JP Journal of Heat and Mass Transfer
© 2015 Pushpa Publishing House, Allahabad, India
Published Online: April 2015
http://dx.doi.org/10.17654/JPHMTMay2015_215_227
Volume 11, Number 2, 2015, Pages 215-227 **ISSN: 0973-5763**

GASIFICATION OF BROWN COAL USING A 915MHz PURE STEAM PLASMA TORCH

Dong Hun Shin[1,2], Chang Hyun Cho[1], Jin Young Huh[1,3], Yong Cheol Hong[1,*], Young Hoon Lee[4] and Young Ki Park[4]

[1]Plasma Technology Research Center
National Fusion Research Institute (NFRI)
814-2 Osikdo-dong, Gunsan-city, Jeollabuk-do 250-806
Republic of Korea

[2]Advanced Green Energy and Environment
Handong Global University
Heunghoe-Eup, Buk-Gu, Pohang, Hyeongbuk 139-701
Republic of Korea

[3]Kwangwoon Academy of Advanced Studies
Kwangwoon University
447-1 Wolgye-Dong, Nowon-Gu, Seoul 139-701
Republic of Korea

[4]Wintech ENG, 5th Floor, Daewoo Building
22 Bangi-dong, Songpa-gu, Seoul 138-827
Republic of Korea
e-mail: ychong@nfri.re.kr

Abstract

This study investigated the gasification of low-grade coal in an atmospheric-pressure pure steam plasma torch operating at 915MHz

Received: October 20, 2014; Accepted: November 11, 2014
Keywords and phrases: steam plasma, coal gasification, 915MHz microwave, low-grade coal.
[*]Corresponding author

microwave. Because it contains a highly active chemical species, a steam plasma torch enhances chemical reaction rates. The fine powder brown coal (average particle size of 70μm) from Indonesia that was used in the experiment was delivered into the torch through a feeder. Two 915MHz microwave system sets were mounted on the upper and lower sections of the gasifier. Upper and lower plasma torches were installed so as to be tangential to the cylindrical gasifier sidewall. A swirl flow from the upper to the lower section occurred, generating longer particle residence than would occur in a gas stream. At rates of 60kg/hr and 30kg/hr, brown coal particles were injected into the upper and lower section plasma torches at microwave power of 40kW and 30kW, respectively. The relative concentrations of the synthesized gases were 36.3% hydrogen, 26.5% carbon monoxide, and 23.3% carbon dioxide. Cold gas efficiency and carbon conversion rates were observed to be 66.1% and 88.9% with 1450°C of average temperature, respectively.

Introduction

The demand for a more efficient use of fossil fuels in the production of energy is rising, due to concerns over the limited reserves of existing fossil fuel resources, environmental sustainability, and greenhouse gas emissions. Power plants applying technology such as the Integrated Coal Gasification Combined Cycle (IGCC), which consumes coal more efficiently and cleanly, are being established worldwide. Coal is the most abundant of all known non-renewable energy resources and is, therefore, the most extensively used source of fuel globally [1, 2]. In the gasification process, pulverized coal enters the gasifier, where it is evaporated at high temperatures. The resultant hydrocarbons react to carbon monoxide and hydrogen, producing synthesized gas through the following reaction:

$$C + H_2O \rightarrow CO + H_2. \tag{1}$$

The synthesized gas that is produced can be used as a fuel in power plants for the production of electricity using a gas engine, and it can also be used to produce synthetic liquid fuels as like di-methyl ether (DME) [2, 3]. In a period of pressing environmental concerns, there is a growing need to establish more efficient and cleaner ways to burn coal in the production of energy. Coal has the highest concentration of carbon of all fossil fuels, making it particularly important to increase the efficiency of the conversion from coal to energy. Power plants in many countries (Russia, Indonesia, and Ukraine, for example), use low quality coal blends containing vast amounts of impurities. Different gasification technologies are currently being developed to expand the types of fuel available for use in the production of energy, including cheaper low-grade fossil fuels [4, 5]. Steam plasma torch technology is one such technique being developed with an application in low-grade coal gasification in mind. A number of previous studies have focused on the gasification of fuels such as biomass and coal [5-9] using an arc plasma torch. However, arc plasma generator electrodes have limited life spans and are vulnerable to steam, which is often used as a gasification agent [4]. A microwave plasma torch can use steam as a plasma forming gas, given its non-electrode structure. Furthermore, the microwave source has superior power transfer efficiency from the generator to the plasma, relative to that of the arc plasma system [10, 11].

