Co-gasification of coal/biomass blends and effects of parameter variation on the performance of gasifier: A Review

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Abstract

Energy security is a prime concern now a days and this crisis can be mitigated by the use of non-conventional energy sources. The syngas produced by the gasification is the most suitable source of energy in the IC engines. The use of biomass and coal as fuel in the gasifier can not only reduce CO_2 but also reduces ash and sulphur content in the coal. A critical review of co-gasification of coal/biomass blends and effects of parameters variation is presented. Gasification of coal and biomass is presented. This is followed by literature review of coal/biomass blends and effects of parameter variation like temperature of bed, gasiying medium, equivalence ratio. Effect of performance parameters like gas yield, cold gas efficiency, gas composition and heating values on co-gasification is also evaluated.

Keywords : *Coal/biomass, Co-gasification, Temperature, Gas yield, Carbon conversion*

1. Introduction

The principal energy demand of all sectors– industrial, agricultural, transport or domestic is in terms of liquid transportation fuel and electricity [1]. Fossil fuels (oil, coal and natural gas) have been the conventional energy sources of society. Oil and natural gas have been the source of transportation fuel, while coal has largely been utilized for electricity generation. The reserves of fossil fuels have been depleting fast. At the present rate of consumption, the oil and gas resources may not last for >50–60 years; whereas the coal may be available for another maximum 200 years [2]. As per data shown in Table 1, the developing economies in Asia, Africa and Middle East are dependent on oil, coal and natural gas as primary energy resource [3]. Major issue with the fossil fuel based energy is the emission of greenhouse gases to atmosphere which causes the problem of global warming and climate change risk. The global concerns of energy security and climate change risk have triggered intense research in alternate and renewable sources of energy, which is also carbon neutral. Among all sources, coal-thermal route for the electricity generation has the lowest capital and operating costs. The combustion route involves generation of steam through energy released from coal combustion, and use of this steam for driving the turbines. The gasification route involves partial oxidation of coal for generation of producer gas which is then fired in an engine coupled with generator set. The major operational problem in coal gasification is the incomplete conversion of the char due to slow kinetics of oxidation. Incomplete char oxidation not only leads to reduction in the energy efficiency of coal gasification but also particulate emissions. In order to enhance the kinetics of char oxidation, alkali or alkaline earth metal based catalysts, transition metal (iron-group metal) catalysts, and also the bimetallic catalysts (Ni-Cu, Ni-cAl_2O_3) have been used with the coal feed. A relatively new concept in coal gasification is the use of biomass and coal blends. Use of biomass with coal in the power plant to avoid problems like high specific cost, low efficiency etc. Blending of low quality coal with biomass and wastes could be attractive from economically, social and environmental point of view in order to make use of possible synergic effects via the production of fuel gas. This concept has received wide attention of researchers some literature has been published in this area. The concept underlying the co-gasification is synergistic effect of the alkali and alkaline earth metal content in the biomass for enhancing the gasification of the char. The synergic effect not only enhances the energy efficiency of the process due to complete gasification of the fuel feedstock, but also alters the composition of the producer gas resulting from the feedstock. Another advantage of this process is the reduction in tar content of producer gas, which makes the gas suitable for applications in engines. The aim of this paper is to give a review of the literature in the area of co-gasification of biomass and coal. The paper touches upon several facets of the co-gasification process such as effect of operational parameters of biomass/coal ratio, the composition gasification media, temperatures of gasification and heating rates on the producer gas composition and yield.

Table 1

Primary energy consumption of some developing countries in Asia, Africa and Middle East in 2016 [3].

Million Tonnes of Oil Equivalent (Mtoe)	Oil	Natural gas	Coal	Nuclear Energy	Hydro Electric	Renewable Energy	Total
India	212.7	45.1	411.9	8.6	29.1	16.5	723.9
Pakistan	27.5	40.9	5.4	1.3	7.7	0.4	83.2
Israel	11.6	8.7	5.7	0	0	0	26.4
Iran	83.8	180.7	1.7	1.4	2.9	0.1	270.7
China	578.7	189.3	1887.6	48.2	263.1	86.1	3053.0
Saudi Arabia	167.9	98.4	0.1	0	0	0	266.5
South Corea	122.1	40.9	81.6	36.7	0.6	4.3	286.2
Malaysia	36.3	38.7	19.9	0	4.2	0.3	99.5
South Africa	26.9	4.6	85.1	3.6	0.2	1.8	122.3

