



## Hydrogen recovery from the thermal plasma gasification of solid waste

Youngchul Byun<sup>a</sup>, Moohyun Cho<sup>a</sup>, Jae Woo Chung<sup>b,\*</sup>, Won Namkung<sup>a</sup>, Hyeon Don Lee<sup>b</sup>,  
Sung Duk Jang<sup>a</sup>, Young-Suk Kim<sup>c</sup>, Jin-Ho Lee<sup>c</sup>, Carg-Ro Lee<sup>c</sup>, Soon-Mo Hwang<sup>c</sup>

<sup>a</sup> School of Environmental Science and Engineering, Pohang University of Science and Technology (POSTECH), San 31, Hyoja-dong, Nam-gu, Pohang 790-600, Republic of Korea

<sup>b</sup> Department of Environmental Engineering, Green Technology Institute, Gyeongnam National University of Science and Technology (GNTECH), Dongjin-ro 33, Jinju 660-758, Republic of Korea

<sup>c</sup> Research center, GS Plasma Technology Company, 461-38 Jeonmin-dong, Yuseong-gu, Daejeon 305-811, Republic of Korea

### ARTICLE INFO

#### Article history:

Received 11 November 2010  
Received in revised form 14 March 2011  
Accepted 14 March 2011  
Available online 22 March 2011

#### Keywords:

Thermal plasma  
Paper mill waste  
Gasification  
Syngas  
H<sub>2</sub> recovery

### ABSTRACT

Thermal plasma gasification has been demonstrated as one of the most effective and environmentally friendly methods for solid waste treatment and energy utilization in many of studies. Therefore, the thermal plasma process of solid waste gasification (paper mill waste, 1.2 ton/day) was applied for the recovery of high purity H<sub>2</sub> (>99.99%). Gases emitted from a gasification furnace equipped with a nontransferred thermal plasma torch were purified using a bag-filter and wet scrubber. Thereafter, the gases, which contained syngas (CO + H<sub>2</sub>), were introduced into a H<sub>2</sub> recovery system, consisting largely of a water gas shift (WGS) unit for the conversion of CO to H<sub>2</sub> and a pressure swing adsorption (PSA) unit for the separation and purification of H<sub>2</sub>. It was successfully demonstrated that the thermal plasma process of solid waste gasification, combined with the WGS and PSA, produced high purity H<sub>2</sub> (20 N m<sup>3</sup>/h (400 H<sub>2</sub>-N m<sup>3</sup>/PMW-ton), up to 99.99%) using a plasma torch with 1.6 MWh/PMW-ton of electricity. The results presented here suggest that the thermal plasma process of solid waste gasification for the production of high purity H<sub>2</sub> may provide a new approach as a future energy infrastructure based on H<sub>2</sub>.

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### 1. Introduction

The recovery of energy from the increasing amounts of solid waste would be very useful as a supply of sustainable energy. Therefore, a more recent trend for the treatment of solid waste is the combination of incineration and energy recovery in the so-called “waste-to-energy (WtE)” plants [1]. This combination helps to solve two problems: one is the energy involved; with increasing or fluctuating oil prices, as well as the imminent exhaustion of oil with time, the demand for energy has still been increasing. The other is the environment; conventional solid waste treatment methods, i.e., landfill, are considered inappropriate from environmental safety and public awareness perspectives. Therefore, thermal gasification of solid waste has been proposed and developed as an alternative solution for the destruction of waste with the simultaneous recovery of energy [2,3].

Plasma gasification technology has attracted increasing attention as an environmental friendly alternative to fuel burning systems for the treatment of waste due to the following unique advantages: (1) the high energy density and temperature, (2) the treatment of a wide range of waste, and (3) the high heat flux density at the reactor boundary that lead to the fast attainment of

steady state condition, etc. [4,5]. With the plasma gasification, the organic components of waste are converted to syngas, mainly composed of carbon monoxide (CO) and hydrogen (H<sub>2</sub>), which can be used directly as a source of fuel in power plants for the production of electricity or synthetic fuels, while the inorganic components are changed into innocuous slag [6]. Therefore, over the past decade, the thermal plasma process has been regarded as a viable alternative for the treatment of highly toxic waste, such as the residue from MSW incineration (bottom ash + fly ash), radioactive, and medical wastes [7–15].

For several years, a pilot test of the thermal plasma process for the purpose of municipal solid waste (MSW) and paper mill waste (PMW) gasification (10 tonnes/day) has been conducted by our institute [5,6]. However, in our previous study, the utilization of the syngas generated was not considered as a source of energy. Methods for the recovery of energy from the gasification of solid waste include: (1) manufacturing fuels or chemicals from the syngas, (2) the recovery and utilization of H<sub>2</sub> as a fuel, (3) the recovery of H<sub>2</sub> and the production of electricity using fuel cells, and (4) the production of electricity using a complex gas-steam turbine cycle [16]. Of these, it is worth noting that the recovery of H<sub>2</sub> from the gasification process has increased, which has motivated the development of H<sub>2</sub> recovery technology in several investigations using the thermal plasma treatment of solid waste, while no purification process has been conducted for the recovery of high purity H<sub>2</sub> [17,18].

