

Clean Hydrogen Energy and Electric Power Production with CO₂ Capturing by Using Coal Gasification

Ahmad, Raheel; Saleem, Iqra^{*+‡}

Department of Chemical Engineering, University of Engineering and Technology, G.T. Rd, Lahore 54890, PAKISTAN

ABSTRACT: *Clean hydrogen is the major energy carrier for power production. The conversion of CO to CO₂ and zero emission during hydrogen energy production causes high capital cost. It is a matter of prestige to optimize the process in order to make zero emission and cost effective production of clean hydrogen energy and electric power. In this era, coal gasification is the most promising technology for the clean hydrogen energy and electric power production with simultaneously capturing of CO₂. The experimental set up used in this scheme consists of Fluidized Bed Coal Gasifier (FBCG), syngas treatment unit, electricity generation unit, CO₂ capturing unit and clean hydrogen adsorption unit. This paper shows the analysis of low sulphur Makarwal (Pakistan) coal. The Oxygen to Steam (O/S) ratio is optimized in order to produce syngas efficiently in the FBCG. The desulphurization unit reduces the H₂S contents below than 1ppm. In this experimental plant, the feed rate 37.5 tons/hr of coal is used and clean hydrogen is produced at the rate of 1.30-1.40 tons/h.*

KEYWORDS: *Makarwal coal; Coal gasification; Clean hydrogen; CO₂ capturing; Fluidized bed coal gasifier.*

INTRODUCTION

Energy remains very expensive and not easily available to everyone during the period of economic uncertainty and decrease in energy resources [1]. Energy demands will play a crucial role in future [2]. Energy resources have been categorized into three main types: fossil fuels, renewable resources and nuclear resources [3]. Amongst all energy resources fossil fuels are abundantly available and a major source of energy production [4]. Coal is one of the abundantly and uniformly available fossil fuel in the world as compared to others. This represents the good cost stability and excellent approach from strategic point of view.

Coal gasification is preferable as compared to others because it enables to generate electric power as well as fuel production with typical reference to hydrogen, which can be used as energy carrier [5]. According to recent analysis, hydrogen production in the world is more than one billions of cubic meter per day and 20% is produced from coal gasification [6].

Recently, a series of H₂ production processes have been reported such as, steam reforming of hydrocarbons [7], partial oxidation (POX) and catalytic partial oxidation (CPOX) of hydrocarbons [8], autothermal reforming of hydrocarbons [9], preferential oxidation and

* To whom correspondence should be addressed.

+ E-mail: iqra.saleem@uet.edu.pk

‡ Author shares equally

1021-9986/2016/4/143

10/\$/6.00

water-gas-shift reaction [10], desulfurization [11], pyrolysis [12], plasma reforming [13], thermocatalytic CO₂-free hydrogen from methane [14], H₂ from biomass [15], biomass gasification process [16], biological hydrogen [17], direct photolysis [18], dark fermentation [19] and photo-fermentative process [20]. However, the drawbacks concerned with these processes are, high steam and catalyst cost [21], high flame temperature [22], low thermal efficiency [23], high CO contents [24], high power consumption [25], NOX formation [26] and limit availability of organic acids and nitrogenase enzyme [27]. Therefore, In order to overcome these drawbacks, still there has been a major challenge to produce H₂ in an environmental-friendly and economical way with high conversion efficiency of CO to CO₂. Currently, global warming and environmental pollution are major concern during the energy production from fossil fuels. Therefore, it is a necessity to develop a platform for clean hydrogen energy and electric power production in reliable and economical way.

In this study, we mainly focussed on the production of hydrogen energy and electric power without creating any disturbance in the existing environment. This study shows that the CO₂-free hydrogen and electricity production via coal gasification with clean gas treatment line is a good approach way as compared to other reported techniques. Carbon sequestering is also a matter of concern in this strategy. Carbon monoxide (CO) is converted to CO₂ in water gas shift reactor and absorbed in efficient way from environmental point of view [28].

The long term benefits and objective of this research is to develop the new technique for energy production from coal in economical and clean way. We also developed the technological solution in the battle to reduce CO₂ emission and are trying to make zero emission platforms for the production of hydrogen energy and electric power, which indicates the minimum level of emission.

EXPERIMENTAL SECTION

Preparation of Optimized Size Coal

Coal is crushed into desirable size (25-50 mm) by utilizing a crusher (HCC cone crusher) and then entered into gasifier. The optimized size of coal was required to produce syngas efficiently. The International Standard Organization (ISO) protocol was followed for size distribution (ISO 1953:2015) [29].

Table 1: Ultimate Analysis of Makarwal Coal.

Component	Composition (%)
Carbon	71.100 ± 0.240
Hydrogen	5.900 ± 0.012
Nitrogen	1.400 ± 0.010
Oxygen	20.000 ± 0.030
Sulphur	1.100 ± 0.010
Ash	14.290 ± 0.015
Moisture contents	0.500 ± 0.010

Table 2: Proximate Analysis of Makarwal Coal.

