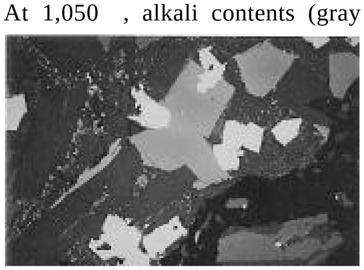
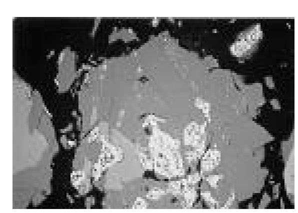


Fig. 6 Effect of particle size on water production rate.

Table 2 Chemical composition of lunar soil simulant. [wt. %]

	Before	After (1,000 , 404 kPa)
SiO_2	50.90	51.10
Al_2O_3	16.00	15.96
TiO_2	2.11	2.11
Fe	0.11	3.86
FeO	8.47	7.48
Fe_2O_3	4.25	0.07
Others	20.27	21.53
Total	100.00	100.00





4. CONCLUSION

The following findings are obtained from the experimental study of hydrogen reduction of lunar soil simulant.

(1) Ferrous oxide (FeO) and ferric oxide (Fe_2O_3) contained in the lunar soil simulant are the major reduced components by hydrogen.

(2) The hydrogen reduction at a reaction temperature of 1,000 produces largest amount of water.

(3) The smaller particles having larger surface areas produce larger amount of water.

(4) The inner part of the larger particles is unreacted.

(5) A mass transfer process inside the particle is considered to be main factor to control the water production rate.

The reaction temperature of 1,000 and smaller particle are recommended for the production of water form lunar soil. Higher pressure is recommended for producing of larger amount of water, while lower pressure is recommended for higher rate of water production.

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