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Gasification of Non-Coking Coals

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Abstract

Increasing energy demand in different sectors such as residential sector, commercial sector, industrial sector and transportation sector is affecting future energy demand-supply chain. Due to the depletion of natural gas and oil sources future energy demand is highly dependent on coal. In India coal is a primary energy source which contributes around 70% in electricity generation. However, Indigenous coal has several drawbacks such as high ash content, lower efficiency and causing environmental pollution which has drastic effect on global warming. Therefore, there is a need of clean coal technology which reduces the causes of CO_2 emission which is badly affecting global warming. Integrated Coal Gasification Combined Cycle (IGCC) technology is developed worldwide to reduce carbon dioxide emission by carbon capture and sequestration. Therefore gasification of coal becomes necessary to meet environmental regulations. In this paper an attempt has been made to compile the investigations carried out by various researchers on coal pyrolysis and gasification.

1. Introduction

The increasing worldwide population and economic growth will continue to lead to drastic increases in energy demand –supply chain. Among the different sources of energy coal has a largest market share in global electricity generation. India is the 4th largest coal producer country in the world after USA, Australia and China as well as India is a 3rd largest coal consumer country in the world after USA and China [1]. Major part of commercial coal in the country is utilized in power generation (72%), rest is utilized in cement (5%) and steel (14% steel, coke oven 10% and steel DR 4%) sectors [2]. Coal will continue to be an important energy source in different sectors worldwide. In the meantime the impact of coal in environment is also taken into consideration because of increasing air pollution and global warming problems. To reduce the CO_2 emission from exhaust gas in conventional coal combustion process is difficult. Therefore clean coal technology has become essential. Clean coal technology along with carbon capture and sequestration is able to emerge as zero emission technology. Some of the important clean coal technologies are oxy fuel combustion, super critical (SC) and ultra super critical (USC), fluidized bed combustion (FBC) and integrated gasification combustion cycle (IGCC) with or without carbon capture. Gasification of coal is a clean environmental regulatory and efficient way to convert solid fuel into gaseous product to produce electricity.

Now Integrated Coal Gasification Combined Cycle (IGCC) power plants are developed worldwide to reduce CO_2 emission. A national IGCC demonstration project in Japan is now underway, and in 2007 a 250 MW IGCC demonstration plant with an air-blown entrained flow coal gasifier will be constructed [3]. Gasification technology of coal depends upon the coal properties, gasification technology and operating conditions. The coal gasification process of IGCC is carried out at high pressure and temperature (1200-1600^{o}C, 2.5 MPa) [4]. Coal gasification occurs in two steps: (a) pyrolysis and (b) gasification. In IGCC plants first fuel gas is generated in coal gasifier and this gas is purified. The purified gas is sent to the gas turbine, where it allows to burn with compressed air to

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produce stream of hot gas which is used to drive turbine which generates electricity. Coal gasification is suitable for the coproduction of electricity and hydrogen. The use of hydrogen produced from gasification of coal in power plants and synthesis application is a considerable interest worldwide. There are several possible alternatives which involve combination of different technologies for the production of liquid fuels, electricity, hydrogen and capture of CO_2. In this paper an attempt has been made to compile the outcome of several researchers [1,2,3,4,5,6,7,8,9,10,11,12,13,14,15] on mechanism of coal pyrolysis, effect of operating condition on coal pyrolysis products, char gasification and effect of operating conditions on char gasification.

2. Coal Pyrolysis

Gasification of coal consists of two major steps first coal pyrolysis and second gasification of char. Coal pyrolysis is the initial step in coal conversion processes such as gasification and combustion. Coal pyrolysis is process which is dependent on the organic properties of the coal. Due to the complexity in coal structure coal pyrolysis consists of series of complex reactions. As the rank of coal increases the coal structure becomes more organized and simplified.