Component	Composition (%)
Fixed Carbon	38.230 ± 0.080
Moisture	0.500 ± 0.010
Volatile matter	46.620 ± 0.050
Ash	14.650 ± 0.017

Ultimate Analysis of coal

The main components of Makarwal (Pakistan) coal are carbon, hydrogen, nitrogen, oxygen, ash and moisture contents (Table 1). The ultimate analysis was performed according to ISO 17247:2013 standard [30]. The percentage composition of all the elements was checked by using automatic element analyser (Flash EA 1112, USA). The flow rates of carrier gas, oxygen and reference gas were set at 120, 220 and 100 mL/min respectively. The temperatures of oven were set at 900 and 70 °C [30]. The elemental analyses were calculated at 1.8-2.0 mg with 0.002 mg precision. The standard deviation shows the three consecutive measurements of each sample. According to *J. Lee et al.*, 2015, the absolute difference should be 0.20-0.32 % for carbon and 0.01-0.02% for hydrogen [31].

Proximate Analysis of coal

In proximate analysis, we calculated fixed carbon, moisture, volatile matter and ash contents (Table 2). The standard deviation shows the three consecutive measurements of each sample. The proximate analysis was performed according to ISO 17246:2013 standard [32]. The proximate analyser was used to calculate the moisture contents. The technical analysis was used to calculate the fixed carbon and ash contents.

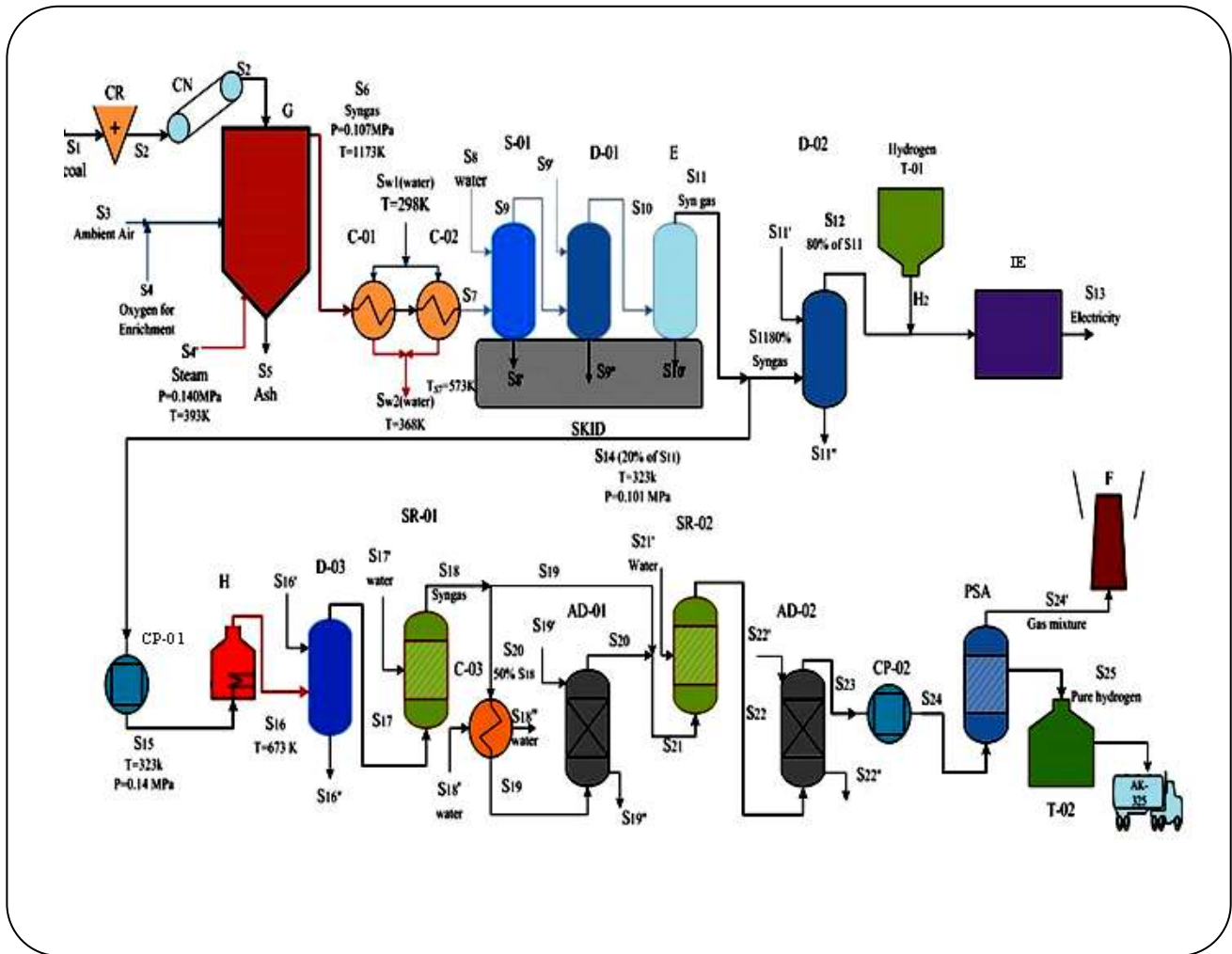
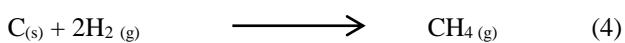
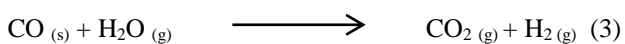
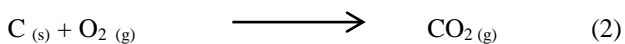
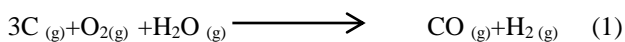


