CHAPTER-I

INTRODUCTION
1.1 Energy Scenario

Per capita energy consumption in India is 30% of the energy consumption of the world average energy consumption. However, this trend is changing because reforms are taking place in the power sector and the government has plans for better quality energy supply and rural electrification. In 2020 energy consumption of India will be 5.3% of world energy consumption.

Currently, coal has a major role as an energy resource in many countries worldwide such as India, China and Australia (Figure-1.1). This is not only because coal is an abundant, widespread and accessible fossil fuel, but also because its mining, transportation and storage are relatively cost effectively.

![Figure-1.1: World primary energy demand and Coal consumption by countries](image)

In India, out of various energy sources coal comprises major role of energy resources available at any point. In 2020, India has forecasted to have 10% of the world’s coal demand. India does not have large reserves of oil but, have large reserves of coal. As an energy security concern, this could prompt the government to look into other ways to obtain the liquid fuels from coal and development of efficient and clean coal technologies to fulfill the energy demand. At present, India’s energy mix consists of coal (52%), oil (32%), gas (10%), hydroelectricity (5%) and nuclear energy (1%) [3][4].

1.2 Types of Coals

"Coal is the altered remains of prehistoric vegetation that originally accumulated in swamps and peat bogs" or in chemistry language, "Coal is a porous macromolecular
structure composed of aromatic and hydro-aromatic building blocks connected each other by cross linking with hetero atoms as the functional groups at the periphery of the building blocks”

Coalification has an important bearing on coal’s physical and chemical properties and is referred to as the ‘rank’ of the coal. The ranks of coals, from those with the least carbon to those with the most carbon, are lignite, sub-bituminous, bituminous and anthracite (Figure-1.2).

1.3 Worldwide Coal Reserves, Production and import/export

Coal is located worldwide—it can be found on every continent in over 70 countries, with the biggest reserves in the USA (28%), Russia (18%), China (13%) and India (7%). The order of consumption also follows the same pattern. Proved worldwide coal reserves at year-end 2008 stood at an estimated 826 billion tons (Gt), representing about 122 years of production at the current rate. Coal reserves are reported by coal types: bituminous and anthracite (46%), sub-bituminous (41%), and lignite (12%) [5].

1.4 Coal Reserves and production in India

Indian coal deposits are primarily concentrated in the Gondwana sediments occurring in the eastern and central parts of peninsular India. Resources of Coal have so far been estimated in the country are given in Table-1.1. In the year 2011-12, coal consumption
in India was 628 Million Tonnes while production was 538 million tons only so there was an import of around 90 Million Tonnes[4].

Table-1.1
Type and Category-wise coal resources of India as on 1.4.2011 (in Million Tonnes) [6]

<table>
<thead>
<tr>
<th>Type of Coal</th>
<th>Proved</th>
<th>Indicated</th>
<th>Inferred</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A) Coking</td>
<td>17669.03</td>
<td>13703.32</td>
<td>2101.91</td>
<td>33474.26</td>
</tr>
<tr>
<td>(B) Non-Coking</td>
<td>95738.76</td>
<td>12368.44</td>
<td>31488.11</td>
<td>250895.31</td>
</tr>
<tr>
<td>(C) Tertiary Coal</td>
<td>593.81</td>
<td>99.34</td>
<td>799.49*</td>
<td>1492.64</td>
</tr>
<tr>
<td>Grand Total</td>
<td>114001.60</td>
<td>137471.10</td>
<td>34389.51</td>
<td>285862.21</td>
</tr>
</tbody>
</table>

* Includes 749.92 M.T. of Inferred resources established through mapping in North-Eastern region.

1.5 Clean Coal Technologies
Coal remains India’s most important fuel and predominantly used for different applications. But with a high ratio of carbon to hydrogen, making control of CO₂, a major concern for the future use of coal. Unfortunately the utilization of coal in present technologies has some undesirable environmental impacts. Concerns over the role of greenhouse gases in forcing global warming have led to the international agreements like the Kyoto Protocol, that have set targets for controlling carbon dioxide emissions. Achieving these goals will require changes in the coal utilization practice.