When the coal is heated in absence of air at high temperature, it is pyrolyzed and is divided into two fractions volatile mater and carbon rich solid residue. If the carbon rich solid residue obtained from coal pyrolysis is in powder form it is called char and if the same is in agglomerated form it is known as coke. Volatile matter is a mixture of oxides of carbon, H_2O, CH_4, C_2H_6, C_2H_2, C_2H_4, H_2, subpar, nitrogen, light oils and tars [1]. Over the past few decades the behaviors of coal pyrolysis under different conditions have been studied [5, 6, 7]. Coal pyrolysis is manly divided into two stages i.e., primary pyrolysis which is upto 550-600^oC and secondary pyrolysis which is upto 1000-1050^oC [1]. Some gases and tar are evolved in primary stage of pyrolysis and only gas is split off in secondary stage of pyrolysis. During pyrolysis non coking coals are not softened and resolidified. Tar and gas yield is highly depend on the rank of coal. High rank coal produces low yield of gases and moderate or low yield of tar while low rank coal produces a low yield of tar and high yield of gases. There are variety of techniques of pyolsis involved in experimental investigations by different researchers, such as drop tube furnance (DTF), wire mesh reactors and thermo gravimetric analyzers.

Solomon et al. [5] gave an imaginary picture of coal at different stages of pyrolysis, Figure 1 shows: a) raw coal, b) tar formation and light hydrocarbons formation during primary pyrolysis and c) condensation of char and cross linking at the time of secondary pyrolysis.

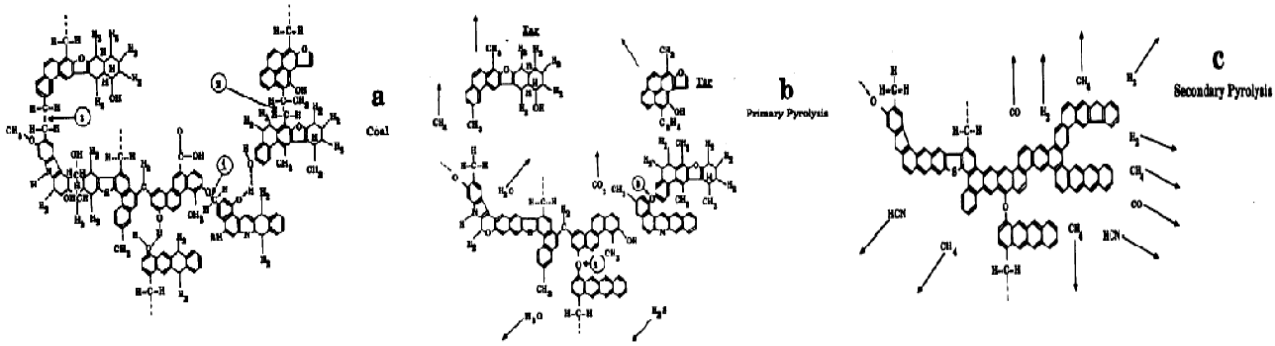

Fig: 1. Hypothetical coal molecule during storage of pyrolysis [5].

Khare et al. [8] proposed five reactions of coal pyrolysis. These five reactions are: reaction 1: dehydration, reaction 2: primary devolatilization/thermal desorption of gases, reaction 3: thermal degradation, reaction 4: secondary devolatization and reaction 5: dehydrogenation/condensation.

3. Effect of Operating Conditions on the Yield of Coal Pyrolysis

3.1Products Effect of Coal Rank

Xu and Tomita [9] studied the pyrolysis of 17 coals and reported that yield of total volatile matter and gas decreases with increase in rank of a coal

3.2Effect of Temperature

Different researchers [10, 11] investigated the effect of temperature on the products of coal pyrolysis. With the increase in peak temperature the yield of pyrolysis products increases. Figure 2 shows effect of temperature.

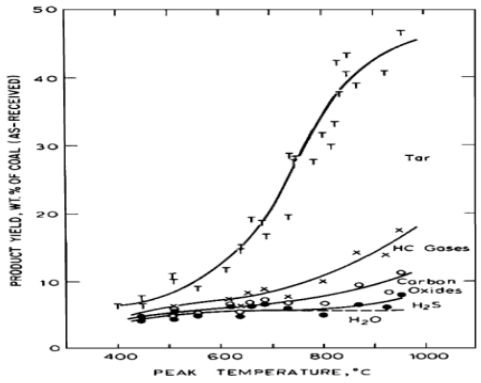

Fig: 1. Yield of pyrolysis products increases as peak temperature increases [10].

