Coal Gasification as a Cleaner Technology -A Scoping Review On Technology, Process and Environment Issues

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Abstract. Coal gasification for various types of fuel production can perform an essential strategic requirement in those emergent countries where coal is the primary fuel resource and oil and gas energy security is a problem. Coal gasification is accepted as a cleaner technology compared with the conventional method of power generation, hydrogen, methanol, and other liquid fluids. This paper presents a review of current research carried out on coal gasification technologies, gasifier performance, and environment-related issues.

INTRODUCTION

The gasification technology is now marching towards development with a history that dates back to the 1800s. In the year 1887, LURGI GmbH registered first patent in Germany. Later, coal gasification technology was used to supply "Town gas" for streetlights in both Europe and the United States. Coal gasification technology have come up for the downstream applications for production of various chemicals like ethanol, methanol, olefins, etc., and combined cycle power generation globally. Selection parameter for coal gasification depends upon the physical and chemical properties of coal and the end process product required from the coal gasification process. Various products can be produced based on coal gasification technology.

Produced syngas from Coal gasification can be use in producing liquid fuel (methanol & ethanol), ammonia for fertilizers,Synthetic Natural Gas (SNG) and petrochemicals. These products will facilitate movement towards independenceunder Atmanirbhar Bharat Abhiyaan. In line with the above purpose, the Ministry of Coal has taken project for utilize coal through coal gasification, and as such this National Coal Gasification Mission [1] has been prepared to achieve 100 MT coal gasifications by the year 2030.

Gasification is a conversion process that converts any carbon-containing material, coal for example, into synthesis gas. Carbon reacts with water in the form of steam and oxygen at comparatively high pressure morethan 30 bar, and at temperaturereach up to 1500 K for production of syngas, a mixture of carbon monoxide and hydrogen and some minor byproducts. The byproducts are removed to produce clean syngas that can be used as a fuel to generate electric energy or steam, as a basic chemical building block for a large number of uses in the petrochemical and refining units, and for the production of hydrogen. Gasification is important for lowor negative-value feedstocks by converting them to viable fuels and products. In the study of Ronald W. Breault [2], the historical development of gasification has been discussed along with the comparison with the combustion process. The hydrodynamics and kinetics of different types of gasifiers are also presented along with the most likely gas composition from each of the technologies when using a variety of fuels under different conditions from the air blown to oxygen blown and atmospheric pressure to several atmospheres.

GASIFICATION CHEMISTRY

Gasification is defined as a process of thermo chemical conversion of carbonaceous material (biomass or solid fuel) to an energy gas (syngas), through partial oxidation with air, oxygen, and/or steam at high temperatures. The composition of the syngas always consists of a mixture of hydrogen (H2), carbon monoxide (CO), methane (CH4), water (H2O), other hydrocarbons, inert gases, soot, tar, and ashes [3].

National Energy Technology Laboratory [4] working under the Department of Energy in the United States of America represents gasification technologies and also explained different types of gasifiers developed in the Energy field. The gasificationchemistry is very complex and is accomplished through a number of physical transformations and chemical reactions within the gasifier. In a gasifier, the carbonaceous feedstock undergoes a number of different processes and/or reactions:

- Dehydration – Any free water element of the feedstock evaporates, leaving dry material and evolving water vapor which may enter into afterward chemical reactions.
- Pyrolysis – This occurs as the feedstock opens to rising temperature in the gasifier. Devolatization and breaking of the weaker chemical bonds occurs, releasing volatile gases such asmethane, tar vapors, and hydrogen, along with heavy char which will undertake gasification reactions.
- Combustion – The volatile products and some of the char react with partial oxygen to form carbon dioxide (CO_2), carbon monoxide (CO), in such a way it provides the heat needed for succeeding gasification reactions.
- Gasification – The remaining char reacts with CO2 and steam to generate CO and hydrogen (H2).
- Water-gas-shift and methanation – These are separate reversible gas phase reactions taking place simultaneously based on gasifier conditions. These are negligible reactions which play a small role within in the gasifier. For required product, the syngas may experience further water-gas shift and methanation processing downstream from the gasifiers.

Gasification reactions are reversible in nature. Theconversionand direction of the reaction are subjected to the constraints of thermodynamic equilibrium and reaction kinetics. The combustion reactions basically go to completion (to the right).

$$C + \tfrac{1}{2} O_2 \rightarrow CO \quad \text{--- (-111 MJ/kmol)}$$

$$CO + \tfrac{1}{2} O_2 \rightarrow CO_2 \text{ ---(-283 MJ/kmol)}$$

$$H_2 + \tfrac{1}{2} O_2 \rightarrow H_2O \text{--- (-242 MJ/kmol)}$$

The thermodynamic equilibrium of the gasification reactions arecomparatively well defined and collectively impose a strongly effect thermal efficiency and the produced syngas composition of a gasification process.