To address these challenges, new coal utilization strategies of clean coal technologies are becoming essential due to certain advantages like high coal conversion efficiency and lower environmental impact [7]. From a technical point of view, both combustion and gasification technology can achieve the near term goals. When looking out for the long term, as the efficiency goals increase further, stack emissions goals tighten, and hydrogen production and CO₂ capture goals are set, gasification technology will have a distinct advantage over combustion steam plants. Steam cycles alone cannot achieve the high plant efficiency targets, and hydrogen production from combustion plants is not possible. Apart from this gasification have several other advantages due to its flexibility in syngas applications.

1.6 Gasification History
At the end of the eighteenth century gas was produced from coal by pyrolysis [8]. William Murdock started the commercial coal-gas industry in Redruth, England, in
In 1861, the Siemens brothers in Germany developed a gas producer for the generation of low calorific value gas, using non-coking coals by passing a mixture of air and steam through a bed of coal [9]. Until the end of the 1920s the only gases that could be produced in a continuous process were blast furnace gas and producer gas [10]. Tully, in 1919, introduced his so-called double-gas plant in which complete gasification took place in two stages and having a calorific value in the range 18-20 MJ/m³. In the late 1920 the firm of Lurgi carried out experiments on the complete gasification of brown coal. The first Lurgi generator was built in 1936 and about two-thirds of the potential heat in the coal is produced as gas [9].

This was the time of the development of some of the other important processes that were the forerunners of many of today’s units: the Winkler fluid-bed process (1926), and the Koppers-Totzek entrained-flow process (1940s). The 1950s was also the time in which both the Texaco and the Shell oil gasification processes were developed. Lurgi developed a slagging version of its existing technology in a partnership with British Gas (BGL). Koppers and Shell joined forces to produce a pressurized version of the Koppers-Totzek gasifier (for a time marketed separately as Prenflo and Shell coal gasification process, or SCGP, respectively). Rheinbraun developed the high-temperature Winkler (HTW) fluid-bed process and Texaco extended its oil gasification process to accept coal feed in a slurry form.

The coals-based IGCC plants that have had significant operational experience using different gasifier but except the fluidized-bed gasifier. The Kellogg-Rust-Westinghouse (KRW) agglomerating fluidized-bed gasifier has been operating at the Sierra Pacific Piñion Pine demonstration plant in Nevada, USA, since 1998 [11].

**1.7 World Gasification Scenario**

Among the countries involved in research and development on IGCC, the USA is the leader and has the maximum number of IGCC plants. Recently, China has achieved breakthroughs in developing and demonstrating advanced-coal gasification technologies [12].

The 2010 worldwide gasification database indicates that existing world gasification capacity has grown to 70,817 MWth of syngas output from 144 operating plants and 412 gasifiers. The 2010 Worldwide Database lists 48 gasification plants that are being
planned to start operations between 2011 and 2016 [13]. The 2010 database for operating plants on a MWth basis shows that chemicals remain the top product generated by gasification plants [13]. Figure-1.3 indicates gasification based existing, under construction and planned syngas capacity according to applications.

Figure-1.3: Applications Of Gasification [9]

1.8 Indian Gasification Scenario [14][12]

Gasification has been used commercially in India since 1963. The purpose of these plants was to produce ammonia from hydrocarbons. The fuels varied from coal to naphtha to lignite. The gasification processes used are mainly entrained flow gasifiers. These are gasifiers that were sourced from outside the country. Many of them have ceased operations.

In India, BHEL has two test facilities: a 150 tpd fluidized bed gasifier located at Trichy and a smaller, 18 tpd fluidized bed gasifier at Hyderabad. BHEL is now setting up a medium scale IGCC unit of 185 MW at Vijayawada using pressurized fluidized bed gasifier (PFBG). The Central Institute of Mining & Fuel Research (CIMFR), Dhanbad worked with a 2.6 tpd K-T entrained bed gasifier and 19 tpd moving bed gasifier. Recently, CIMFR has installed pressurized fluidized bed gasification (PFBG) R&D setup having a coal feed rate capacity between 10-20 kg/h. The Indian Institute of Chemical Technology (IICT), Hyderabad has worked with a 24 tpd Lurgi moving bed gasifier since 1983.

