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Effect of fuel blend composition on the efficiency of hydrogen-rich gas production in co-gasification of coal and biomass

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HIGHLIGHTS

- Steam co-gasification of coal and biomass for efficient hydrogen generation.
- Synergy effects: increase in total gas and hydrogen yields.
- Potential influence of biomass ash components in steam co-gasification.

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ABSTRACT

Energy generation is predominantly based on fossil fuels. This is related to their high energy density and abundance of resources, as well as market availability and maturity of conversion technologies. Increasing awareness of environmental concerns reflected in relevant regulations regarding the allowable levels of emission of contaminants in energy sector on the one hand, and increasing energy demand on the other impose, however; the need for development of more environment friendly energy technologies and wider utilization of renewable energy resources. Since the latter still faces technological and efficiency problems reflected in unsatisfactory economic characteristics, the efforts could be made to combine the advantages of stable supplies of coal, availability of market-ready, highly efficient and environment friendly gasification technology and utilization of renewable energy resources, biomass. Production of hydrogen as a prospective, environmental friendly energy carrier in the process of co-gasification make this option even more attractive, especially if some synergy effects could be observed. In the paper the experimental results proving the influence of a fuel blend composition, in terms of biomass type and content, and process temperature on the total gas volume, gas composition, carbon conversion rate and process efficiency are presented. Synergy effects were reported in co-gasification of coal and biomass of selected energy crops under operating conditions adopted, including increase in the total gas and hydrogen yields when compared to the values observed in coal and biomass gasification. A correlation between ash composition and the synergy effects was also stated. The energy crops types and steam co-gasification operating parameters optimal in terms of hydrogen-rich gas production were also determined.

1. Introduction

Market limitations affecting supplies of two basic fossil fuels, crude oil and natural gas, as well as the environmental concerns related to the processing of coal in energy sector are the main driving forces of the development of so called clean coal technologies and support given to the activities aiming at increasing the share of renewable energy resources in the energy balance. Gasification, as an alternative to combustion, offers increased efficiency, lower negative environmental impact and wider application range of the main product – synthesis gas – in power generation and chemical synthesis. It is also considered as one of the most viable options for hydrogen production, as an environment friendly energy carrier [1–3]. Coal gasification applied in Integrated Gasification Combined Cycle offers lower environmental impact, when compared to conventional power generation systems based on natural gas, and higher efficiency than supercritical pulverized coal boilers and steam turbines, by combining production of heat and power, and even hydrogen with carbon dioxide capture [4,5]. There is an increasing trend in the share of electricity generation and coal application as a fuel in the worldwide gasification capacities [6]. Biomass is also considered as a fuel for gasification systems. However, the locally limited resources of biomass, low energy density

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and operational problems related to its physical properties and chemical composition make its application still economically uncompetitive. Most of the present-day gasification reactors dedicated for fossil fuels utilization is unsuitable for biomass processing because of its high content of alkali and alkali earth metals, and relatively high amount of tars released in the process [7–9]. The downdraft moving bed reactors, most commonly applied in biomass processing, produce gas of the lowest particulates and tars content of 0.1–0.2 and 0.1–1.2 g/Nm^3 [10], respectively, but are unsuitable for processing of high moisture content biomass. The entrained flow gasifiers, operated at the highest temperatures and pressures, give the product gas free of tars, but their usual capacities are too high for locally limited resources of biomass. They also require energy-consuming pretreatment of biomass in torrefaction or fast pyrolysis processes. Biomass gasification in pressurized fluidized bed reactors creates problems with fuel feeders operation. On the other hand, gas generated in atmospheric fluidized bed reactors is more contaminated than from pressurized ones and contains considerable amounts of particulates (2–35 g/Nm^3) and tars (1–15 g/Nm^3) [10]. All this makes biomass gasification still a niche area with only 0.3% (402 MW$_{th}$) of synthesis gas generated worldwide [6]. Waste biomass is, however; a significant element of renewable energy balance in many countries and efforts should be made to make its utilization more efficient than it is in conventional combustion systems. Cultivation of energy crops, especially when combined with industrially degraded area reclamation, may be also of interest, since the waste biomass could satisfy only approximately 7.5% of the world energy demand. Biomass derived gas may be combusted to produce electricity in steam turbines or, after treatment, in gas turbines. Nowadays the first option prevails [7]. Catalysts applied in biomass gasification should decompose tars, prove catalytic activity in methane reforming (if synthesis gas is to be the final product) and/or facilitate production of gas of the desired CO/H$_2$ ratio. Furthermore, they should be resistant to deactivation, when exposed to H_2S, HCl and to sintering, be easily regenerated and cost competitive. The compounds most commonly studied in this respect are: calcined dolomite ($MgCO_3 \cdot CaCO_3$), calcium carbonate ($CaCO_3$), olivine (including Fe_2SiO_4 and Mg_2SiO_4), limonite (FeOH), hematite (Fe_2O_3), nickel catalysts, alkali metal salts (Li_2CO_3, Cs_2CO_3, $CsNO_3$, KNO_3, K_2CO_3, K_2SO_4, $NaCO_3$ and $CaSO_4$) [11]. When hydrogen-rich gas production is considered the most promising are nickel catalysts [12,13], olivine and dolomite [13–15], compounds of potassium [16,17], calcium and iron [16,18].