\* Corresponding author. Tel.: +82 55 751 3348; fax: +82 55 751 3484.  
E-mail address: [jwchung@gntech.ac.kr](mailto:jwchung@gntech.ac.kr) (J.W. Chung).

Hydrogen is emerging as an influential alternative to fossil fuels; therefore, intensive research activities for the production of H<sub>2</sub> are progressing based on many principles. A future energy infrastructure based on H<sub>2</sub> has long been proposed as an ideal long-term solution to energy-related environmental and supply security problems [19,20]. Therefore, the recovery of H<sub>2</sub> from the thermal plasma treatment of waste has been considered as a useful and economically feasible tool [17,18]. To date; however, little work has been conducted on the recovery of H<sub>2</sub> from the thermal plasma gasification of waste combined with pressure swing adsorption (PSA). Therefore, for the first time, the recovery of high purity H<sub>2</sub> from the thermal plasma gasification of paper mill waste (1.2 ton/day) combined with PSA was conducted using a self-developed pilot plant. This study had two objectives: one was to produce syngas, which can be utilized as a H<sub>2</sub> recovery source from the thermal plasma gasification of paper mill waste, with the other being to optimize the H<sub>2</sub> recovery process using water gas shift (WGS) plus PSA to produce H<sub>2</sub> with high purity, i.e., over 99.99%. The following article reports the results of these tests.

## 2. Materials and methods

The schematic diagram and a picture of the thermal plasma gasification/H<sub>2</sub> recovery systems are shown in Fig. 1. The process was composed of two sub systems: a thermal plasma gasification system, which converts the organic components of the feed waste into syngas, and an H<sub>2</sub> recovery system, which converts the syngas generated by the thermal plasma gasification of PMW into high purity H<sub>2</sub> (>99.99%) using WGS and PSA.

### 2.1. Thermal plasma gasification system

The thermal plasma gasification system was a 3 tonnes/day scale apparatus (maximum capacity), consisting of a waste feeding system, a thermal plasma furnace equipped with a nontransferred plasma torch, a heat exchanger, flue gas treatment units, and a post-combustion chamber. A pressurized ram type feeder was used to supply waste into the plasma furnace. Approximately 1–2 kg of waste, enveloped in a plastic bag, was placed in the entrance slot, and then pushed into the plasma furnace continuously by a 10 cm diameter piston. The waste feed rate was about 50 kg/h. A nontransferred plasma torch, with a power capacity of 100 kW, was installed in the plasma furnace at a 20° angle. The torch angle induced cyclonic flows of the gas streams to allow effective gas mixing and prevent the emission of fly ash [5]. The operational voltage and current of the plasma torch were maintained to 350 ± 10 V and 200 A, respectively; the energy efficiency of the plasma torch was 70%. O<sub>2</sub> (12 N m<sup>3</sup>/h at 506.5 kPa), which was produced by a two stage PSA reactor packed with a zeolite molecular sieve and activated carbon on sites with a purity of 93%, was injected into the plasma torch. An auxiliary gas burner, which used liquefied natural gas (LNG), was also installed at the top of plasma torch to preheat the furnace (LNG: 2 N m<sup>3</sup>/h and air: 20 N m<sup>3</sup>/h). The temperature in the plasma gasification furnace was maintained at 1400–1450 °C. An outlet for the molten slag was placed at the bottom of the furnace. The heat exchanger played the role of decreasing the flue gas temperature to about 180 °C. A bag filter and wet scrubber were used to eliminate particulate matters and acidic gases produced from the thermal plasma gasification. The bag filter was composed of 18 filters and a gas pulsing system to remove the particles adhered to the bag surface. An inert gas, either N<sub>2</sub> or CO<sub>2</sub>, was used as the bag filter pulsing gas to prevent the syngas from exploding. Caustic soda (NaOH) was used to adjust the acidity of the scrubbing solution to pH 7. The syngas produced was supplied to the H<sub>2</sub> recovery

system or post-combustion chamber which was equipped with a gas burner to combust the syngas.

### 2.2. H<sub>2</sub> recovery system

The H<sub>2</sub> recovery system was mainly composed of the WGS and the PSA connected in series. The gases entering the WGS were compressed to nearly 700 kPa. Two stage WGS reactors were used, connected in series: one was a high temperature shift (HTS) reactor operated at about 350 °C, with the other being a low temperature shift (LTS) reactor operated at approximately 200 °C. The HTS and LTS reactors were filled with Fe/Cr type and Cu/Zn type catalysts, respectively. In addition, a guard bed for the removal of H<sub>2</sub>S was installed between the HTS and LTS as the catalyst packed in LTS can be deactivated by the deposition of sulfur [21].