Fig. 1: Experimental plant configuration. (CR= Crusher, CN= Conveyor, G= Gasifier, C= Cooler, S= Scrubber, D= Desulphurizer, E= Electrostatic precipitator, IE= Internal combustion engine, H= Heater, CP= Compressor, SR= Shift reactor, AD= Absorber, PSA= Pressure Swing Adsorption Unit, T= Storage tank, F= Flare).

Experimental Procedure

A simple plant layout for the experimental test consists of Fluidized Bed Coal Gasifier (FBCG). The main reason to choose this type of coal gasifier is the higher conversion efficiency to syngas [32]. In this plant configuration, a coal is entered into gasifier at the flow rate of 37.5 tons/h and oxygen to steam (O/S) ratio was adjusted at 0.6. The following reactions were occurred in gasifier.



The main goal of this experimental test is to get hydrogen energy and electric power in optimized and clean way. The hot gases from gasifier were sent into cooler where temperature was reduced from 900 to 50 °C. After that the cold gases were sent into SKID (consists of scrubber, desulphurizer and electrostatic precipitator assembly) for tar, H₂S and dust removal, respectively. The major function of ElectroStatic Precipitator (ESP) was to remove dust and charge particles to make the stream of gases fit for internal combustion engine for the generation of electric power [34].

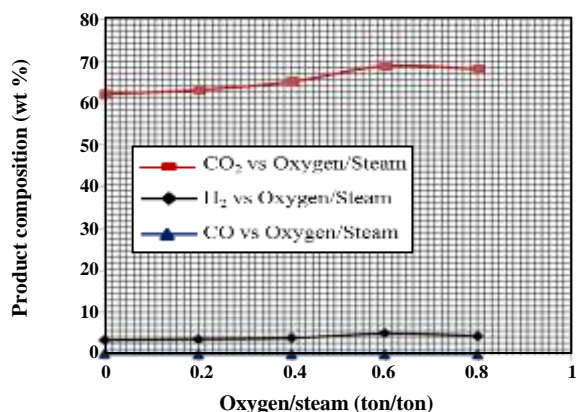


Fig. 2: Optimization of Oxygen to Steam (O/S) ratio.

After the SKID, the gas stream was divided into two proportions, 80% of stream was sent into the cold gas desulphurization unit to remove the remaining H₂S by absorption process. The diluted mixture of soda and sodium hypochlorite (Sigma-Aldrich, Analytical Grade, USA) solvent was used as an absorption media [35]. Next, the clean gas stream was sent into internal combustion engine to utilize these gases for power generation. The remaining 20% gas stream was sent into heater, where the temperature of the gases were raised from 50 to 400 °C for the removal of H₂S contents through two stage hot gas desulphurizer unit in which ZnO (Sigma-Aldrich, Analytical Grade, USA) was used as an absorption media [35]. Carbon monoxide (CO) was converted into CO₂ by utilizing the water gas shift reactor in which pressure was maintained at (0.25-0.3 MPa) and absorbed through integrated absorption system in which monoethanolamine (MEA) was used as an absorption media. The CO₂ absorption efficiency was 98%. Finally, the purified hydrogen was adsorbed by using Pressure Swing Adsorption (PSA) unit. The pressure (300 kPa) was maintained in the PSA unit to obtain the maximum adsorption efficiency. After certain limit of hydrogen adsorption, the adsorption bed was saturated and regeneration of the bed was needed. For the recovery of hydrogen and regeneration of adsorption bed, fixed value of pressure was released and hydrogen comes out from adsorption bed and regeneration was done by pressure gradient principle. Adsorption efficiency was 99.99% in this system. The flexibility and proper management of the plant was fully assured. The equipments of the plant can be modified according to need without significant increase in the cost.

RESULTS AND DISCUSSION

Optimization of Oxygen to Steam ratio (O/S ratio)

Fig. 2 shows the effect of Oxygen to Steam (O/S) ratio on the composition of product. As the O/S ratio was increased, firstly the amount of CO₂ was increased and finally reached at maximum value of 68.7% (percentage composition) at 0.60 O/S ratio, after that it started to decrease. Therefore, with the increased in O/S ratio CO contents reduced and finally started to increase after 0.6 O/S ratio, the minimum amount was reached to 0.12% (percentage composition) in this study. Moreover, when the O/S ratio was 0.6.