2. Gasification Mechanism

The main reactions involved during the gasification of coal, biomass or their blends are given below [4,5]:

Boudouard:

$$C_{biomass} + CO_2 \longrightarrow 2CO \quad \Delta H= 172.5 kJ/kg$$

Water gas:

$$C_{biomass} + H_2O \longrightarrow CO + H_2 \quad \Delta H= 131.3 kJ/kg$$

Methanation:

$$C_{biomass} + 2H_2 \longrightarrow CH_4 \quad \Delta H=-74.9 kJ/kg$$

Water gas shift:

$$CO + H_2O \longrightarrow CO_2 + H_2 \quad \Delta H= -41.2\ kJ/mol$$

Steam reforming:

$CH_4 + H_2O \longrightarrow CO + 3H2\ \Delta H = 206.2$ kJ/mol

Dry reforming:

$CH_4 + CO_2 \longrightarrow CO + 2H_2\ \ \Delta H = 247.4$ kJ/mol

3. Facets of co-gasification of coal/biomass

Masnadi et al. [6] has given a review of catalytic effects in coal gasification. Inorganic material that act as catalyst in coal gasification can be categorized in three groups, viz. alkali metals, alkaline earth metals and transition metals. Kaewpanha et al. [7] has done experiment with brown seaweed, Japanese cedar and apple branch with steam and water as gasifying agent. They concludes that seaweeds have alkaline species and acted as catalyst and reduce tars. Seaweeds in the large amount increase gas yields due to decrease in char and tar cracking. With increase in water flow the H_2 content increased but after that it decreases. Effects of temperature and gasification medium had studied by Pinto et al. [8] with gasification medium such as only air, only steam and mixture of both in the optimized co-gasification with waste and coal. H_2 production increased by 70% and CH_4 and other hydrocarbon reduced 30% and 36%.

Li et al. [9] have studied syngas production by co-gasification of coal and biomass in a fluidized bed. Effect of equivalence ratio (oxygen content in gasification medium), steam/- carbon ratio and biomass/coal ratio on the composition of producer gas was studied. Higher yield of producer gas was obtained at relatively lower equivalence ratio. The steam ratio showed an optimum with respect to yield of syngas. For steam/carbon ratio <0.5, occurrence of water gas reaction, water gas shift reaction and steam reforming reaction increased the yield of syngas. For steam/carbon ratio >0.5, the bed temperature dropped leading to reduction of the H2 yield. The H2 content of the producer gas increases with the biomass content of the feed.

Valdes et al. [10] used palm kernel shell and sub-bituminus coal as fuel in FBG to meet the energy requirement for baking in tunnel kiln. They took standard proportion of 90/10 wt.% of coal and palm kernel shell, air/steam as gasifying agent. With this inputs they found H_2 and CO contents 12% and 14% respectively with high heating value about 5MJ/Nm^3. With increase in equivalence ratio the carbon conversion increases. Also cold and hot thermal efficiencies were found high as values 66.8% and 76% respectively. Pan et al. [11] have studied the co-gasification of blends of pine/black (low grade) coal and pine/sabero (refuse) coal in a fluidized bed reactor with varying coal/biomass mass ratio in the range 0/100–100/0. The study revealed that the highest calorific value of the producer gas and highest carbon conversion was obtained for the feedstock with pine/refuse coal mass ratio of 20:80 and pine/refuse coal mass ratio of 40:60. The best results in terms of calorific value of producer gas and the net yield of producer gas were as follows: 80/20 blend of pine chip/black coal 4.56 MJ/Nm3, 3.2 Nm3/kg; 80/20 blend of pine chip/Sabero coal 4.7 MJ/Nm3, 1.75 Nm3/kg. Thus, blending of biomass with coal was beneficial for increasing the thermal efficiency of the gasifier.