A pure steam torch [12, 13] generated by microwaves has attracted a great deal of attention over the past few years, because it can serve as a heat source for environmental cleanup activities, and may also be applied in the production of renewable energy sources. Steam plasma powered by microwaves provides an abundance of oxidizing radicals, including oxygen atoms and hydroxyls, which are highly efficient in gasifying coal. Coal gasification by microwave steam plasma can be conducted in a laboratory setting [14-16], suggesting the potential promise of efficient gasification. Containing highly active species [13], a steam torch enhances the chemical reaction rate and eliminates the need for the use of catalysts in material processing. Therefore, it might be postulated that microwave steam plasma torch technology promises near-perfect combustion, with an enlarged high-temperature, large-volume plasma-flame. All of these are achievable with the injection not only of liquid hydrocarbon fuels [17, 18], but also solid fuels, maximizing the chemical reaction rate.

Experimental Apparatus and Method

The atmospheric microwave plasma system consists mainly of the 915MHz magnetron with a maximum output power of 75kW, WR975 waveguide components, including an isolator, a directional coupler, and a three-stub tuner, and a field applicator forcing the excitation of the TE_{10} mode of the electromagnetic field. 915MHz microwave generators with a power rating up to 100kW are currently commercially available. The WR975 waveguide (248mm × 124mm) used in the microwave plasma torch is tapered to a shorted cross section of half of its height to obtain higher electric field strength in the discharge tube, in order to effectively deliver the microwave power into the discharge tube [12-18]. The discharge tube, with an inner diameter of 75mm, is inserted vertically, meaning it is perpendicular to the wide wall of the waveguide. The center of the discharge tube is located 110mm (a quarter of the waveguide wavelengths) from the short-circuited end. The plasma torch generated inside the fused quartz discharge tube is stabilized by injecting a swirl gas that is forced into the discharge tube sideways, creating a vortex flow in the tube and keeping the torch flame temperature of 5,000°C from making contact with the discharge tube wall. A steam generator provides steam of temperatures above 150°C. The steam enters the discharge tube as a swirl gas, as not shown in Figure 1. A directional coupler and a three-stub tuner control the reflected power of the plasma torch.

The swirl-type gasifier, with a capacity of 500kW of thermal energy, was designed for use in two microwave systems with maximum power levels of 75kW and operated at 915MHz. The first microwave plasma system is installed on the upper section and the second system on the lower section of the gasifier. Figure 1 shows the gasification system fully set up. The interior images in Figures 1(a) and 1(b) depict the installation of microwave systems on the upper and lower sections of the gasifier, respectively. The inner configuration of the swirl-type gasifier is of a cylindrical shape with a diameter of 900mm and a height of 1800mm. The inner surface of the gasifier is made of a fire resistant ceramic material called HACT180.

HACT180 can withstand temperatures up to 1800°C. The next layer is an insulating-cement known as INCT120. Five thermometers are vertically installed along the inner surface of the gasifier to monitor the inner-surface temperature, as not shown in Figure 1. The plasma from the microwave system in the upper section of the gasifier enters the inner chamber of the gasifier sideways and slightly downwards, creating a swirling plasma flame along the inner wall. Meanwhile, the plasma from the microwave system in the lower section enters the inner chamber of the gasifier sideways. The coal powder feeding system, as shown in Figure 1, supplied coal powder to the gasifier near the plasma flame using an air blower. The temperature of the synthesized gas is monitored at the bent point of the synthesized gas stack. The ash gathers into an ash tank under the gasifier, as not shown in Figure 1. A coal powder storage tank supplied to coal feeding system by the air-blown coal powder.