Temperature Profiles in Fluidized Bed Coal Gasifier

Fig. 3, shows the temperature profile of FBCG. There are four different temperature zones in the gasifier. The phase 1 has been measured 20 min later and phase 2 after another 20 min (maximum temperature reached at 550 °C). Phase 3 was obtained at 100 min, when the combustion and gasification reactions were in progress. The steady state (phase 4, in which the maximum temperature in the combustion and gasification zone was approximately 900 °C) was reached at 150 min after the start of gasification.

Integrated CO-shift reactor and CO₂ Capturing

In order to enrich the syngas in hydrogen, the plant was equipped with an integrated CO-shift and CO₂ absorption process. In particular, desulphurized syngas was enriched with steam and sent to the high temperature CO-shift stage (which operates at 400 °C). A portion of the reacted gas (about 20%, according with the design conditions) was cooled and sent to the first CO₂ absorption stage and subsequently sent to the low temperature CO-shift reactor (operating at 250 °C). Downwards the second CO-shift stage, all reacted syngas was sent to the final CO₂ absorption reactor. This integrated configuration allowed to maximize the carbon monoxide conversion and to reduce the steam injection. The high and low temperature CO-shift reactors were filled with two different non piroforic platinum-based catalysts [35].

In these operative conditions, a CO conversion was very close to those corresponding to the chemical equilibrium (higher than 90% in the first stage and about

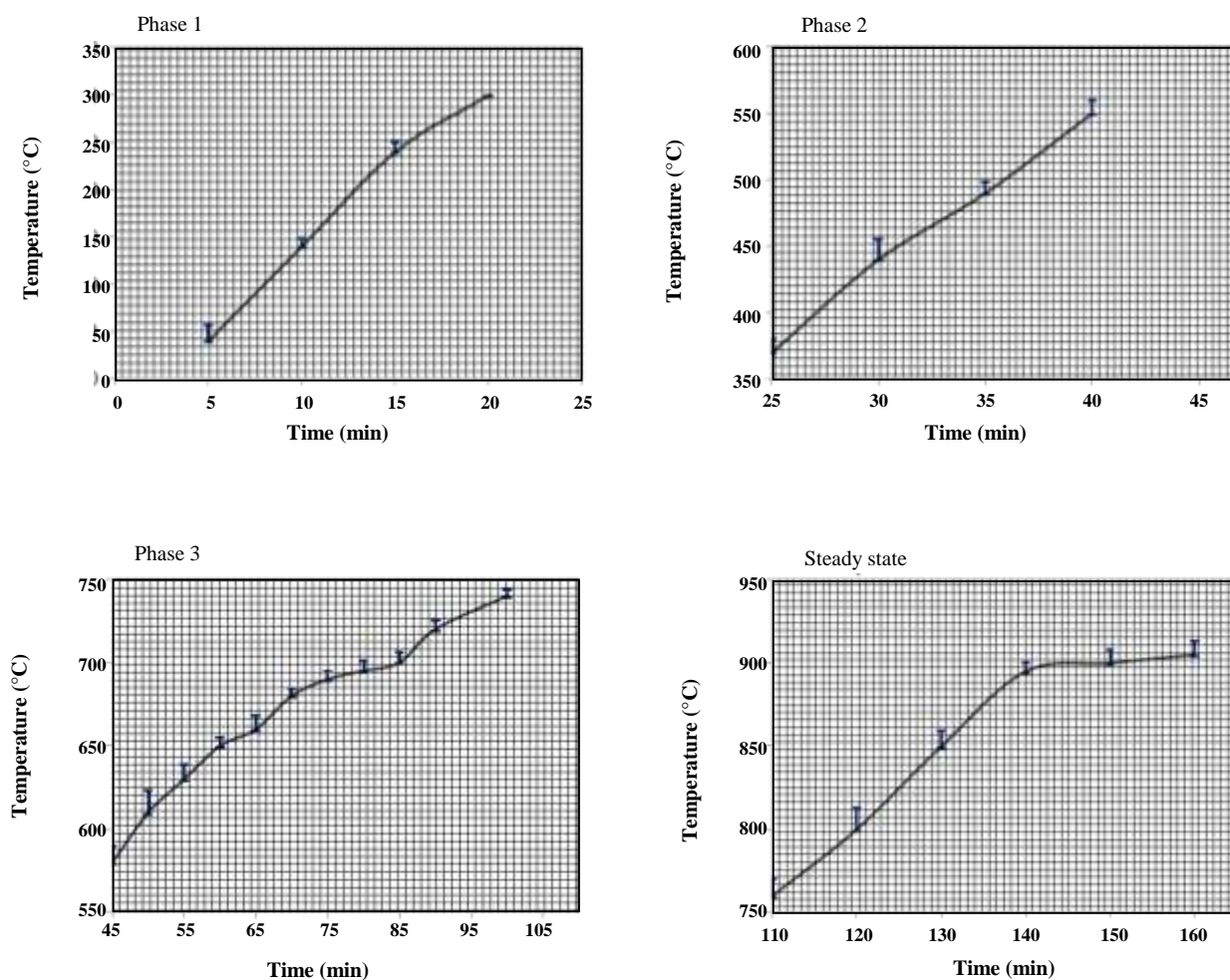


Fig. 3: Temperature Profiles in Gasifier.