Tata Steel and Jindal Steel & Power Ltd. (JSPL) have taken the lead to utilize this huge inferior coal deposits to produce ultra clean liquid fuels. Jindal Synfuels limited (JSFL)
plans to set up a CTL (Coal to Liquid) plant with a capacity of 80,000 barrels per day of oil products. Tata Steel in joint venture with South Africa based Sasol Synfuels will set up a 3.6-million-tonne per annum CTL plant in Orissa. JSPL have installed KBR TRIG gasifier to generate Reducing Gas for Direct Reduction of Iron (DRI) India using high ash coals from Odisha. Reliance has plans to install 10 gasifiers at their Jamnagar refinery area to substitute LNG with syngas [15]. NTPC, is planning to build a 100 MWe demonstration plant either with a foreign technology or with BHEL-developed technology Several Indian groups like ONGC, GMDC, NLC, CIL, Gail, Essar, Adani Group, Shiv Vani, Abhijeet Group are entering into underground gasification (UCG) area.

1.9 Chemistry of Gasification:
Gasification is a thermo chemical process that converts carbonaceous materials into combustible gases by the reactions of the carbonaceous materials with steam, controlled amount of air or oxygen, or a mixture of these gases at a temperature exceeding 700°C, to yield a gaseous product suitable for use either as a source of energy or as a raw material for the synthesis of chemicals, liquid fuels or other gaseous fuels [16][17]. The product gas is fuel gas and consist mainly carbon monoxide and hydrogen. However, the desired gas composition can be achieved using different technologies. The gasification process can be applied to any hydrocarbon-based feedstock, but mainly used for coal, petroleum residues and biomasses. It is a fully developed commercial process [18][19].
Gasification of coal involves two primary steps: Initial rapid pyrolysis of coal (devolatilization) to produce char, tar and gases followed by the gasification of the generated char as given below.

**Pyrolysis**

\[
\text{Coal} + \text{Heat} \rightarrow \text{char} + \text{liquids} + \text{gases (H}_2, \text{ CO, CO}_2, \text{ CH}_4, \text{ C}_2\text{H}_2, \text{ C}_2\text{H}_4) \quad (1.1)
\]

**Gasification**

\[
\text{Char} + \text{gasifying agent (Air/O}_2/\text{H}_2\text{O)} + \text{Heat} \rightarrow \text{ash} + \text{Syngas (H}_2, \text{ CO, CO}_2, \text{ CH}_4, \text{ C}_2\text{H}_4, \text{ N}_2, \text{ H}_2\text{O)} \quad (1.2)
\]
In the gasifier, the hot gases first dry the coal particle. The pyrolysis step starts as the temperature of the coal particle exceeds 400°C. Tars, oils and Phenols are evolved as liquid, Hydrogen rich volatile hydrocarbons in gaseous form. The residue as char contains remaining carbon and mineral matters. After attaining 700°C gasification reactions begins.

1.10 Pyrolysis
As discussed above, coal gasification involves two primary steps: initial rapid pyrolysis of coal (devolatilization) to produce char, tar and gases; and subsequent gasification of the char generated. Char consists of carbon, hydrogen, oxygen, ash and a small amount of hetero atoms such as N and S [20]. Pyrolysis and gasification are mainly endothermic processes and require heat to drive them. This requirement is fulfilled by the oxidation of a part of coal to CO₂ [21]. As gasification progresses, upon heating, first of all moisture gets evolved, then coal becomes metaplastic and gives off volatile matter leaving a stable coke/char. Thus, coal may be regarded to be composed of two distinguished portions differing greatly in reactivity. The highly reactive portion relates to the volatile portion of coal characterized by the aliphatic hydrocarbon side chain, and oxygenated functional groups present. The lower reactive portion is the residual carbonaceous char/coke.