The role of the PSA system was to produce high purity H<sub>2</sub> by separating the impurities by the different volatilities and polarities of the gas components. The PSA system was composed of four-bed reactors operated in parallel. The adsorption and regeneration cycles were continuously repeated in a controlled sequence to generate high purity H<sub>2</sub>. The H<sub>2</sub> produced was also used as a purging gas to regenerate the PSA adsorbent after the adsorption cycle. The operating pressure of the PSA reactor was controlled by a gas compressor installed in front of the H<sub>2</sub> recovery system. The optimization of H<sub>2</sub> recovery system was conducted focusing on the PSA unit, since the performance of the WGS system was stable throughout the entire experimental procedures.

### 2.3. Waste characteristics and gas analysis

The waste generated from the process of raw materials in a paper mill plant was used as the feed material for the recovery of H<sub>2</sub>; the chemical characteristics of this material were similar to those of biomass reported in the literature [22–25]. The waste was made up of 68.8% combustibles, 20.6% moisture, and 10.6% non-combustibles. The most abundant element was carbon, at 46.8%, followed by oxygen, hydrogen, nitrogen, chlorine, and sulfur at 33.7, 7.5, 0.9, 0.1, and 0.02%, respectively. The lowest heating value of the waste was 3300 kcal/kg.

Almost all the operational processes, such as the operational voltage, O<sub>2</sub> supply, cooling water supply for the plasma torch, the air pollution control system, and H<sub>2</sub> recovery system, were automatically controlled and monitored. A gas analyzer (A&D 9000 series, Korea) and gas chromatography (Acme 6100, PDHID, Younglin, Korea) were used to analyze the gas components.

## 3. Results and discussion

Five sets of experiment were carried out over a 6 month period using paper mill waste, focusing on the compositions and environmental safety of the gases generated from the thermal plasma gasification system and the optimization of the H<sub>2</sub> recovery system (WGS + PSA units) for the production of high purity H<sub>2</sub> (>99.99%).

### 3.1. Characteristics of syngas generation

The concentrations of air pollutants, such as HCl, NO<sub>x</sub>, and SO<sub>2</sub>, were measured at the wet scrubber outlet (Table 1). The major air pollutants were observed to have much lower concentrations than those in the regulatory standards in Korea, USA, and EU [5,26,27]. In addition, the concentrations of dioxins were also measured at the stack (Fig. 2, 0.021 ng-TEQ/N m<sup>3</sup>), and were also much lower than the emission regulation of Korea (0.1 ng-TEQ/N m<sup>3</sup>), USA, and EU (0.1 ng-TEQ/N m<sup>3</sup>), indicating that all the organics in the waste were effectively decomposed by the high temperature in the thermal plasma furnace [5,26,27]. These low air pollutant