Much of the gasification of coal may be performed at temperatures over 1200°C. Therefore, it is necessary to preheat the inner temperature of the gasifier. The plasma flames may have proven insufficient to preheat the gasifier. Therefore, a kerosene burner was installed in the lower section of the gasifier for preheating purposes. The kerosene burner and the plasma flames preheat the gasifier to 1300°C. The kerosene burner is then turned off. After preheating the gasifier, the upper and lower plasma torches are powered to 40kW with 26kg/hr of steam as swirl gas, and to 30kW with 14kg/hr of steam, respectively. An additional 20kg/hr of steam then enters the upper section of the gasifier. Indonesian brown coal is injected into the gasifier at an injection rate of 90kg/hr through an injection port (60kg/hr) near the upper plasma flame, and also through another injection port (30kg/hr) near the lower plasma flame. Fine coal powder, with an average particle size of 70μm, is delivered through a waterproof bag for use in the experiment. The analysis of Indonesian brown coal powder is presented in Table 1, demonstrating an ash and moisture content of 33.17%. The 10.71% water content in the 90kg/hr coal injection means an additional injection of water of 9.6kg/hr, producing a total water injection into the gasifier of 69.6kg/hr. This is estimated to represent 1444lpm under room temperature conditions. The coal powder is blown into the gasifier by air compressors at a rate of 400lpm. The nitrogen level is 320lpm and oxygen is at 80lpm. An additional 330lpm of oxygen is injected into the gasifier to achieve a partial oxidation of the coal. Under room temperature conditions, the total oxygen input from water, air and additional oxygen injection is calculated as 1132lpm.

The inner temperature of the gasifier increases with the continuous input of coal powder and oxygen and the continuous operation of microwave plasmas. Thermometers are installed at locations from the top to the down of the gasifier. Figure 2 is a graph illustrating the temperature of the inner wall in terms of measurement time. Usually, the thermometers in the lower section suggest higher temperatures than in the upper section. The temperature of the gas fluid element may potentially decrease as it moves from the bottom of the gasifier to the top. The temperature of synthesized gas exiting the gasifier is almost 1000°C, even for very high wall temperatures. The heavy fluctuation of temperatures in the beginning is caused by an unsteady input of coal powder. Synthesized gas is sampled at the synthesized gas stack, as shown in Figure 1 and analyzed through gas chromatography (with error rates lower than 5% for CO, CO_2, O_2 and CH_4 measurement). However, the gas analyzer used is not able to measure H_2O and N_2 through this form of chromatography. Figure 3 reveals plots of the relative concentrations of synthesized gas species in terms of measurement time. The concentration of carbon monoxide is much higher than that of carbon dioxide at a high gas temperature, which is to be expected.

Results and Discussion

The gasification performance of the present gasification system being examined can be evaluated by estimating its cold gas efficiency and carbon conversion rate of the gasification of low-grade coal. The most important parameters to consider when making these evaluations are the relative concentrations of gas species in the synthesized gas, as plotted in Figure 3, which provides the relative concentrations of H_2, CO, CO_2, CH_4, O_2 and the remaining, including N_2, H_2O, etc. The other parameter that needs to be measured for the purpose of these performance evaluations is the total flow rate of the synthesized gas. This was extremely difficult to measure in this experiment due to the high volumes used, the high gas temperatures reached, water content, untreated coal, and ash powder, etc. Therefore, the only reliable data available for these particular evaluations are as per the gas analysis graph, as shown in Figure 3.

The nitrogen gas that entered the gasifier was air blown at 320lpm for coal powder injection. What happens at high temperatures to nitrogen is not fully understood. Nitrogen at high temperatures may produce nitric oxides, which disappears immediately in an environment of a high concentration of hydrogen [19] without any loss of nitrogen gas. In this context, we might assume that the 320lpm air blown nitrogen gas entered the gasifier would exit without any loss or increase. Any extra addition of nitrogen gas may lead to an overestimation of the cold gas efficiency. In addition, the total flow rate F_T of synthesized gas is connected to the relative concentration of nitrogen gas N_2 as $F_T = 320/N_2$, which is in units of lpm. A further consideration is the oxygen gas that enters the gasifier as steam, as water content in the coal, and as oxides, some of which may remain in oxide materials in the ash following gasification. The total oxygen input of 1132lpm, then may exit the gasifier in the forms of CO, CO_2 and H_2O. The relative concentration of oxygen decreases to almost zero, which is negligible and within the accepted error range. The oxygen flow rate resulting from the exiting of CO, CO_2 and H_2O is $(1/2)COF_T + CO_2F_T + (1/2)H_2OF_T$, which balances out with the total oxygen input of 1132lpm. Therefore, the balance equation of oxygen gas is expressed as $160(CO + 2CO_2 + H_2O) = 1132N_2$, where use has been made of the equation $F_T = 320/N_2$. Finally, with the sum of all the relative concentrations being unity at $H_2 + CO + CO_2 + H_2O + N_2 = 100\%$, we eventually obtain a concentration of $N_2 = 0.1238(1 + CO_2 - H_2)$, which provides an estimate of the relative concentration of nitrogen in the synthesized gas. The relative average concentrations of synthesized gases were 36.3% hydrogen, 26.5% carbon monoxide, and 23.3% carbon dioxide, as shown in Figure 3. Additionally, the results of N_2 and H_2O relative concentrations are 10.8% and 3.1%, respectively. As a result, the total flow rate is calculated as F_T = 2962.9lpm and the average temperature T_A of the gasifier inner wall is 1450°C. The calorific power of the coal is 90kg/hr × 4640kcal/kg = 487.2kW. Microwave power totals 70kW. 60kg/hr of steam enters the gasifier as swirl gas through the microwave plasma, thereafter, forming gas and additional steam. One gram of steam has latent heat of 539cal. Thus, latent heat of 60kg/hr of steam is calculated to be equivalent to 38kW. Therefore, the total input energy entering the gasification process is 487.2kW + 70kW + 38kW = 595.2kW.