Pyrolysis is an endothermic thermal decomposition process in an inert atmosphere that results variable amounts of syngas, liquids (tars and oils) and a solid carbonaceous residue referred as char [22]. The quantity of each product depends on the pyrolysis conditions like temperature, heating rate, particle size, pressure, residence time and the type of fuel.

1.11 Gasification reactions:
1.11.1 Partial oxidation Combustion Reaction
These reactions are controlled by the O/C ratio into the gasifier, by the maximum temperature and pressure and by the heating rate. Most of the oxygen consumed in the hydrogen and carbon combustion and in the carbon partial oxidation. These reactions are highly exothermic and provide the heat necessary for the gasification reactions.
\[ C + \frac{1}{2} O_2 \rightarrow CO \quad \Delta H = -123 \text{ kJ/mol} \quad (1.3) \quad [23] \]

\[ C + O_2 \rightarrow CO_2 \quad \Delta H = -406 \text{ kJ/mol} \quad (1.4) \quad [23][24][25] \]

1.11.2 Gasification with steam

\[ C +H_2O \leftrightarrow CO + H_2 \quad \Delta H = +118.9 \text{ kJ/mol} \quad (1.5) \quad [23][24][25][26] \]

\[ C +2 H_2O \leftrightarrow CO_2 + 2H_2 \quad \Delta H = +78 \text{ kJ/mol} \quad (1.6) \quad [23][24][25][26] \]

The water gas reaction produces both CO and H\(_2\) and is therefore the principal gasification reaction [27]. Steam to the process can come from the gasifying medium, combustion or the evaporation of the moisture in the fuel. This reaction is endothermic requiring thermal energy and favoured by high temperature and low pressure. The equilibrium in Figure 1.4 representing the H\(_2\)O, CO and H\(_2\) concentrations shows that this reaction is not so heavily affected by temperature as the Boudouard reaction. After 800 °C the concentrations do not change significantly [28].

Figure 1.4: Water gas Equilibrium Diagram
1.11.3 Boudouard Reaction

\[ C + CO_2 \leftrightarrow 2CO \quad \Delta H = +159.7 \text{ kJ/mol} \quad (1.7) \]

[25][29][30][31]

This reaction is the most important reaction in gasification. The Boudouard reaction is endothermic and, in the absence of a catalyst, occurs very slowly at temperatures under 700°C. Temperature should be at least 700°C in atmospheric pressure if CO formation is favored [28]. This reaction is favored by high temperature and low pressure. Figure-1.5 shows the CO and CO\(_2\) concentrations for carbon gasification with oxygen as a function of temperature. The reaction is inhibited by the CO produced in the partial oxidation and carbon gasification with steam.

At temperatures above 900°C, CO is much more stable than CO\(_2\), so once this has been exceeded, CO quenches in. Below ~ 700°C, CO\(_2\) dominates the reaction, so little CO is made. Because, the equilibrium favors CO\(_2\) at low temperatures (below 700°C) and CO at high temperatures (above 900°C). However, kinetically the forward direction is very fast and makes CO easily, while the reverse reaction requires a catalyst and is much slower.

Further, formation enthalpy of CO\(_2\) is higher than that of CO, the formation entropy is much lower. Consequently, according to the Ellingham diagram, the overall free energy change of formation of CO\(_2\) by oxidation of carbon is almost constant and indifferent of the temperature, while the free energy change of formation of CO is a decreasing line. These two lines meet at 700°C, so the Boudouard reaction implies that on lower temperatures the equilibrium is on the exothermic carbon dioxide side and on higher temperatures the endothermic formation of carbon monoxide is the dominant reaction.

For instance, in the high temperature reducing environment of a smokestack, carbon monoxide is the stable product. When the carbon monoxide reaches the top of the smokestack, and the cooler air, the reverse Boudouard Reaction takes place; the carbon monoxide is oxidized into carbon dioxide, and the graphite precipitates as soot. This reaction also occurs in steel mills where CO is continually passing through pipes at temperatures 500-800°C as well as in blast furnace, gas ducts etc.
This reaction had been utilized in producing graphite flakes, filamentous graphite and lamellar graphite crystallites, as well as producing carbon nanotubes [32].