3.3Effect of Pressure

Yield of volatile matter and tar decrease and yield of gases increases with increase in pressure [10, 12].

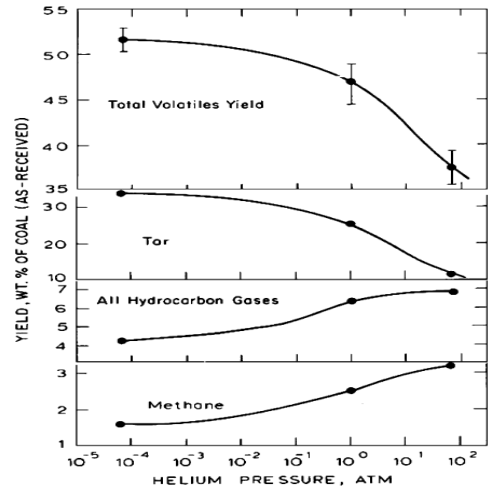

Fig: 3. yield of products verses pressure during pyrolysis (Pittsburgh no. 8 coal at 997oC)[10].

3.4Effect of Particle Size

Yield of products of pyrolysis is affected by particle size. Yield of tar deceases and yield of char increases with increase in particle size [1]. Anthony [13] reported that with the increase in particle size within the range of 53-100 mm for Pittsburgh seam bituminous coal the yield of volatile matter decreases.

4. Char Gasification

Coal gasification is defined as the reaction of coal at elevated temperature (exceeding 700^{o}C) with air, oxygen, carbon dioxide and steam to yield gaseous products which are suitable to use as a gaseous fuel. Gasification technology is used in IGCC plants for the production of electricity with reduced emission of carbon dioxide. Oxygen gasification can be a route of production of hydrogen from coal with CO_2 capture and sequestration because it is easy to remove carbon dioxide from pressurised syngas (precombustion) rather than the exhaust gas. There is a continuous reduction in weight loss of char during gsification process due to conversion of char into gaseous products. Captured CO_2 gas can be put to good use even on a commercial basis for recovery of oil (EOR). Combustion of coal is carried out in the excess of air while in gasification of coal usually one fifth to one third of theoretical amount of oxygen is required for complete combustion. Gasification process is a controlled form of combustion process in limited supply of oxygen.

During gasification process coal particles are dried with the help of hot gas which is followed by the pyrolysis of coal as the temperature of coal particles reaches 400^{o}C [1]. The products of pyrolysis is tar, phenol, oils, hydrogen rich volatile hydrocarbon gases and carbon residue as char which contains mainly carbon and mineral matter. Gasification reactions begins after the temperature of char exceeds 700^{o}C.char gasification reactions are [1]:

1. **Partial combustion:**
   $C+1/2\ O_2 = CO$ ΔH=-123.1 KJ/mol (1)
2. **Oxygen combustion:**
   $C+O_2 = CO_2$ ΔH=-405.9 KJ/mol (2)
3. **Carbon gasification (Boudouard reaction)**:
   $C+CO_2 = 2CO$ ΔH= 159.7 KJ/mol (3)
4. **Steam gasification (water gas reaction):**
   $C+H_2O= CO=H_2$ ΔH=118.9 KJ/mol (4)
5. **Hydrogen gasification (hydro gasification reaction):** $C+2H_2= CH_4$ ΔH=-87.4KJ/mol (5)
6. **Water gas shift reaction:**
   $CO+H_2O= H_2+CO_2$ ΔH= -40.9 KJ/mol (6)
7. **Methanation:**
   $CO+3H_2= CH_4+H_2O$ ΔH=-206.3 KJ/mol (7)

Future use and chemical composition of the gas produced during gasification are depending on several parameters such as [1]: a) coal particle size, b) pyrolysis conditions such as temperature, pressure, heating rate and time, c) rank and properties of coal, d) gasifying agent employed, e) types of gasifier, f) gasification conditions such as temperature, pressure, residence time and heating rate.