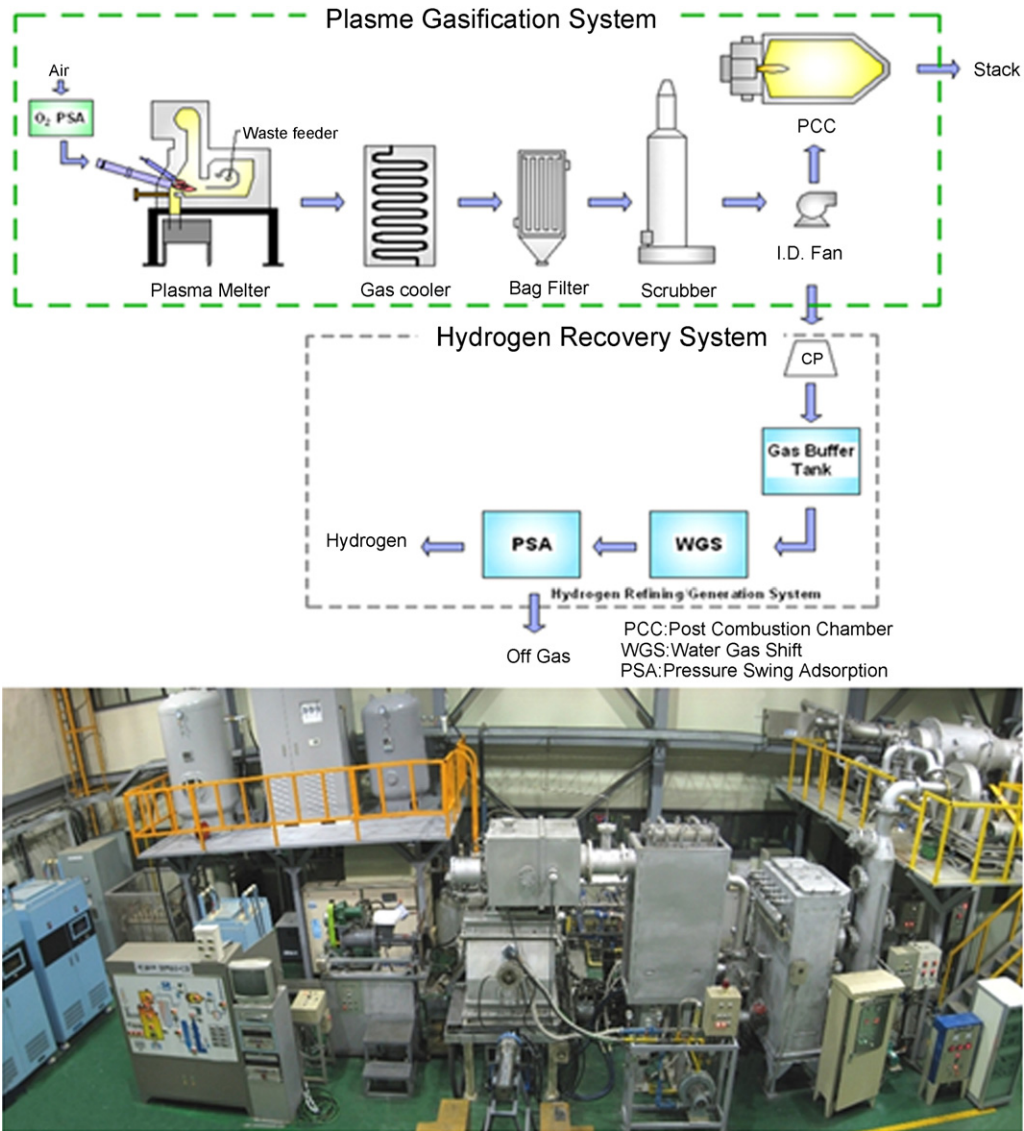


Fig. 1. Schematic diagram of the thermal plasma process for the recovery of high purity H<sub>2</sub>. Bottom picture has shown the overall demonstrated plant.

concentrations were sustained during all the experimental sets. These results show that thermal plasma gasification is an environmentally friendly process for the recovery of H<sub>2</sub> from solid waste.

The concentrations of CO<sub>2</sub>, CO, and H<sub>2</sub> were also measured at the wet scrubber outlet; the flow rate of the gases was 65.2 N m<sup>3</sup>/h during the five experimental sets. The total average concentrations of CO and H<sub>2</sub> were 39.56% and 34.90%, respectively, resulting in a sum 74.46% for the two components (Table 2). These results suggest the production rates of CO and H<sub>2</sub> from the inlet PMW were 516 and 455 N m<sup>3</sup>/PMW-ton, respectively. In addition, the concentration of CO<sub>2</sub> emitted during the five experiments was 12.6% (164 N m<sup>3</sup>/PMW-ton). From the concentrations of CO and CO<sub>2</sub>, we

calculated the carbon conversion efficiency as follow;

carbon conversion efficiency(%)

$$= \frac{\text{total reacted carbon in the system (kg)}}{\text{total carbon fed in the system (kg)}} \times 100 \quad (1)$$

The total amounts of reacted carbon in the system were obtained from the CO and CO<sub>2</sub> concentrations generated. As a result, a 97% carbon conversion efficiency was obtained. This result suggests that the process of thermal plasma gasification completely gasified the solid waste.

The yields of syngas in our study were compared with the other reported gasification process, i.e., fuel burning; the selection of the

Table 1

Comparison of the concentrations of air pollutants emitted at the outlet of the wet scrubber with the regulatory standards in Korea, USA and the EU.

Species	Emissions (ppm, 2% O <sub>2</sub> )	Regulatory standard in Korea (ppm, 12% O <sub>2</sub> )	Regulatory standard in EU (ppm, 11% O <sub>2</sub> )	Regulatory standard in USA <sup>a</sup> (ppm, 7% O <sub>2</sub> )
NO <sub>x</sub>	18 ± 10	100	97 (200 mg/N m <sup>3</sup> )	140
SO <sub>x</sub>	2.5 ± 1.5	50	18 (50 mg/N m <sup>3</sup> )	3.6
HCl	2 ± 1.5	20	6 (10 mg/N m <sup>3</sup> )	1.5

<sup>a</sup> In the case of waste-burning kilns.