The calorific power of synthesized gas from H_2 and CO is given by 2883.6mol/hr × 285kJ/mol + 2102.4mol/hr × 283kJ/mol = 228.3kW + 165.3kW = 393.6kW with $T_A = 1450^\circ$C. Here, 285kJ/mol is water enthalpy. 283kJ/mol is the difference between the enthalpies of carbon dioxide and carbon monoxide. Cold gas efficiency (CGE) at the high heating value is the calorific power of synthesized gas divided by the total input power of 595.2kW, given by CGE = (393.6kW/595.2kW) × 100 = 66.1%. The carbon mole fraction in the synthesized gas per time unit may be estimated by the sum of CO and CO_2 mole fractions. Therefore, the carbon mole fraction in the synthesized gas is given by 3949.3mole/hr with $T_A = 1450^\circ$C. The carbon conversion rate (CCR) is the carbon mole fraction in the synthesized gas divided by the mole fraction of the total carbon input of 4442.4mole/hr, given by CCR = (3949.3mole/hr/4442.4mole/hr) × 100 = 88.9%.

The very high temperature obtained, $T_A = 1450^\circ$C, is due to the high temperature of the microwave steam plasma, which causes an almost 90% carbon conversion of the low-grade coal with a high content of ash and moisture. This was predicted in a previous study [6]. Also, of note, we observed that cold gas efficiency was CGE = 66.1% with $T_A = 1450^\circ$C, a very high level in a relatively compact gasifier unit. The difference between the calorific power of the input value and synthesized gas is 595.2 – 393.6 = 201.6kW, possibly attributable to radiation and conduction loss as a result of the gasifier being hot and due to convective loss through the discharge of hot gas of an average temperature of 2000K. There may also has been some remaining unburned coal powder that was difficult to detect in the experiment. The temperature of the synthesized gas was measured at the bent point of the synthesized gas stack at almost 1000°C, as shown in Figure 1. The radiation and conduction loss experienced through the gasifier may be minimized with improved design configuration and the use of thermal insulating materials. The carbon dioxide concentration may be reduced by eliminating oxygen feeding as a carrier gas. According to these analyses, we noted that both the carbon conversion rate and cold gas efficiency improved dramatically as the gas temperature increased due to microwave steam plasma. The steam content in the synthesized gas also decreased substantially as the gas temperature increased.

Conclusions

Coal gasification using pure steam plasma through the use of 915MHz microwave conditions has been tested with low-grade Indonesian brown coal. We fabricated a swirl-type gasifier with two 915MHz microwave pure steam plasma units increasing the gas temperature in a 1145 liter gasifier. The low-grade Indonesian brown coal used in this gasification experiment had a calorific value of 4640kcal/kg, and ash and moisture content of 22.46% and 10.71%, respectively. The gasification conditions were a 1450°C average temperature and 90kg/hr of coal injection near the plasma flame. The air, oxygen and steam at over 150°C were entirely supplied at 400lpm, 330lpm and 60kg/hr, respectively. The relative concentrations of synthesized gases were 36.3% hydrogen, 26.5% carbon monoxide and 23.3% carbon dioxide. The cold gas efficiency and carbon conversion rates were 66.1% and 88.9%, respectively. The total calorific value of the synthesized gas was almost 400kW, demonstrating excellent gasification performance in a small operating system. The microwave steam plasma torch may also be useful for the combustion of biomass materials such as rice husks and wood chips.