The Figure 1.5 shows the equilibrium relationship for this reaction, which is called Boudouard's equilibrium. When the gas concentration of carbon monoxide is below this curve, the reaction proceeds in the direction for forming carbon monoxide. On the other hand, when the gas concentration of carbon monoxide is in the region above curve, a carbon deposition reaction occurs according to equilibrium theory; that is, carbon monoxide is dissociated into carbon dioxide and carbon, and carbon is deposited. However, due to its extremely slow speed, this reaction does not practically proceed at lower temperatures and low carbon monoxide concentrations. Carbon deposition actually occurs in the region where metallic iron coexists to provide strong catalytic action, and in the region of high temperature and high carbon monoxide concentration.

1.11.4 Hydrogenation Reaction

\[ C + 2H_2 \rightarrow CH_4 \quad \Delta H = -88.4 \text{ kJ/mol} \]  

[25][29][30][33]
The hydrogenation reaction differs from the previous reactions as it is favored by low temperature and high pressure. As it is an exothermic reaction it occurs at low temperatures in the presence of a catalyst and pressure has not effect on increasing hydrogen yield [28]. Conditions in atmospheric gasifiers are often not favorable for this reaction and it can become almost insignificant. Methane has a higher heating value than CO or H\(_2\). Therefore, it is a desired product in thermal applications. Figure-1.6 shows the equilibrium curve for hydrogenation reaction at 1 bar and 20 bar pressure.

![Figure-1.6: Hydrogenation Reaction Equilibrium Diagram.](image)

CO water shift reaction and gasification with steam in the solid phase are the sole reactions providing hydrogen. Hydrogen is consumed in the hydrogenation reaction but it occurs very slowly except under high pressure.

1.11.5 Reactions in the gas phase:

**Water shift Reaction**

\[
CO + H_2O \rightarrow CO_2 + H_2 \quad \Delta H = -40.9 \text{ kJ/mol} \quad (1.9)[25][29][30][33]
\]
The water shift reaction is important for hydrogen production. This reaction is used to adjust the H$_2$/CO ratio in the gas. The shift conversion is reversible, mildly exothermic reaction that has the tendency to increase the amount of H$_2$ compared to CO in the product gas [28]. The direction of the reaction however depends on the conditions in the gasifier. If the temperature is high enough the reverse reaction takes place and the amount of CO increases in the expense of H$_2$. According to Rezaiyan and Cheremisinoff [27], the optimum temperature for H$_2$ yield is up to 260\(^\circ\)C, when catalyst is used. Pressure does not affect on the H$_2$ yield through this reaction. Figure 1.7 shows the equilibrium curve for Water-gas shift Reaction at 1 bar and 20 bar pressure.

Figure 1.7: Water-gas shift Reaction Equilibrium Diagram.

**Methanation Reaction**

\[
CO + 3H_2 \leftrightarrow CH_4 + H_2O \quad \Delta H = -206.3 \text{ kJ/mol} \quad (1.10)
\]

[22][34][35]

The methanation reaction proceeds very slowly and at low temperatures except if the pressure is high enough or a specific catalyst is used. This reaction is endothermic and requires a high amount of energy. The steam methane reforming reaction also takes place in the gasifier but it proceeds very slowly requiring relatively low temperature and catalyst [27]. Hence, CH$_4$ concentration is generally low in the gasifier.
Figure 1.8: Methanation Reaction Equilibrium Diagram.

The Figure 1.8 shows the equilibrium relationship for methanation reaction at 1 bar and 20 bar pressure. Gómez-Barea and Leckner [36] state that this reaction is kinetically limited in gasification conditions and is far from equilibrium.