85% in the second stage, with a final CO content lower than 1%) has been obtained (Table 3 & 4). On the other hand, the CO₂ was captured (Table 5) in two identical reactors (operating at 30 °C) by using a monoethanolamine (MEA) solution (diluted in water) as a solvent [35].

Hydrogen Production and power generation

As mentioned earlier, pure hydrogen was obtained by CO₂ capturing process and adsorbed by utilizing Pressure Swing Adsorption (PSA) unit (Table 6). The shifted carbon dioxide was removed in a bulk carbon dioxide removal system for sequestration. The synthesis gas with the carbon dioxide removed was sent into the PSA units, where 99.99% of pure hydrogen was recovered. The PSA

tail gas was compressed and sent to the combined cycle (CC) plant for power production [36, 37].

Behaviour of Pressure Swing Adsorption Unit

Finally, the remaining gas stream contained enriched and purified hydrogen. The Fig. 4 represents the profile of pressure swing adsorption unit in which pure hydrogen was adsorbed up to 99.99%. The steady state of the system was reached after (90-100 min) and regeneration step was needed after saturation state.

Overall Experimental Plant Results

The entering and leaving streams across the gasifier are shown in Fig. S1. The gasification test results suggested that the 95% of carbon (C) was converted into syngas,

Table 3: Integrated CO-Shift Reactor 1.

Component	Input S17+S17' (tons/h)	Output S18 (tons/h)
H ₂ O	0.021	--
N ₂	5.810	5.810
H ₂	1.388	1.160
CO	0.012	0.005
CO ₂	18.867	18.874
CH ₄	0.176	0.176
H ₂ S	0.001	0.001
COS	0.002	0.002
Total	26.277	26.028 ± 0.249

Table 4: Integrated CO-Shift Reactor 2.

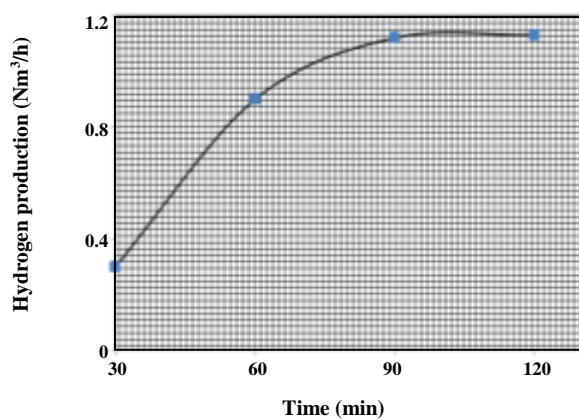
Component	Input S21+S21' (tons/h)	Output S22 (tons/h)
H ₂ O	0.003	--
N ₂	5.810	5.810
H ₂	1.388	1.388
CO	0.005	0.000
CO ₂	10.384	10.390
CH ₄	0.176	0.176
H ₂ S	0.000	0.000
COS	0.009	0.009
Total	17.775	16.954 ± 0.731

Table 5: CO₂ Capturing by MEA.

Component	Input S22+S22' (tons/h)	Output S22" (tons/h)	Output S23 (tons/h)
MEA	28.332	28.332	--
N ₂	5.810	--	5.810
H ₂	1.388	--	1.388
CO	0.001	--	0.001
CO ₂	10.388	9.870	0.484
CH ₄	0.176	--	0.176
H ₂ S	0.000	--	0.000
COS	0.009	--	0.009
Total	46.068	38.202 ± 0.280	7.868 ± 0.127

Table 6: H₂ Adsorption by PSA.

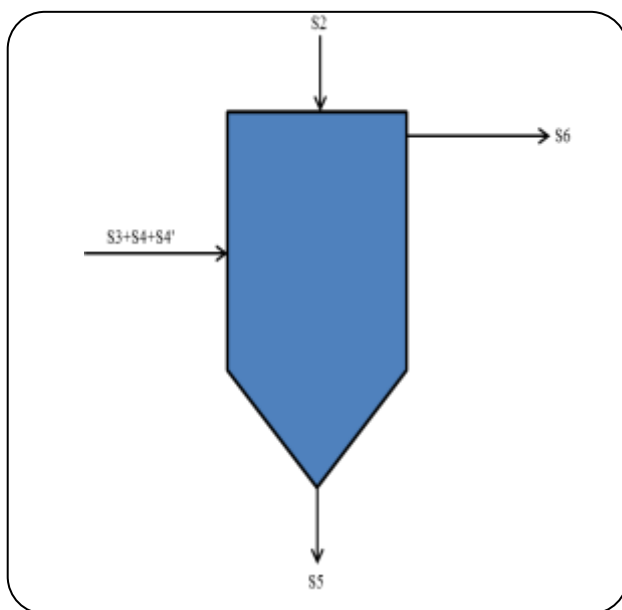
Component	Input S24 (tons/h)	Output S25 (tons/h)	Output S24' (tons/h)
N ₂	5.810	--	5.810
H ₂	1.388	1.387	0.001
CO	0.001	--	0.001
CO ₂	0.484	--	0.484
CH ₄	0.176	--	0.176
H ₂ S	0.000	--	0.000
COS	0.009	--	0.009
Total	7.640	1.340±0.05	6.480 ± 0.003