5. Effects of Operating Conditions on Char Gasification

5.1Pyrolysis Conditions

Effect of different pyrolysis conditions on char gasification are discussed below [1]:

a. **Heating rate:** During pyrolysis affects the gasification reaction, as heating rate decreases gasification reaction become slower.
b. **Temperature:** With increase in peak temperature during pyrolysis char gasification reaction becomes slower.
c. **Pressure:** There is also a effect of pressure during pyrolysis on char gasification but still no common trend has been found between gasification reactivity and pyrolysis pressure.

5.2Effect of Gasification Temperature

Several researchers studied [14, 15] the effect of temperature on gasification reaction. In the case of CO_2 and steam gasification reactions, reaction rates increase with increase in temperature. Ye et al. [14] investigated the effect of temperature on the reaction rate of H_2O and CO_2 gasification of Bowmans coal of particle size 1.6-2.4 mm. Figure 4 shows that with the increasing reaction temperature for H_2O and CO_2 gasification, gasification rate increases.

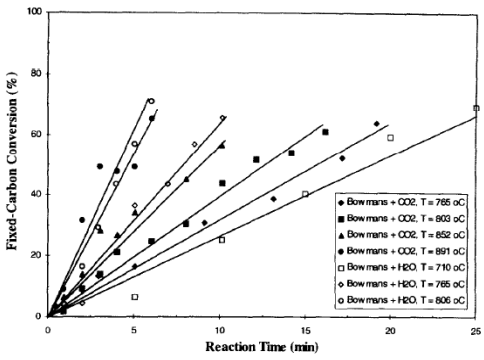

Fig: 4. Fractional conversion verses reaction time for CO2 and H2O gasification of Bowmans coal at different temperatures [14].

Liu et al. [15] also investigated the effect of temperature on three different chars under a stream of CO_2 at atmospheric pressure and temperature ranging from 1000-1300^oC and results of Liu et al. [15] showed that for each char with same reaction time, percentage of carbon conversion increases with temperature so the gasification rate is temperature dependent.

5.3Effect of Pressure on Gasification

Pressure affects the gasification reaction in two ways[1]: 1) by changing the reactant partial pressure or concentration and keeping total system pressure constant, 2) by changing the total system pressure and keeping reactant partial pressure fixed. Several researchers studied the effect of pressure on gasification reaction.

5.4 Effect of Particle Size on Gasification:

There is a significant effect of particle size on the gasification reaction. Generally, with the decrease in particle size rate of gasification reaction increases. Ye et al. [14] investigated the effect of size of particle on fixed carbon conversion of Bowmans coal during CO_2 and steam gasification at a temperature of 765^oC.figure shows the results of Ye et al. [14]. It can be seen from the Figure 5 that both CO_2 and H_2O gasification are independent of particle size. Within the range of accuracy of experiment, it can be stated that the particle size does not influence the gasification rate under experimental conditions of Ye et al. [14].

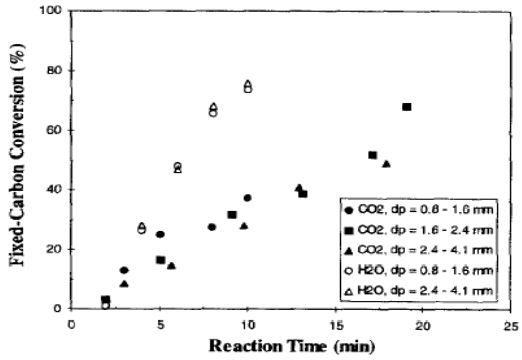

Fig: 5. Fixed carbon conversion of Bowmans coal during H2O and CO2 gasification for different particle size at reaction temperature of 765oC [14].

6. Conclusion

On the basis of results of various authors reviewed and discussed in the papers the following conclusions have been drawn:

1. Gasification of coal take place in three steps namely pyrolysis, combustion and gasification, each step plays very important role.
2. The physico-chemical properties and degree of pyrolysis plays very important role in determining the gasification behavior of char.
3. Processing parameters like temperature, pressure and types of gasifier are responsible for controlling the gasification behavior of char.

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