The rate of a gasification reactions mainly depends on the reactivity of the fuel and the reaction potential of the gasifying medium i.e. most active O$_2$, and less active H$_2$O, CO$_2$ [28]. Process temperature and pressure also have an effect on the reaction rates. The combustion reactions are faster than gasification and they occur first rapidly consuming the oxygen. Basu [28] claims that the water-gas reaction is the fastest of char reactions. Blasi et al. [37] states that in char gasification water-gas reaction is two to five times faster than the Boudouard reaction. An interesting estimation is presented about the relative reaction rates of these four reactions at 800°C and 10 kPa pressure in Table 1.2.
Table 1.2:
Relative reaction rates and effect of temperature and pressure on gasification reactions

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Relative reaction rate</th>
<th>Effect of Temperature</th>
<th>Effect of Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partial Oxidation</td>
<td>$10^5$</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>Water-gas</td>
<td>$10^3$</td>
<td>↑</td>
<td>↓</td>
</tr>
<tr>
<td>Boudouard</td>
<td>$10^2$</td>
<td>↑</td>
<td>↓</td>
</tr>
<tr>
<td>Methanation</td>
<td>$3 \times 10^{-3}$</td>
<td>↓</td>
<td>↑</td>
</tr>
</tbody>
</table>

1.12 Type of Gasifiers [38][39]
A large number of gasification technologies exist however these can be classified into three main categories of gasifier configurations according to their flow geometry:

- Moving bed (also called fixed bed) gasifiers, in which gases flow relatively slowly upward through the bed of coal feed. Both concurrent and counter concurrent technologies are available but the latter is more common.
- Fluidized bed gasifiers, in which coal particles are suspended in the gas flow; coal feed particles are mixed with the particles undergoing gasification.
- Entrained flow gasifiers, in which pulverized coal particles and gases flow concurrently at high speed. They are the most commonly used gasifiers for coal gasification.

1.13 Factors affecting gasifier selection
The choice of a gasification technology is difficult as it depends on diverse factors such as;

- Coal properties;
- Gasifier end use locations and application;
- Size constraints: production rate of energy per unit cross sectional area;
• Heating value of the gas and gas purity (S, CO₂, etc.) and cleanliness (tars, soot, ash) for meeting international regulations, plant requirements and further use of the gas products.

Coal choice may be the least flexible factor for economic, geographical and political reasons and it is thus necessary to adapt the gasification technology to the base coal to be processed. Following properties have to be considered for the gasifier selection for specific coal.

**Coal moisture content:** the energy value of the produced gas depends in part on the moisture content of the fuel. The control of moisture in the feedstock is critical for an efficient gasification. Besides, it can determine whether the coal feed into the gasifier must be dry or slurry.

**Volatile matter of the fuel:** Determines the extent and rate of gasification reactions. Affects to the generation capacity.

**Ash content:** Ash content decreases the system efficiency and increases the slag production and disposal cost. It can cause slagging or clinker formation in the reaction due to the melting and agglomeration of the ashes. Slagging can block the reactor, mainly in fixed bed gasifiers [40].

**Ash compounds:** Certain substances contained in the ash (CaO, SiO₂, Fe₂O₃) can attack the refractory material and give rise to cracks [38]. Sodium compounds (NaCl or NaOH) and other alkali matter diffuse into the refractory lining of the reactor which leads in turn to a gradual disintegration and loss of life of the refractory [41]. Besides, in up-flow gasifiers where the gas is cooled and not water quenched, alkaline compounds can evaporate and leave the gasifier together with the gas, adhering later on the pipe's wall. Agglomeration is another ash-derived problem that can affect the process.

**Ash fusion temperatures (AFT), temperature of critical viscosity (TCV), softening temperature (ST):** During the slag cooling, if the temperature of critical viscosity (TCV) is reached, the formation of solids (crystals) makes the fluid behave as a non-
Newtonian fluid, increasing the apparent viscosity of the slag. Softening temperature (ST) is considered as the temperature where agglomeration starts. Depending on the ash disposal characteristics of the gasifier, operating temperature should be above or not the ash fusion temperature. For dry ash withdrawal system, operational temperature must be always lower than the AFT. For slagging type gasifier, operating temperature must be over AFT. In slagging gasifiers the slag should be removed at a temperature above the TCV in order to avoid the effect of the crystals. In agglomerating type gasifier, operating temperature must be over the softening temperature and below the fluid temperature.