Moreover, the pure steam plasma applied to the reforming of hydrocarbons as a clean energy source is effective for generating hydrogen with CO.

Table 1. Proximate and element analysis of Indonesian brown coal

Proximate analysis (wt.%)		Element analysis (wt.%)	
Water	10.71	Carbon	59.23
Volatile matter	32.53	Hydrogen	4.27
Ash	22.46	Nitrogen	1.19
Fixed carbon	34.30	Oxygen	12.71
Calorific value	4640(kcal/kg)	Sulfur	0.24

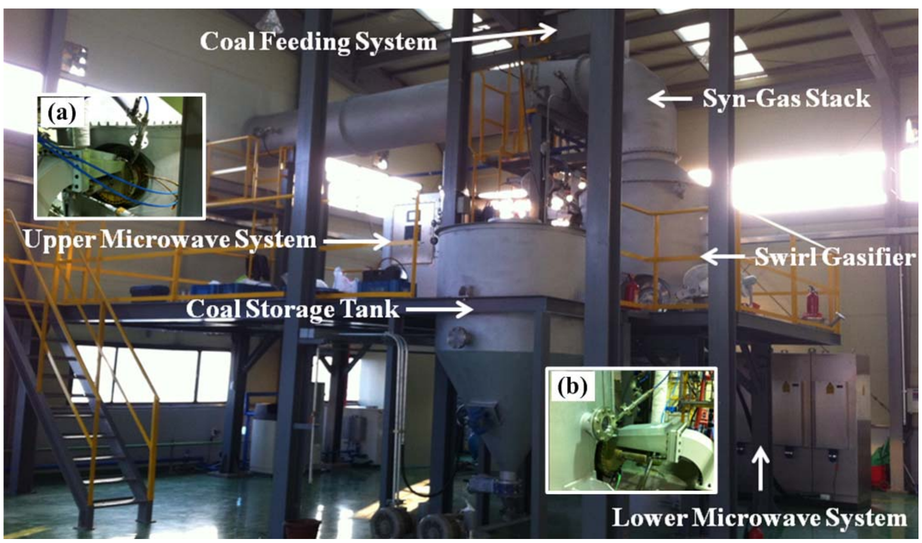

Figure 1. Image of the 500kW steam plasma gasification system. The 915MHz microwave plasma system was fully established on the (a) upper and (b) lower sections of the plasma gasifier.

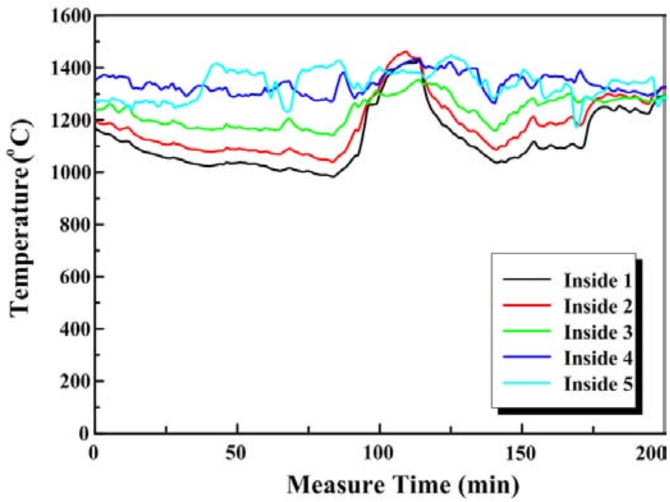

Figure 2. Temperature plots of the inner wall of the plasma gasifier in terms of measurement time. A total of five thermometers was vertically installed from the top (Temp. 1) to the bottom (Temp. 5) along the inner surface of the gasifier.