To minimize the plastic waste Mastellone et al. [12] had used coal, plastic and wood in the BFB reactor. They had found that H_2 and CH_4 content increases with decrease in equivalence ratio. They also observed that addition of plastic into fuel leads to increase in the product gas yields as well as low heat value of the product gas. The gas yields was observed 2.5Nm^3/kg and specific energy was 4kw/kg for the mixtures having 50% plastic in it. With wood alone as fuel the LHV increases as a consequence of high CO and H_2 of volume 20% and 15% respectively but the syngas yield was somewhat decreased and found 1.3Nm^3/kg of fuel. Tar concentration was found 25-45g/Nm^3 in all the mixture cases. Aznar et al. [13] have also studied with coal, biomass and plastics and reported as light increase in CH_4 contents at temperatures greater than 820̊C in the presence of dolomite due to an increase in the rate of the methanation reaction. However, they observe an opposite trend for the concentration of light hydrocarbons which decrease due to the cracking reactions.

4. Effect of temperature

Temperature plays pivot role in the gasification phenomena. It affects the producer gas composition, heating values, tar contents etc. in the process. In gasification most of the processes are endo thermic in nature so high temperature would increases the reaction rate and produce the gas with high H_2 content [5]. Too high temperature is not desired because it reduces the heating value. There is a limitation to how high the temperature for the gasification process can go upto due to its effect upon (1)The volatile matter content in fuels; (2)Materials of construction used in the gasifier; (3)The production of undesirable gases such as NOx; and (4)Its effect on the ash fusion.

The temperature range is reported between 700-1000° C in fluidized bed and LHV was found increase with temperature [4-15]. Increase in temperature would increase in carbon conversion and gas yields because of reduction in tar content in the syngas [6]. However, this value varies with different kinds of fuels as well as types of gasifiers used.

4.1 Effect of Equivalence Ratio

Equivalence Ratio is the most important operating parameter in gasification based Waste to Energy units. Equivalence ratio is the ratio of air to biomass and strongly affects the gas composition. ER value value close to zero corresponds to pyrolysis condition while value equal or above one indicates combustion. Lower value of ER leave unconverted char and higher tar content while higher value of tar determine oxidation. Increase in ER increases H_2 and CO contents, which in turn increase the heating value of syngas. Aydar et al. [14] studied the effect of gasifying agent on gas composition. Coal crushed to size below 1mm. They used ER between 0.23-0.33 and found Maximum energy content 9.21MJ/Nm^3 which was at ER of 0.21 with temperature 850° C. As ER varies from 0.23-0.33 the H_2 content increase from 9% to 15%(v/v). Similarly CO content also showed increasing trend. CH_4 and CO_2 content decreased from 8.4%-2% and 14.2%-11.2% respectively. Heating value increases with decrease in ER is observed by most authors.

4.2 Gaseous composition (%)

Mainly hydrogen and carbon monoxide components of syngas are important due to the high heating value of syngas. Carbon monoxide can be easily converted to hydrogen by water gas shift reaction. Hydrogen production is increased with increase in temperature [8,10,13]. Aznar et al. [13] used secondary air injection of small amount(<10%) showed decrease in H_2 and 50% decrease in tars. Fermoso et al. [5] used different ranks of coals such as DT(high volatile bituminous coal from China) and SA (medium volatile bituminous coal from South Africa) and observed that coals having higher carbon contents and reactivity could react more with steam and produce higher contents of H_2. It was also reported that lignite volatiles contain more H_2 than bituminous volatiles.

Upon increasing the temperature the CO_2 level starts decreasing due to an increase in the rate of endothermic reactions such as Boudouard reaction which involves the consumption of CO_2. With the rise of temperature, the CO production is also increased due to an increase in the rate of heterogeneous and endothermic reactions such as water gas and Boudouard reactions. In other words at higher temperatures carbon tends to react with steam(water gas reaction) and CO_2 (Boudouard reaction) to produce higher amounts of CO. The concentration of CH_4 remains almost constant at low as well as at high temperatures..

4.3 Coal to biomass ratio

It is another important parameter in co-gasification as it decides the heating value and efficiencies of gasification. The researchers have used several blends of c/b, In case of Pan et al. [11]take several blends viz 60/40, 80/20 etc. Blend of pine chip/black coal (80/20) found the maximum LHV of gasification. With 90/10 wt.% of coal and palm kernel shell, air/steam as gasifying agent Valdes et al. [10] found H_2 and CO contents 12% and 14% respectively with high heating value about 5MJ/Nm^3. Many researchers have reported that With increase in the c/b ratio the heating value increases[10,11,12].