**Fig. 4: Behaviour of PSA.**

carbon dioxide and methane (Table 7). The energy required for gasification reaction is shown in Table 8. We calculated the total energy on base of law of conservation of energy [38]. Fig. 6 (19 streams entered and 18 streams leaved) and Fig. 7 (19 streams entered and 22 streams leaved) shows the general sketch of the whole experimental plant for easy understanding and calculations of material and energy balances. The Table 9 shows the overall material entering, utilizing at each section and leaving across the plant, while Table 10 shows the overall energy entering, utilizing at each section and leaving across the plant.

Table 7: Gasification Test Result (Material Balance).

Components	Input S2 (tons/h)	Input S3+S4+S4' (tons/h)	Output S5+S6 (tons/h)
Coal	37.500	--	--
Steam	--	44.625	--
O ₂	--	26.593	--
N ₂	--	28.603	29.050
H ₂	--	--	6.940
CO	--	--	0.168
CO ₂	--	--	94.160
CH ₄	--	--	0.880
COS	--	--	0.185
H ₂ S	--	--	0.316
Tar	--	--	0.263
Ash	--	--	5.360
Total	37.500	99.822	137.100 ± 0.160%

**Fig. 5: General Sketch of Gasifier.**

CONCLUSIONS

The coal to hydrogen and electric power production experimental plant allowed obtaining data and optimizing the process of entire plant. The result shows the pure hydrogen (1.14-1.16 tons/h) and electric power (approx.300 MW_{th}) were produced at a coal feed rate of 37.5 tons/hr. All sulphur contents and particulate solids are removed by syngas cleaning system to meet environmental standards. The hot gas desulphurization unit with ZnO as absorbent was used to reduce H₂S concentration below than 1 ppm in the exit stream. The CO₂ was produced from CO in water gas shift reactor captured by carbon sequestration process in which absorbed efficiency was 98%. Finally, the pure hydrogen was adsorbed by using pressure swing adsorption unit in which 99.99% pure hydrogen was adsorbed. Therefore, this developed strategy worked perfect in accordance with global energy balance. This plant layout is very

Table 8: Gasification Test Result (Energy Balance).

Component	Input S2		Input S3+S4+S4'		Output S5+S6		
	m' (tons/h)	ΔH (MJ/h)	m' (tons/h)	ΔH (MJ/h)	m' (tons/h)	ΔH (MJ/h)	ΔH°_r (MJ/h)
Coal	37.500	768750	--	--	--	--	507700.700
Steam	--	--	2.478	2501	--	--	--
O ₂	--	--	--	--	--	--	--
N ₂	--	--	--	--	29.050	49447.060	--
H ₂	--	--	--	--	6.940	115595.700	--
CO	--	--	--	--	0.168	279.350	870120.100
CO ₂	--	--	--	--	94.160	174348.400	--
CH ₄	--	--	--	--	0.880	3883.600	--
COS	--	--	--	--	0.185	607.670	--
H ₂ S	--	--	--	--	0.315	795.650	--
Tar	--	--	--	--	0.263	3186.850	--
Total	--	768750	--	25011	--	348138.700± 0.180%	587820.800± 0.210%

Table 9: Overall Plant Experimental Test Result (For Material Balance).

Total In (tons/hr)	Total Out (tons/hr)
S2+S3+S4+S7+S8+S9+S10+S11+S16+S17+S19+S21+S4'+S9'+S11'+S16'+S17'+S21'+S22'	S5+S9+S10+S12+S17+S18+S20+S22+S23+S8'+S9'+S10'+S11'+S16'+S19'+S21'+S22'+S24'
701.400	700 ± 0.2%

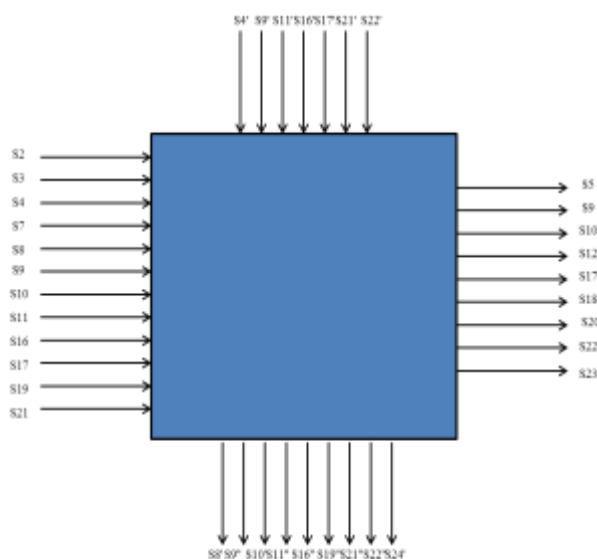


Fig. 6: General Sketch of Plant Layout (For Material Balance).