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad \text{Water-Gas-Shift Reaction" (-41 MJ/kmol)}$$

$$CH_4 + H_2O \leftrightarrow CO_2 + 3\,H_2 \quad \text{Steam-Methane-Reforming Reaction" (+206 MJ/kmol)}$$

GASIFIER CONFIGURATION

P.Randditsheni et al.[5] represented a detailed review on coal gasification as part of the transition in SA thermal coal power generation. A gasifier is the most important device for the process of coal gasification, as it is where all the changes of coal to gas occur and the type of gasifier used influences the final gas produced. There are mainly three types of gasifiers, namely, the bubbling gasifier, commonly known as fixed bed gasifier, fluidized bed gasifier, and entrained flow gasifier. Each type offers a diversity of merits and demerits, deciding which to use depends on the desired product, (Fig.1) shows the above-stated gasifier types and fluid movement in each**.**

The bubbling gasifier or fixed bed gasifier is the oldest technologyin the gasification process, opposing to its name fixed the fluid within the gasifier moves due to gravity flow. The gasifying agent is introduced at the bottom of the component at high temperatures, while the coal is added at the top of the gasifier, this design results in the maximum heat economy where the conditions of low temperatures and oxygen at the top result in gas with a high composition of methane, therefore, a higher heating value. However, the gasifier is limited to a specific feedstock as it is incapable to process coal with a moisture content greater than 35% as these cracking coals tend to swell when heated and lead to mal distribution further causing process failure.

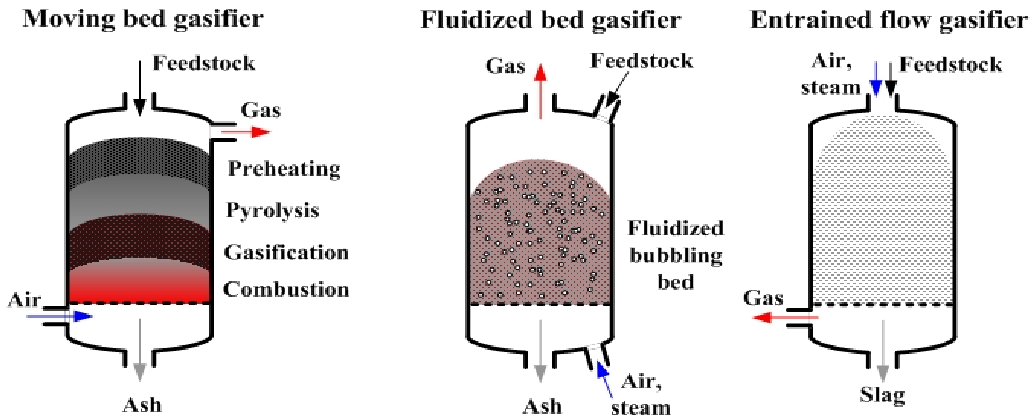

Figure 1. Types of Coal Gasifiers[5]

Entrained flow gasifier offers extreme mixing of the coal and gasifying agents as the gasifier maintains uniform values in temperature and coal mass. This allows the system to use a range of coals including cracking coals, however, the configuration of the gasifier affects the carbon conversion during gasification, and till date the best existing fluid bed has a carbon conversion of 97% which is much lower than the other bed each at 99% carbon conversion. The advantage of the entrained bed is that it can handle any coal feedstock while producing clean tar-free gas. However, this comes at a cost of more coal preparation work and very high oxygen consumption. Although these gasifiers work in a different way the general working principle is the same.

PERFORMANCE ANALYSIS OF COAL GASIFIER

Coal is an economic source of energy but not a consistent source as it results in high CO_2 emissions. Power plants are likely to decrease CO_2 emissions to stop global warming. Coal gasification is a process that reduces CO_2 emissions and introduces as a cleaner coal technology. The coal gasification process is controlled by several operating parameters. A Number of experiments have been carried out to improve gasification efficiency. A critical review of the work done by several researchers in the field of coal gasification has been presented by Akanksha Mishra et al [6]. The effect of several operating parameters such as coal rank, temperature, pressure, porosity, reaction time, and catalyst on gasification has been presented as follows:

- Carbon conversion increases with an increase in reaction time irrespective of different operating atmospheres.
- With increase temperature, gasification rate also increase.
- Pressure also affects the gasification process but still its relationship not been found.
- High rank coals are less reactive then low rank coal.
- Porosity of char controls the gasification reaction rate although it is not a controlling factor for highly reactive chars.
- Percentage of catalyst effects the reactivity of char i.e., reactivity increases with increasing catalyst percentage up to a certain limit beyond that it is not significant. The rank of coal controls the catalytic reactivity.