5. Carbon conversion

Carbon conversion is defined as the total carbon content of gas produced (CO,CO_2 and CH_4) during gasification to the total contents of the feedstock. Carbon conversion increases with the increase in temperature due to the oxidation and gasification reactions which cause high yields of gases from coal. Low rank coals give high carbon conversion yields than semi-anthracite due to more reactivity, i.e., they react more easily and rapidly with the gasifying agents [5].

6. Gas yield

Gas yield is defined as the flow rate of total inert-free gas produced to mass flow rate of dry and ash free value of feedstock. As carbon conversion increases with the rise in temperature hence gas yield also increases. Researchers have described the influence of temperature on gas yield in co-gasification and they have found similar results as that[5,7,9]. They claimed that with an increase in temperature, total gas yield also increased due to high releases of gaseous products from further pyrolysis, steam reforming, gasification and cracking reactions.

7. Calorific value

Calorific value or heating value of a fuel is defined as the quantity of heat released by combusting a specific amount of fuel under normal conditions. It is expressed as high heating value (HHV) or gross calorific value, and low heating value (LHV). It is reported that heating value depends on the contents of CO,H_2 and CH_4. With the rise of temperature, LHV is increased because of an increase in H_2 production. However, Pinto et al. [8] illustrate that HHV decrease due to reduction in the contents of methane and hydrocarbons. Link et al. [15] used leaching pre-treatment and found that pre-treatment lowers the LHV of the producer gas, reason behind this was the moisture content. Experiments showed that with the addition of reed and woody fuels increases the tar content and lowers the LHV of producer gas.

8. Cold gas efficiency

It can be calculated as the heating value of total gas production rate to the heating value of the feed rate. It is found that due to the increase in gas yield and heating value of the produced gas at elevated temperatures, CGE also increases [5,12]. CGE of different ranks of coal has a similar trend as that of HHV. The semi-anthracite has the lowest HHV among different coals because of the lower HHV of the produced gas and also the high HHV of the semi-anthracite, while DT and SA coals have the highest HHV because they react easily in the presence of oxygen and steam [5]. Simultaneous increase of space time and temperature, CGE increases more because of a large increase in H_2 and CO contents as well as LHV gaseous products.

9. Tar contents

It is mostly produced in the pyrolysis zone and its physical properties are affected by temperature and heating rate. Tar is one of the most unpleasant by product during gasification. It causes envir- onmental and operational problems such as condensation. It can be reduced by using thermal cracking or catalysts. It is reported that by increasing temperature, tar is converted to H_2, CO and lighter hydro- carbons. This increase in temperature causes an increase in endothermic reactions such as tar cracking and steam reforming [13].

10. Conclusions

This review reports the effect of temperature on gasification products under catalytic and non-catalytic conditions for co-gasification processes as it plays a very significant role in all gasification processes. It is observed that H_2, CO, carbon conversion and CGE are increased while on the other hand CO_2, CH_4, hydrocarbons and tar contents are decreased with the rise of temperature. This is mainly due to the involved endothermic reactions in the gasification process which become more dominant at higher temperatures. Gasification is dependent on various parameters such as temperature, pressure, types of fuel used (coal and biomass or their blends) and the fuel/gasifying agent ratio. In addition, these parameters are equally important and correlated with each other during gasification but temperature is the most significant one amongst them. Co-gasification can be improved by finding optimum values of these aforementioned parameters. It can be concluded that Co-gasification seems to be a promising technology, which can reduce the consumption of fossil fuels and increase the use of renewable resources, such as biomass and wastes. Also it produces less unpleasant products like tar and has higher carbon conversion and gas yield than Coal gasification and Biomass Gasification. For future prospects, more technologies need to be developed which can maximize the yield of hydrogen production and mitigate CO_2, N_2 and sulphur emissions as these are some of the main challenges, i.e. ,to enhance the H_2 concentration by using the water gas shift reaction.

Abbreviations

BFB – Bubbling Fluidized Bed

CGE - Cold Gas efficiency

DT - High volatile bituminous coal

ER - Equivalence ratio

HHV - High heating value (MJ/Nm^3)

LHV - Low heating value (MJ/Nm^3)

SA - Medium volatile bituminous coal

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