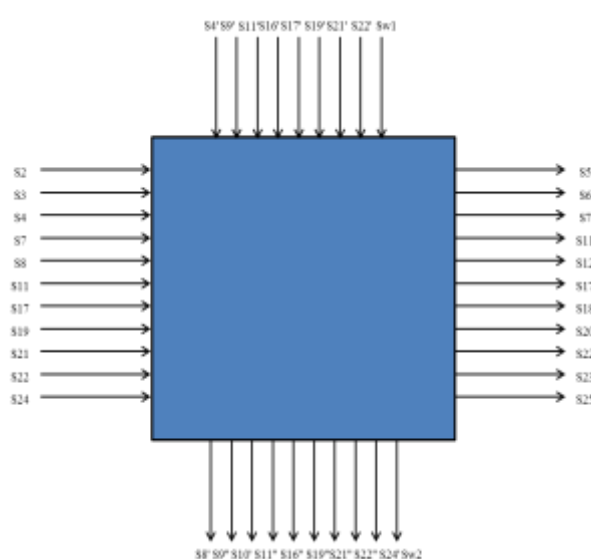


Fig. 7: General Sketch of Plant Layout (For Energy Balance).

Table 10: Overall Plant Experimental Test Result (For Energy Balance).

Total In (MJ/h)	Total Out (MJ/h)
S2+S3+S4+S4'+S7+S8+S9+S11+S11'+S16+S17+S17'+S19+S19'+S21+S21'+S16'+S17'+S21'+S22+S22'+S24+Sw1	S5+S6+S7+S8'+S9'+S10'+S11+S11'+S12+S16'+S9'+S10'+S11'+S16'+S18+S19'+S20+S21'+S22+S22'+S23+S24+S25+Sw2
1.500×10^6	$1.490 \times 10^6 \pm 0.600\%$

compatible for clean hydrogen energy and electric power production by simultaneous capturing of CO₂ in cost efficient and clean environment way.

Acknowledgement

We acknowledged the support of the Department of Chemical Engineering, University of Engineering and Technology Lahore, Pakistan

Received : Feb. 15, 2016 ; Accepted : Jun 13, 2016

REFERENCES

- [1] "World Energy Outlook.", [International Energy Agency](#) IEA 9 Rue de la Fédération 75739 Paris Cedex 15, France, WEO:IEA (2015).
- [2] Demirba S.A., [Global Renewable Energy Resources](#), *Energy Sources*, **28**: 779-792 (2006).
- [3] Demirba S.A., [Energy Facilities and Nuclear Power Program by 2020 in Turkey](#), *Energy Sources*, **23**: 401-415 (2001).
- [4] "World Energy Outlook.", [International Energy Agency](#), IEA 9 Rue de la Fédération 75739 Paris Cedex 15, France, WEO:IEA (2008).
- [5] Gary J., Stiegel., Massood, Ramezan., [Hydrogen from Coal Gasification: An Economical Pathway to a Sustainable Energy Future](#), *Int. J. Coal. Geol.*, **65**: 173-190 (2006).
- [6] [Coal Information](#), International Energy Agency, 9 Rue de la Fédération 75739 Paris Cedex 15, France, IEA (2016).
- [7] Farrauto R., Hwang S., Shore L., Ruettinger W., Lampert J., Giroux T., Liu Y., Ilinich O., [New Material Needs for Hydrocarbon Fuel Processing: Generating Hydrogen for the Pem Fuel Cell](#), *Annual Review of Materials Research*, **33**: 1-27 (2003).
- [8] Timm D.L., Onsan Z.I., [On Board Fuel Conversion for Hydrogen-Fuel-Cell-Driven Vehicles](#), *Catalysis Review*, **43**: 31-84 (2001).
- [9] Krumpelt M., Krause T.R., Carter J.D., Kopasz J.P., Ahmed S., [Fuel Processing for Fuel Cell Systems in Transportation and Portable Power Applications](#), *Catalysis Today*, **77**: 3-16 (2002)
- [10] Pietrogrande P., Bezzeccheri M., in: Blomen L.J.M.J., Mugerwa M.N., "[Fuel Cell Systems](#)", Plenum Press, New York pp. 121–156 (1993).
- [11] Ke Liu1, Chunshan Song, Velu Subramani., [Hydrogen and Syngas Production and Purification Technologies](#), John Wiley & Sons, Ltd (2009).
- [12] Muradov N., [Thermocatalytic CO₂-Free Production of Hydrogen from Hydrocarbon Fuels](#), *Power P., Source J.*, **118**: 320-324 (2003).
- [13] Matsui Y., Kawakami S., Takashima K., Katsura S., Mizuno A., [Liquid-Phase Fuel Re-Forming at Room Temperature Using Nonthermal Plasma](#), *Energy Fuels*, **19**: 1561-1565 (2005).
- [14] Yan, Wei, Hoekman, S. Kent., [Production of CO₂-Free Hydrogen from Methane Dissociation: A Review](#), *Environ. Prog. Sustainable Energy*, **33**(1): 1944-7450 (2005).
- [15] Chum H.L., Overend R.P., [Biomass and Renewable Fuels](#), *Fuel Process Technol.*, **71**: 187-195 (2001).
- [16] Demirbas M.F., [Hydrogen from Various Biomass Species via Pyrolysis and Steam Gasification Processes](#), *Energy Sources*, **28**: 245-252 (2006)
- [17] Carrieri D., Kolling D., Ananyev G., Dismukes G.C., [Prospecting for Biohydrogen Fuel](#), *Ind Biotechno*, **2**: 133-137 (2006).
- [18] Turner J., Sverdrup G., Mann M.K., Maness P.-C., Kroposki B., Ghirardi M., Evans R.J., Blake D., [Renewable hydrogen production](#), *Int. J. Hydrogen Energy*, **32**:379–407 (2008)
- [19] Khanal S.K., Chen W.-H., Li L., Sung S., [Biohydrogen Production in Continuous-Flow Reactor Using Mixed Microbial Culture](#), *Water Environment Research*, **78**: 110-117 (2006).