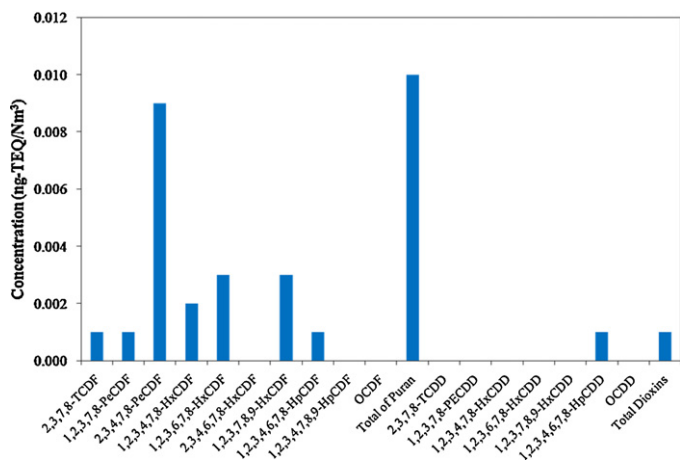


Fig. 2. The concentration of dioxins measured at the stack.

Table 2

Concentration of emitted CO and H<sub>2</sub> measured at the outlet of wet scrubber according to the experimental set.

	Avg. CO (%)	Avg. H <sub>2</sub> (%)	Sum of CO + H <sub>2</sub> (%)
Exp. 1	38.77	35.21	73.98
Exp. 2	40.58	34.65	75.23
Exp. 3	37.65	33.93	71.58
Exp. 4	40.38	35.60	75.98
Exp. 5	40.44	35.09	75.53
Total avg. (%)	39.56	34.90	74.46

feed material was restricted to biomass because the chemical characteristics of biomass are similar to those of the paper mill waste used in this study (Fig. 3) [22–25]. Lv et al. [22] conducted biomass gasification both with and without the addition of steam. In some cases (the upright triangles in Fig. 3), the production rates of H<sub>2</sub> and CO were higher than those in our study due to the addition of steam. It has been reported that steam/oxygen gasification has an advantageous hydrogen yield [28]. However, steam was not added in our gasification process. With the exception of this case (the upright triangles in Fig. 3), thermal plasma gasification has higher H<sub>2</sub> and CO yields (the circle in Fig. 3) than those in other reports. In addition, the rate of CO<sub>2</sub> generated compared to CO was lower than with the other gasification process (0.32 in our study). This was thought

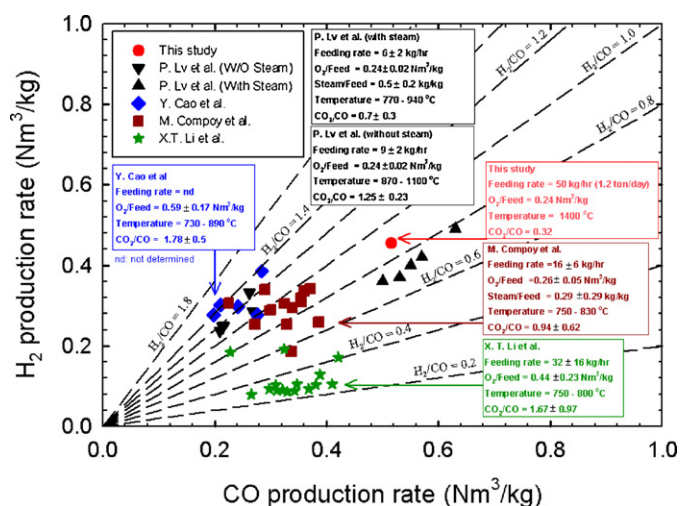


Fig. 3. Comparison of the thermal plasma gasification process with the fuel burning gasification processes on the syngas yields. The selections of gasified materials were restricted to biomass. The dotted lines show the ratio of H<sub>2</sub> to CO.

Table 3

Comparison of gas composition between inlet and outlet of WGS reactor.

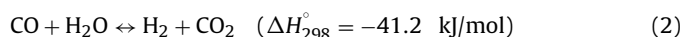
	Exp.1 and Exp. 2		Exp. 3		Exp. 4 and Exp. 5	
	Inlet (%)	Outlet (%)	Inlet (%)	Outlet (%)	Inlet (%)	Outlet (%)
CO	37–40	0.2–0.3	40	0.3	37–40	0.3–0.4
CO <sub>2</sub>	13–15	35–36	12.3	42.1	14–18	36–37
H <sub>2</sub>	34.5	52	40.3	45.6	34–37	52–55
N <sub>2</sub>	8–10	7–9.5	7.4	12	5–6	4–5.5
H <sub>2</sub> O	4	4	–	–	4	4

to have been caused for the following reasons: compared with the other biomass gasification process, the lower O<sub>2</sub> feeding rate (0.24 in this study, the circle in Fig. 3) into the thermal plasma furnace lead to the partial oxidation of carbon and the higher temperature originating from the thermal plasma lead to a higher carbon conversion rate. From these results, it was concluded that the plasma treatment of solid waste can achieve a greater syngas yield and lower CO<sub>2</sub> emissions than those burning fuel (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.).