SNG production based on coal gasification starts with the gasification of coal to generate crude syngas implying that coal rank and gasification technology would have a significant impact on the process efficiency and quality of product. In research by Jingpeng Zhang et al [7] a series of coal-based SNG processes with different coal ranks and gasification technologies were investigated and analyzed based on rigorous process modeling and simulation. Sensitivity analysis was carried out to optimize key parameters and explore their effects on process performance.

The results indicate that the low-rank coal with the Lurgi gasifier could effectively improve the energy conversion efficiency when compared with various combinations of coal ranks and gasification technologies.

The lignite coal with the Lurgi gasifier could improve the energy efficiency by up to 61% with a Wobbe index of 52 MJ/m3, a carbon yield of 44%, and a minimum CO_2 emission of 3.5 kgCO_2/kg-SNG. The economic analysis suggests that the total equipment investment for the process based on lignite is 20% and 27% lower than that based on bituminous and anthracite, respectively. However, the Lurgi gasifier could save 12% on equipment investment compared with the Texaco gasifier when the process is based on the same coal rank. The research provided quantitative direction for the design and optimization of coal-based SNG processes.

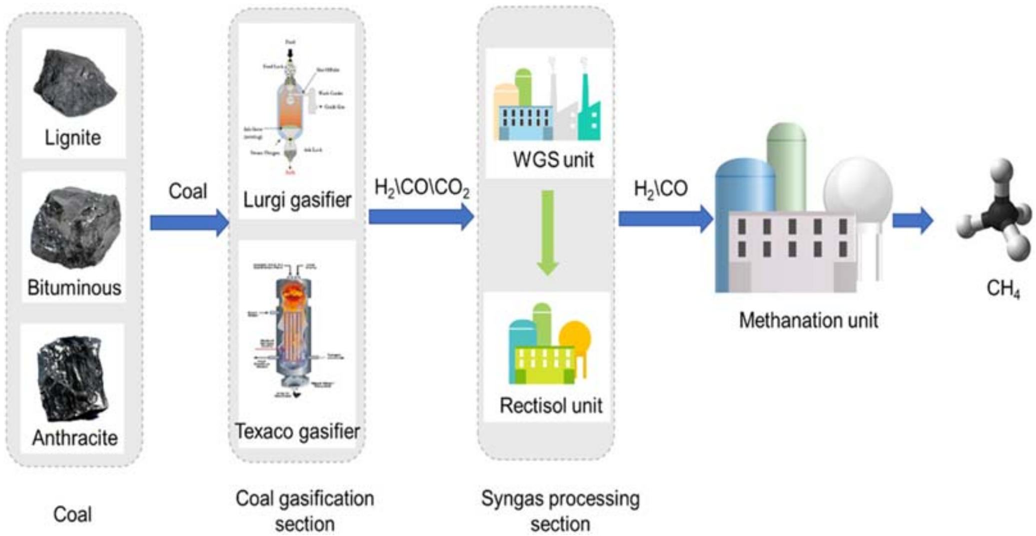

Figure 2. – Flow Sheet of Coal-Based SNG Process [7]

According to the research of Alka D. Kambleet al.[8] Co-gasification of coal and biomass is rising as potential clean fuel technology to attain high thermodynamic efficiency with relatively low CO_2 emission. Coal and biomass have been exclusively gasified for more than a century to obtain gas–liquid fuels and the production of chemicals. Co-gasification has higher efficiency than solitary coal gasification because the cellulose, hemicelluloses, and lignin content of biomass help to ignite and enhance the rate of gasification. It is suggested that extensive research on carbon reactivity patterns, heat release, reaction kinetics, etc. may support reducing the uncertainties in the co-gasification performance of coal and biomass blends, particularly in India. The prospects of co-gasification technology in the Indian context have been discussed considering the great quantity of varieties of coal and biomass. The appropriateness of existing gasifier procedures and their limitations with working parameters like feed rate, temperature, agglomeration intensity, residence time, density optimization, , the tar formation, and techno-economics involved are described.

