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Review article

Co-gasification of coal and biomass blends: Chemistry and engineering

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HIGHLIGHTS

- Review of chemistry and engineering aspects of coal/biomass co-gasification.
- Critical analysis of thermogravimetric studies on co-gasification of coal/biomass chars.
- Critical analysis of gasification of coal/biomass blends in fluidized beds.
- Analysis of the kinetic models for co-gasification and variations in kinetic parameters.
- Identification and analysis of synergistic effects in gasification of coal/biomass blends.

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ABSTRACT

A critical review and analysis of co-gasification of coal/biomass blends is presented. Initially, the chemistry of gasification of coal and biomass has been described along with different models for pyrolysis of cellulose/biomass. The mechanistic issues of catalytic effect of alkali metals on coal char gasification have been reviewed. This is followed by literature review on gasification of coal/biomass blends in two parts, viz. thermogravimetric and fluidized bed gasification. First part deals with effects of operational parameters on char reactivity. Second part analyzes influence of these parameters on gasification chemistry and producer gas. Factors governing tar content in producer gas have been discussed. Finally, the literature on kinetic modeling of coal/biomass blends has been analyzed. Some new approaches in kinetic modeling of solid-state reactions have been discussed.

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1. Introduction

The global energy consumption has significantly increased in recent decades due to fast urbanization and industrial development accompanied with economic growth and population rise. Total global energy consumption in 2005 was 10,940 Mtoe, which increased to 13,147 Mtoe in 2015 [1]. The principal energy demand of all sectors – industrial, agricultural, transport or domestic – is in terms of liquid transportation fuel and electricity [2]. Fossil fuels (in terms of oil, coal and natural gas) have been the conventional energy sources of mankind. 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 [1]. Oil and natural gas have been the source of transportation fuel, while coal has largely been utilized for electricity generation. However, the natural 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 [3]. Another major issue with the fossil fuel based energy is the emission of greenhouse and other gases to atmosphere leading to problem of global warming and climate change risk. The emissions from use of fossil fuels in engines and power plants include carbon dioxide (CO_2), oxides of nitrogen (NO_x) and oxides of sulphur (SO_x) in addition to particulate matters and (unburnt) carbon. The total global CO_2 emission in 1970 was ~16 Gton, which has increased to 36.25 Gton in 2015 [4]. Out of the total CO_2 emission of 36.25 Gton in 2015, an estimated 11 Gton was contributed via coal-based power and heat generation. 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 (in that it does not contribute to the carbon in environment). Among all sources of electricity, coal-thermal route has the lowest capital and operating costs, and thus, the smallest per unit manufacturing cost. There are two thermal routes for obtaining energy from coal, viz. combustion and gasification. The combustion route essentially 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 (a mixture of CO, H_2, CO_2 and small proportions of other hydrocarbon gases such as CH_4), which is then fired in an engine coupled with generator set. Among combustion and gasification, the overall energy efficiency of the latter is much higher (~40%). 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-γAl_2O_3) have been used with the coal feed by several authors [5–14]. A relatively new concept in coal gasification is the use of biomass and coal blends. This concept has received wide attention of researchers and large amount of literature has been published in this area. The basic idea 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 resulting from coal pyrolysis. This synergistic effect not only enhances the energy efficiency of the process due to complete gasification of the feedstock, but also alters the composition of the producer gas resulting from the feedstock. Another added advantage of this process is the reduction in tar content of producer gas, which makes the gas suitable for applications in engines. The purpose of this paper is to give a critical review and analysis of the literature in the area of co-gasification of biomass and coal. The analysis in this paper touches upon several facets of this the co-gasification process such as effect of operational parameters of biomass/coal ratio, the composition (proximate/ultimate analyses of biomass and coal), gasification media, temperatures of gasification and heating rates on the gasification kinetics, producer gas composition and yield. The paper also reviews the kinetic models for the co-gasification process and variation of the kinetic parameters with operational conditions and feedstock. The kinetic parameters essentially are the manifestations of the synergistic effects in the gasification process. We begin with presentation of some basic concepts of the gasification process in the next section.

2. Gasification process: Coal versus biomass

The gasification behavior of carbonaceous material like coal and biomass is a major function of their compositions. In this section, we have made a comprehensive evaluation of the properties of biomass and coal, and as how these properties are manifested in terms of their gasification behavior. The composition of carbonaceous material is evaluated in terms of proximate and ultimate analysis. The ultimate and proximate analyses of different coal and biomass species, which have been widely used as feedstock for gasification, are listed in Table S.1 in supplementary material. The major distinction between compositions of coal and biomass is in terms of the volatile matter, fixed carbon and ash. Biomass contains more volatile matter, while coal has more fixed carbon. The ash content of coal is higher than biomass. Another interesting distinction between compositions of biomass and coal is in terms

Table 1
Primary energy consumption (and its distribution among different sources) of some developing countries in Asia, Africa and Middle East in 2015 [1].

Million Tonnes of Oil Equivalent (Mtoe)	Oil	Natural Gas	Coal	Nuclear Energy	Hydro Electric	Renewable Energy	Total
Iran	88.90	172	1.20	0.80	4.10	0.10	267.10
Israel	11.00	7.6	6.70	0	0	0	25.30
Saudi Arabia	168.10	95.80	0.10	0	0	0	264
Algeria	19.30	35.10	0.20	0	0	0	54.60
Egypt	39.20	43	0.70	0	0.30	0.40	83.60
South Africa	31.10	4.50	85	2.40	0.20	1	124.20
Bangladesh	5.50	24.10	0.80	0	0.20	0.10	30.70
India	195.50	45.50	407.20	8.60	28.10	15.50	700.40
Indonesia	73.50	35.80	80.30	0	3.60	2.40	195.60
Japan	189.60	102.10	119.40	1	21.90	14.50	448.30
Malaysia	36.20	35.80	17.60	0	3.30	0.20	93.10
Pakistan	25.20	39	4.70	1.10	7.80	0.40	78.20
China	559.70	177.60	1920.40	38.60	254.90	62.70	3013.90
South Korea	113.70	39.20	84.50	37.30	0.70	1.60	277
Taiwan	46	16.50	37.80	8.30	1	1	110.60