Char reactivity: A measure of the rate at which residual char from a given coal will react with CO\textsubscript{2} under arbitrary and fixed conditions of temperature and gas composition. It affects the gasification efficiency, the temperature distribution in the furnace etc. Reactivity dictates the dimensions of reduction zone that are required and the residence time required for complete gasification. Coals with low char yield and high char reactivity (as lignites or brown coals) are more suitable mainly for fluidized bed gasifiers. However, those working with slagging ash can operate with higher rank coals.

Other compounds
Sulfur may cause corrosion of heat exchanger surfaces. In most of the cases the solution is to avoid higher temperatures rather than lower the sulfur content of the fuel Chlorine causes formation of HCl which is a reactive, corrosive, and toxic gas that can cause corrosion.

Grindability: Indicates the ease of pulverizing a coal in comparison to a reference coal. Coals with high HGI are more suitable for slurry feed gasifiers. Fluidized bed gasifiers use only crushed fuels (except the transport reactor)

Bulk density: A high bulk density means a higher energy-for-volume value. The reactor dimensions are more reduced for a given refueling time. Low bulk density fuels sometimes give rise to insufficient flow under gravity, resulting in lower gas heating values and ultimately in the burning of the char in the reduction zone [40].
Table-1.3 gather the reference value for most of the explained parameters, based on the type of gasifier. This criterion is very important to select the matching gasifier based on basic coal properties.

Table-1.3:
Reference values of the gasifier parameters [42].

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>FIXED BED</th>
<th>FLUIDIZED BED</th>
<th>ENTRAINED FLOW</th>
</tr>
</thead>
</table>
| Moisture           | • Dry feed: 2%  
                     • Slurry feed: 10%  
                     Counter-current gasifier is more tolerant.      | <55%                                               | Can handle a wide range of moisture content. |
| Volatile matter    | A wide range is used                                      | A wide range is used                               | A wide range is used               |
| Ash content        | <15%                                                       | <40%                                               | <25%                               |
| Ash compounds      | Low Fe₂O₃, SO₃, and sodium silicates                       | Low alkali compounds                               | Low alkali compounds               |
|                    | Low alkali compounds                                       |                                                   | Low alkali compounds in up-flowed gasifiers and refractory lined |
| Ash fusion temperature | • Dry ash: T_c AFT                                      | T< AFT                                            | T< AFT                             |
|                    | • Slagging T_f AFT                                          | AFT>1100°C                                        | AFT<1500°C                         |
| Sulphur and Chlorine| S<1.5%                                                     | S<1.5%                                            | S<1.5%                            |
|                    | Cl<0.4%                                                    | Cl<0.4%                                           | Cl<0.4%                           |
| Char reactivity    | • Dry: High reactivity chars to allow carbon conversion at low temperatures  
                     • Slagging: A range of reactivity can be used because of the high operational temperature (T) | High reactivity chars to allow carbon conversion at low temperatures | A range of reactivity can be used because of the high operational temperature (T) |
| Grindability       | Low (except if slurry feed)                                | Medium                                            | High                               |

Apart from coal properties, gasifier operating parameters are also important factors that affect gasification performance. An understanding of coal behavior at the conditions relevant to the emerging gasification technologies is required to enable the optimum design for efficient coal utilization techniques and to allow the prediction of the gasification performance of the coal in a gasifier. These issues are particularly important for Indian coals because of the different nature of Indian coals specifically high ash content and ash fusion temperature.

In this view, the issues related to understanding of the characteristics of coal char, char gasification reactions, rate determining step, gasification reactions, the kinetics of these processes (in particular low-temperature kinetics) and the factors that affect gasification kinetics, methods of kinetic studies & instruments used, different kinetics models, suitability of kinetic models are thoroughly discussed in the next chapter.