DESIGN AND OPTIMIZATION OF COAL GASIFIER TECHNOLOGY

The coal technology that has progressively more attracted attention in recent years is the gasification of coal to produce hydrogen. Coal gasification may offer a greater potential for CO_2 sequestration, for reduction of other pollutants such as NO_x and SO_x, and also for conventional electricity generation than other hydrogen production processes. When a water gas shift (WGS) reaction is carried out in two adiabatic reactors, a low-temperature shift (LTS) reactor and a high-temperature shift (HTS) reactor in series, H_2 purity increases. Apart from HTS and LTS reactors, a high-performance catalyst with stability in the presence of sulfur impurities is also important for the production of hydrogen in the coal gasification system.

In the research of Yun Ju Lee et al.[9], the conceptual design of a coal gasification system for the production of hydrogen was undertaken using the PRO-II Simulation program. The working conditions for the gasifier were tuned to between 1200ºC to 1,500ºC, 15atm- 30atm, and to a feed molar ratio of $C:H_2O:O_2$=1:0.5-1:025-0.5. The refinery temperature and pressure were kept at 550 C and 24.5 atm. The syngas produced goes to water gas shift (WGS) reactors operated at temperature 400ºC, pressure 24 atm-HTS, and at temperature 250ºC, pressure 23.5 atm-LTS. It is observed that the production of hydrogen was found to be independent of the concentration of steam in the feed as gasifying agent. However, when other operating conditions are constant, the hydrogen output changes dramatically with changes to the concentration of O_2 in the feed. In this research optimized operating conditions for the production of hydrogen by the gasification of Drayton coal were found to be: 1500ºC, 25 atm, and a feed ratio $C:H_2O: O_2$ = 1:0.58:0.43.

Gasification processes with complex reaction systems typically involve stable operating conditions. However, variations in feedstock flow, the composition of the feedstock, and environmental factors, as well as other factors, may cause abnormal operating conditions. In the research work of Zhikai Cao et al.[10] proposed a novel systems modeling and analysis method by combining computational fluid dynamics (CFD) and process simulation for the Shell pulverized coal gasifier. The projected method considers the Shell pulverized coal entrained-flow gasifier with two parts: a gasification core zone and a heat exchange and water gas shift zone. High-fidelity CFD models of gasification core zone are developed to obtain characteristics of the flow field, temperature field, and composition profiles within the gasification core zone. An equation-oriented process simulation model is further developed for the heat exchange & water gas shift zone. The proposed hybrid method was validated by comparing it with industrial operating data. Three cases of abnormal operating conditions were further investigated with the proposed hybrid model. The most important factors that influence the process operability were found to be the characteristics of gas and particle hydrodynamic behaviors of the inner layer of the gasification core zone.

Methanol is an important feedstock and it is mainly produced by coal route the coal-to-methanol suffers from serious CO_2emissions .In the study of Dong Xiang et al [11] a novel coal-to-methanol process integrated with coke-oven gas chemical looping hydrogen and chemical looping air separation was designed and analyzed to improve carbon utilization efficiency, methanol production, and reduce CO_2 emissions.

The major benefit of the novel process is that the integration between coal gasification and chemical looping technology can eliminate the water gas shift unit and reduce fuel consumption. To produce one-tonne methanol, the coal consumption is 1.45 tonne for the coal-to-methanol, while the coal consumption for the novel process is reduced to 0.75 tonnes at the cost of additional 0.35-tonne coke-oven gas under optimized operating conditions. By parameter optimization and process integration, the carbon utilization of the novel process is increased from 38.4% to 56.1%, and the CO2 generation of the novel process is therefore reduced from 1.47 to 0.71 kmol/kmol methanol. The novel process also possesses quite large prospects in terms of economic performance.

Robert Mota et al[12] described an experimental and computational fluid dynamics (CFD) effort toward optimizing: hydrogen-rich syngas production and cold gas efficiencies during the thermochemical conversion of lignite coal using oxygen and steam as gasifying agents. A bubbling bed gasifier was systematically designed, constructed, and commissioned to achieve these objectives. The bed temperature was maintained at 1023 K during the gasification testing of the highly reactive lignite coal. The hydrogen levels in the syngas were examined as a function of oxygen, coal, and steam flow rates. A maximum hydrogen concentration of 50% (dry-basis) was achieved at low oxygen to carbon ratios and the cold gas efficiencies were in the range of 80-90%. The observed experimental trends in syngas compositions and cold gas efficiencies were reasonably well represented by the CFD simulations and compared favorably with data obtained from a transport reactor integrated gasification system. Simulations predicted that the major product gases at the reactor outlet were close to their equilibrium levels. The decrease in hydrogen concentrations in the syngas at high oxygen and steam flow rates resulted from changes in the oxidation reaction rates, hydrodynamics, and steam levels. The levels of steam were attaining saturation conditions.