- [20] Sørensen B., “Hydrogen and Fuel Cells Emerging Technologies and Applications”, Elsevier Academic Press, New York, pp. 450 (2011)
- [21] Song H, Zhang L., Ozkan U.S., Effect of Synthesis Parameters on the Catalytic Activity of Co–ZrO₂ for Bio-Ethanol Steam Reforming, *Green Chemistry*, **9**: 686-694 (2007).
- [22] Tonkovich A.Y., Perry S., Wang Y., Rogers W.A., Qui D., Peng Y., Microchannel Process Technology for Compact Methane Steam Reforming, *Chem. Eng. Sci.*, **98**:575–581 (2004).
- [23] Tomasz C, Marek S., Co-Gasification of Biomass and Coal for Methanol Synthesis, *Applied Energy*, **74**:393-403 (2003)
- [24] TeGrotenhuis W.E., King D.L., Brooks K.P., Golladay B.J., Wegeng R.S., in: Baselt J.P., Eul U., Wegeng R.S. (Eds.), “Optimizing Microchannel Reactors by Trading off Equilibrium and Reaction Kinetics Through Temperature Management”, AIChE, New Orleans, LA, p. 18 (2002).
- [25] O’Brien C.J., Hochgreb S., Rabinovich A., Bromberg L., Cohn D.R., in: “Proceedings of the Intersociety Energy Conversion Engineering Conference, Hydrogen Production via Plasma Reformers”, IEEE, Piscataway, Washington, DC, USA, pp, 1747–1752 (1996)
- [26] Belafi-Bako K., Bucsu D., Pientka Z., Balint B., Herbel Z., Kovacs K.L., Wessling M., Integration of Biohydrogen Fermentation and Gas Separation Processes to Recover and Enrich Hydrogen, *Int. J. Hydrogen Energy*, **31**: 1490–1495 (2006)
- [27] Kovacs K.L., Maroti G., Rakhely G., A Novel Approach for Biohydrogen Production, *Int. J. Hydrogen Energy*, **31**: 460–1468 (2006).
- [28] Adennis Y. C. Leung., Giorgio. Caramanna B.M. Mercedes Maroto-Valer. B., An Overview of Current Status of Carbon Dioxide Capture and Storage Technologies, *Renewable & Sustainable Energy Reviews*, **39**: 426–443 (2006).
- [29] International Standard Organization, “ISO 1953:2015, Hard Coal-Size Analysis by Sieving”, Geneva Switzerland (2015).
- [30] International Standard Organization, “ISO 17247:2013, Coal-Ultimate Analysis”, Geneva Switzerland (2013).
- [31] Lee J., Im G., Yoo J.-H., Lee S., Jeon E.-C., Development of Greenhouse Gas (CO₂) Emission Factored for Korean Coal Briquettes, *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, **37**:1415–1423 (2015).
- [32] International Standard Organization “ISO 17246:2010, Coal-Proximate Analysis”. Geneva Switzerland (2010)
- [33] Pan Y.G., Velo E., Roca X., Manya` J.J., Puigjaner L., Fluidized-bed Co-Gasification of Residual Biomass/Poor Coal Blends for Fuel Gas Production, *Fuel*, **79**:1317-1326 (2000).
- [34] Buonicore. A.J., “Air Pollution Control Equipment, Design, Selection, Operation and Maintenance”: Prentice-Hall (1982).
- [35] Pettinau A, Orsini A, Calì G, Ferrara F., The Sotacarbo Coal Gasification Experimental Plant For a CO₂-Free Hydrogen Production, *Int. J. Hydrogen Energy*, **35**: 9836-9844 (2010).
- [36] Benini. E., “Progress in Gas Turbine Performance”, InTech, (2013).
- [37] Avinash K.A., Biofuels (Alcohols and Biodiesel) Applications as Fuels for Internal Combustion Engines, *Prog. Energy Combust. Sci.*, **33**: 233-271 (2007).
- [38] Himmelblau D.M., “Basic Principles & Calculations in Chemical Engineering”: Prentice-Hall (1989).