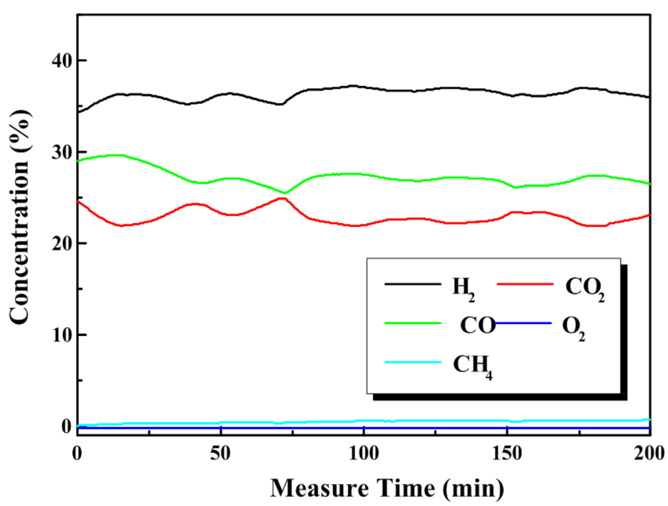

Figure 3. Relative concentrations of gas species in syn-gas in terms of measurement time. The gas analysis data provided the relative concentrations of H_2, CO, CO_2, CH_4, O_2 and the remaining gases, including N_2, H_2O, etc.

Acknowledgements

This study was funded by a grant in the 2013 National Agenda Project of the Korea Research Council of Fundamental Science and Technology. The study was also supported by the Korea Micro Energy Grid (K-MEG) project of the Korean Ministry of the Knowledge Economy and partially by the Degree and Research Center Program of the Korea Research Council of Fundamental Science and Technology.

References

[1] J. J. Minchener, Fuel 84 (2005), 2222.

[2] H. Watanabe and M. Otake, Fuel 85 (2006), 1935.

[3] H. Sekiguchi and Y. Mori, Thin Solid Films 435 (2003), 44.

[4] P. M. Kanilo, V. I. Kazantsev, N. I. Rasyuk, K. Schunemann and D. M. Vavriv, Fuel 82 (2003), 187.

[5] V. Galvita, V. E. Messerle and A. B. Ustimenko, Int. J. Hydrogen Energy 32 (2007), 3899.

[6] S. J. Yoon and J. G. Lee, Int. J. Hydrogen Energy 37 (2012), 17093.

[7] Y. Kalinci, A. Hepbasli and I. Dincer, Int. J. Hydrogen Energy 36 (2011), 11408.

[8] Ph. G. Rutberg, A. N. Bratsev, V. A. Kuznetsov, V. E. Popov, A. A. Ufimtsev and S. V. Shtengel, Biomass Bioenergy 35 (2011), 495.

[9] M. Minutillo, A. Perna and D. D. Bona, Energy Convers. Manag. 50 (2009), 2837.

[10] T. Fleisch, Y. Kabouzi, M. Moisan, J. Pollak, E. Castanos-Martinez, H. Nowakowska and Z. Zakrzewski, Plasma Sources Sci. Technol. 16 (2007), 173.

[11] G. Shanmugavelayutham and V. Selvarajan, Pramana-J. Phys. 61 (2003), 1109.

[12] H. S. Uhm, J. H. Kim and Y. C. Hong, Appl. Phys. Lett. 90 (2007), 211502.

[13] H. S. Uhm, J. H. Kim and Y. C. Hong, Phys. Plasmas 14 (2007), 073502.

[14] H. S. Uhm, Y. C. Hong, D. H. Shin and B. J. Lee, Phys. Plasmas 18 (2011), 104505.

[15] Y. C. Hong, S. J. Lee, D. H. Shin, Y. J. Kim, B. J. Lee, S. Y. Cho and H. S. Chang, Energy 47 (2012), 36.

[16] D. H. Shin, Y. C. Hong, S. J. Lee, Y. J. Kim, C. H. Cho, S. H. Ma, S. M. Chun, B. J. Lee and H. S. Uhm, Surf. Coat. Technol. 228 (2013), S520.

[17] Y. C. Hong and H. S. Uhm, Phys. Plasmas 13 (2006), 113501.

[18] Y. C. Hong, D. H. Shin and H. S. Uhm, Appl. Phys. Lett. 91 (2007), 161502.

[19] H. S. Uhm, S. C. Cho, I. G. Park and M. S. Hong, J. Korean Phys. Soc. 52 (2008), 1800.