ENVIRONMENTAL IMPACTS OF THE GASIFICATION PROCESSES

In the study of D. Vamvuka[13] on the Environmental Impacts of Coal utilization on the Ecosystem, various aspects of emissions of pollutants linked with coal combustion and conversion facilities have been discussed. It reviews the key impacts on the environment, health, and safety from coal processing and utilization and describes briefly the control technologies and protective strategies applied, to mitigate the dangerous effects of these activities.

ENVIRONMENT POLLUTION

With the increase in the global use of coal, as a source of energy, may be expected to make worse certain environmental, health and safety problems. Despite of the conversion process (combustion, gasification, or liquefaction), large amounts of pollutants will be emitted, the nature of which will be determined both by the characteristics of the fuel and the process conditionsinvolved. Such pollutants include various gases (No_x,Co_x, So_x, CH, etc.), tar, soot, ash, much different liquid and solid wastes, as well as toxic polycyclic aromatic hydrocarbons and trace components.

AIR POLLUTION

Compared to a coal combustion plant, a gasification plant generatesfewer amounts of the traditional air pollutants, such as Co_x, So_x, No_x, and hydrocarbons. The well-known gaseous effluents of coal gasification facilities consist of H_2S, COS, SO_2, and NH_3, among the secondary air pollutants, which occur in gaseous streams in gasification units, the most important ones are sulfur compounds, reduced nitrogen compounds, and trace elements.

A wide variety of toxic trace elements, such as Hg, As, P_b, C_d, and Se, have appreciable volatility, under the high-temperature conditions present in gasification. Among pollutant gases exhausted by coal plants, environmentally the most dangerous are acid gases, i.e. So_x, NO_x from coal combustion, and H_2S from coal gasification and liquefaction. These gases are extremely toxic, even when diluted to concentrations deemed safe for short exposures.

WATER POLLUTION

The major liquid waste streams in coal gasification aplantincludes gas liquors process condensate blow down and raw gas and ash quench water. This processgenerates high concentration of tars, oils, phenols, naphthas, cresols, sulfur, and nitrogen compounds (mainly hydrogen sulfide, ammonia, and hydrogen cyanide), particulate matter, and dissolved solids. Also, various other compounds, such as fluorides, sulfates, and chlorides, which build up in reuse systems, call for careful consideration. Water discharged into natural water resources like rivers or lakes, after use in the cooling systems of the plants, has two potential ecological effects. First, the return of water used for direct cooling raises the temperature of the receiving waters, altering their nature as a habitat, and second, the water returned from evaporative cooling systems, though creating less thermal pollution, mainly contains twice the initial salt concentration. Because wastewater dilution, treatment, and recycling appear to be mandatory for coal utilization facilities, releases of toxic effluents causing immediate death to fish and other aquatic organisms probably will not occur, of possible concern however are chronic, sub-acute stresses.

CONTAMINATION OF GROUND

From coal gasification about 10 to 30% of supplied coal volume is generated as solid waste. The range of these wastes includes bottom ash and fly ash.It also includes carbonaceous char or residue, that can be burned, gasified, or used for activated carbon, but will ultimately require disposal. Other solid wastes include high concentrations of Hg, Se, As and other elements, and spent activated carbon. It must be noticed, that the major differences between the ash from gasification processes and from combustion are expected to be the presence of organic matter in residues from coal conversion and the existence of the elements in a reduced, rather than oxidized form. The method of treating these residues before disposal is very much essential to prevent land pollution.

ASSESSMENT METHODS OF THE ENVIRONMENTAL IMPACT

Coal gasification technology is a better technology because of the low cost for the removal of CO_2 compared to conventional energy systems rooted in direct coal combustion Coal gasification technology is an integrated way that produces electricity, chemical products, fertilizer, etc. It also includes hydrogen, methanol, and liquid fuel such as diesel, etc. It is the most significant technology for the production of hydrogen economy as coal gasification is a dominant way to produce hydrogen gas coal gasification has a scope and demand in India. However, harmful gases which are produced at different stages of coal gasification affect the environment. Thus, it is important to assess the environmental impact of these gases. Life cycle analysis (LCA) is a method used for evaluation of the impact on the environment It is a process to quantify the greenhouse gas emission and fossil energy consumption systematically.

CONCLUSION

This paper presents a review of the literature on coal gasification technologies. The main three types of gasifiers fluidized fixed bed, fixed bed, and Entrained flow were discussed. The effect of various operating parameters such as coal rank, temperature, pressure, porosity, reaction time, and catalyst on the performance of coal gasification is also presented. The gasification of coal is seen as a promising technology for clean development, allowing greater economic, social, and environmental sustainability.

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