As mentioned above, steam can be an important role on the generation of H<sub>2</sub>. Many researchers have also reported the importance of steam. Especially, Gil et al. reported that the use of steam as a gasifying agent doubles the H<sub>2</sub> content of the gas compared with the use of O<sub>2</sub> as the gasifying agent at the same temperature [29]. This is because a relatively high steam content in the flue gas increases steam reforming and water gas shift reactions. However, in a gasification system without an external heat source, a steam injection lowers the operating temperature. This could lead to a decrease in the syngas content and increase the tar yield [30]. Therefore, in the thermal plasma process, the input of electricity to the plasma torch must be increased to maintain the desired operating temperature, which leads to decreased electrical efficiency. Our current objective is to optimize thermal plasma gasification/vitrification combined with the PSA and WGS. Therefore, the detailed effect of steam has not yet been carefully investigated. However, we are now planning to investigate the effect of steam in the gasification/vitrification of solid waste using thermal plasma with respect to the electrical efficiency and syngas yield.

### 3.2. Optimization of the H<sub>2</sub> recovery process

Before the introduction of the gases into the PSA for the separation and purification of H<sub>2</sub>, a WGS unit was installed, which played a role in converting CO to H<sub>2</sub>, using a catalyst, via the following reaction with the supplied steam (H<sub>2</sub>O) [21].



The reforming reaction is exothermic; the yield of H<sub>2</sub> is decreased with increasing temperature. Therefore, a two-stage WGS unit was used, which considered the yield as well as the kinetics of the reaction with respect to the temperature. One unit was the HTS packed with the Fe/Cr catalyst. The other unit was the LTS packed with the Cu/Zn catalyst. The lifetime of WGS catalysts is typically determined by sulfur poisoning. Mostly, sulfur only deactivated the Cu/Zn catalyst of the LTS because the high temperature of the HTS prevents the adsorption of sulfur onto the surface of the Fe/Cr catalyst in the HTS; the capacity of the Fe/Cr catalyst for sulfur adsorption is also low [21]. Therefore, a guard bed packed with copper oxide/zinc oxide/chromia catalyst was installed between the HTS and LTS to adsorb the H<sub>2</sub>S. The H<sub>2</sub>S concentrations at the inlet and outlet of guard bed were 1 ppm and below 0.1 ppm, respectively. After passing the gases through the guard bed, they entered the LTS. Table 3 presents comparisons of the gas compositions for all five experimental sets between the inlet and outlet of the

**Table 4**  
Operating sequence and H<sub>2</sub> recovery results.

	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5
Bag filter pulsing gas	N <sub>2</sub>	N <sub>2</sub>	N <sub>2</sub>	CO <sub>2</sub>	CO <sub>2</sub>
Flow rate of input syngas (N m <sup>3</sup> /h)	25–35	25–35	35–45	28–36	36–42
Operating parameters of PSA					
Pressure (kPa)	709.1	810.4	861.1–911.7	861.1–911.7	810.4
Adsorption time (min)	3–4	3–4	3–4	3–4	2
Purge H <sub>2</sub> flow rate (L/min)	50	100	100	50	100
Recovered H <sub>2</sub> purity (%)	nd	99.5	90.0	99.6	>99.99%

nd, not determined.

**Table 5**  
Inlet and outlet gas composition of PSA according to experimental sequence.

		H <sub>2</sub>	CO	CO <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub>	H <sub>2</sub> O
Exp. 1	Inlet (%)	52	0.2–0.3	35–36	ND	7–9.5	4
	Outlet (ppm)	nd	1373	0	114	>2000	5
Exp. 2	Inlet (%)	52	0.2–0.3	35–36	ND	7–9.5	4
	Outlet (ppm)	99.50%	260	0	20	>2000	5
Exp. 3	Inlet (%)	45.6	0.3	42.1	ND	12	4
	Outlet (ppm)	90.13%	2700	800	200	9.5%	0.54
Exp. 4	Inlet (%)	53	0.3	38	ND	6	4
	Outlet (ppm)	99.96%	102.12	125.14	ND	130.34	0.54
Exp. 5	Inlet (%)	53	0.3–0.4	36–37	ND	4–5.5	4
	Outlet (ppm)	99.99%	4.95	15.34	ND	64.99	0.28

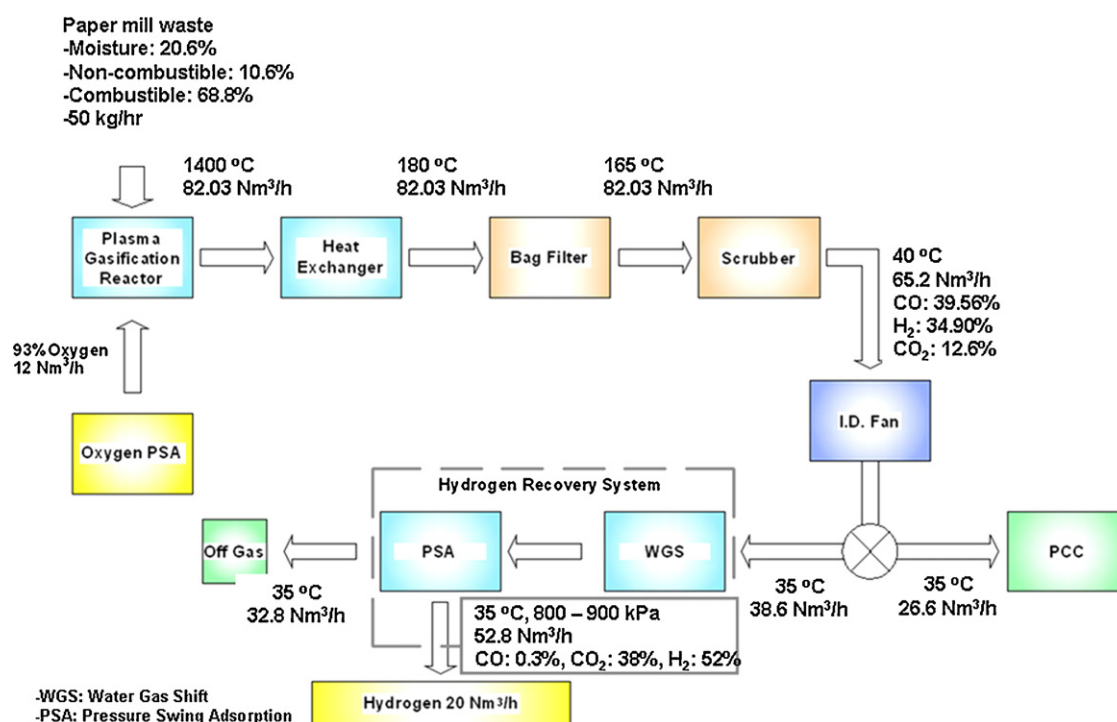
nd, not determined; ND, not detected.

WGS reactor (HTS + LTS). Almost all the CO was converted to CO<sub>2</sub>, with an increase in the production of H<sub>2</sub> after passing through the WGS reactor. The initial CO concentration, 37–40%, was decreased to 0.2–0.3% and the 34.5% H<sub>2</sub> was increased to 52%. The performance of the WGS reactor was properly sustained throughout all the experimental sets.

The gases that had passed through the WGS entered the PSA. The PSA is a mature technology widely used for the purification and separation of H<sub>2</sub> from different components [31]. This technology is based on the effect of pressure changes due to H<sub>2</sub> adsorption in a fixed bed. However, optimization of the PSA is necessary due to the

complicated nature of the cyclic process, as well as the large number of design parameters, such as step time, pressure, and gas velocity, which can affect the PSA performance. Therefore, five experimental sets were performed as the optimization process to obtain high purity H<sub>2</sub> from the PSA (>99.99%).

Multiple adsorbents were placed in layers on the beds of PSA. The compositions of the bottom and top layers were activated carbon and zeolite, respectively. The gases flow rate introduced into the PSA was 52 N m<sup>3</sup>/h (0.3% for CO, 38% for CO<sub>2</sub>, and 52% for H<sub>2</sub>). In our study, the most troublesome gas component in obtaining high purity H<sub>2</sub> (>99.99%) was N<sub>2</sub>; N<sub>2</sub> cannot be perfectly trapped in the

**Fig. 4.** Material balance of the overall process for the recovery of high purity H<sub>2</sub> using thermal plasma.

**Table 6**  
H<sub>2</sub> production cost based on Korean prices.

	Price	Notes
Total capital cost	898472 US\$	–
Operational cost	835 US\$/day	Operational cost per one day
Depreciation cost	164 US\$/day	Depreciation period = 15 years
Labor cost	270 US\$/day	Five labors
Electricity cost	272 US\$/day	180 kWh/h × 24 h/day × 0.063 US\$/kWh
LNG cost	60 US\$/day	4 N m <sup>3</sup> /h × 24 h/day × 0.63 US\$/N m <sup>3</sup>
Maintenance cost	25 US\$/day	1% of capital cost
Consumables cost	45 US\$/day	Water supply, chemical additives, etc.
H <sub>2</sub> production cost	1.74 US\$/N m <sup>3</sup>	20 N m <sup>3</sup> /h (480 N m <sup>3</sup> /day), (835 US\$/day)/(480 N m <sup>3</sup> /day) = (1.74 US\$/N m <sup>3</sup> )

bed. Initially, N<sub>2</sub> was used in the pulsing gases of the bag filter (Exp. 1–3 of Table 4), leading to an observed N<sub>2</sub> concentration entered the PSA of 9.5 ± 2.5%. In these cases, the required H<sub>2</sub> purity (>99.99%) could not be obtained. Thereafter, the pulsing gas for bag filter was changed from N<sub>2</sub> to CO<sub>2</sub>, resulting in an N<sub>2</sub> concentration entering the PSA of nearly 5 ± 1%. Therefore, H<sub>2</sub> with a purity of 99.6% was obtained (Exp. 4 in Table 4). However, this value was also not our H<sub>2</sub> purity goal. Eić et al. conducted parametric studies to obtain high purity H<sub>2</sub> on the PSA system and concluded that a decreased adsorption time and increased purging time resulted in greater cleaning of the adsorption bed, which enhanced the purity [31]. Therefore, the adsorption time was reduced from 3–4 min to 2 min and the flow rate of the H<sub>2</sub> purging gas increased from 50 L/min to 100 L/min for greater cleaning of the adsorption bed (Exp. 5 of Table 4). As a result, high purity H<sub>2</sub> (>99.99%) was obtained, where the flow rate of H<sub>2</sub> was 20 N m<sup>3</sup>/h; the recovery rate of H<sub>2</sub> was 73% to the amount of H<sub>2</sub> contained in the inlet of the PSA. The detailed gas compositions at both the inlet and outlet of the PSA are shown in Table 5 for all five experimental sets. From these results, it was concluded that the thermal plasma gasification, combined with the PSA, can be viable for the production of high purity H<sub>2</sub> (>99.99%).

### 3.3. Material balance and cost analysis

The technical and economical justification of the effectiveness of this plasma gasification technology has been fulfilled by this study. Fig. 4 shows the material balance on the basis of the experimental results of the optimized thermal plasma gasification/H<sub>2</sub> recovery systems. Commercially available H<sub>2</sub>, with purity higher than 99.99%, was produced at a rate of 20 N m<sup>3</sup>/h. This result led us to conclude that the H<sub>2</sub> production rate for the amount of injected PMW was 400 H<sub>2</sub>-N m<sup>3</sup>/PSM-ton.

The consumption of electricity and the supplementary fuels were based on the actual amounts consumed into practice. That is, a total of 180 kWh of electricity (thermal plasma torch 80 kWh/h + utility 100 kWh/h) was used for operating the plasma torch and supplemental apparatuses. In addition, the 4 N m<sup>3</sup>/h of LNG was used to preheat the plasma gasification reactor and post-combustion chamber. The market prices of industrial electricity and LNG in Korea are 0.063 US\$/kWh and 0.63 US\$/N m<sup>3</sup>. Using these results, the production cost of H<sub>2</sub> was obtained. A depreciation period of 15 years was considered, with the labor cost estimated on the basis of the real wages of five simple laborers, because the process can be simply operated due to automation. One percent of the capital cost was considered for the maintenance costs (Table 6). Using these results, the calculated H<sub>2</sub> production cost was approximately 1.74 US\$/N m<sup>3</sup>, which is very expensive compared with the required retail price of H<sub>2</sub> from coal to H<sub>2</sub> produced of about 0.1 US\$/N m<sup>3</sup> [31]. In addition, the electric efficiency was obtained using the consideration of gas turbine efficiency. Generally, the efficiency of the gas turbine using hydrogen was ~40% [32]. Therefore, 20 N m<sup>3</sup>/h of H<sub>2</sub> can produce 60 kW of electricity. We used an 80 kW thermal torch and 100 kW utility power, mean-

ing that the electrical efficiency was 33%. This result led the high H<sub>2</sub> product cost compared with the market price mentioned in the manuscript. However, it is worth noting that H<sub>2</sub> obtained from this study was originated from not coal paid but solid waste been paid. Therefore, the economical feasibility is expected to be positive with the added profits from waste treatment and potentially recoverable CO<sub>2</sub>. Scale-up of the process can also reduce the H<sub>2</sub> production cost on an economy of scale.

## 4. Conclusions

The production of high purity H<sub>2</sub> from the thermal plasma process of solid waste with WGS and PSA systems was performed. The results from this study crucially show the feasibility of the production of high purity H<sub>2</sub> (>99.99%) from the thermal plasma gasification of waste. However, many tasks still remain for the development of a more reliable and stable process, which are as follows: (1) the process scale-up must be accomplished to reduce the H<sub>2</sub> production cost, (2) the technology for the stable operations of both the thermal plasma gasification and H<sub>2</sub> recovery systems must be accomplished on a larger capacity than that currently in operation, and (3) additional research must be conducted to obtain higher purity of H<sub>2</sub> (>99.999%) than at present (>99.99%) for the utilization of H<sub>2</sub> in the fuel cells, such as a proton exchange membrane fuel cell (PEMFC). The detailed design is currently under consideration, which will be applied to our next goal of constructing an H<sub>2</sub> recovery process using a thermal plasma (H<sub>2</sub> = 1000 N m<sup>3</sup>/h, up to 99.999%).

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