In the light of the above the process of co-gasification of coal and biomass may be promising, especially if some synergy effects could be observed, and the advantage of catalytic properties of biomass ash components could be taken. Most of the literature data on co-pyrolysis and co-gasification concerns processing of waste biomass and problems related to the optimization of feeder designs, fuel blends compositions, operating parameters, as well as biomass pre-treatment and application of catalysts in the process [19]. In some of the works published synergy effects in processing of various fuel blends, including blends of coal and biomass, were reported [20–31], but the need for further research studies in these terms is also claimed [19,21]. In the paper the results of the experimental study on the influence of a fuel blend composition, in terms of biomass type and content, and process temperature on the total gas and hydrogen yields, gas composition, carbon conversion rate and process efficiency were presented. Synergy effects in terms of the total gas and hydrogen yields in the process of steam co-gasification of coal and biomass, in a fixed-bed reactor were also identified. This makes the work complementary to the still limited number of reports on hydrogen-rich gas production in the process of co-gasification of coal and biomass [32–37].

2. Methods and materials

2.1. Materials

The fuels tested were provided by M&D Farms Sp. z o.o. in Świerczów, Poland (*Salix Viminalis*, SV), Department of Agricultural Sciences in Zamość of University of Life Sciences in Lublin, Poland (*Andropogon Gerardi*, AG; *Helianthus Tuberosus*, HT; *Sida Hermaphrodita*, SH and *Spartina Pectinata*, SP*)*, plantation in Főhren, Germany (*Miscanthus X Giganteus*, MXG*)* and Piast coal mine, Bieruń, Poland (coal seam 208, heading 1291, HC). The selection of biomass types was based on the yielding data as well as the specification of soil, land and climatic requirements of energy crops, which could be met in Poland [38–41].

The proximate and ultimate analyses of the tested fuels were performed in the accredited laboratory of the Department of Solid Fuel Quality Assessment of the Central Mining Institute with application of relevant standards, testing procedures and analyzers. These included: automatic thermogravimetric analyzers LECO: TGA 701 or MAC 500 (contents of moisture, ash, volatiles acc. to PN-G-04560:1998 and PN-G-04516:1998), calorimeters LECO: AC-600 and AC-350 (heat of combustion acc. to PN-G-04513:1981), TruSpecCHN analyzer (contents of carbon, hydrogen, nitrogen acc. to PN-G-04571:1998) and TruSpecS analyzer (sulfur acc. to PN-G-04584:2001). Oxygen content was calculated as: $100\% - W^a - A^a - C^a_t - H^a_t - S^a_c$ (PN-G-04510:1991), and fixed carbon as: $100\% - W^a - A^a - V^a$ (PN-G-04516:1998). Ash composition was analyzed in the accredited Laboratory of Solid Waste Analyses of the Department of Environmental Engineering of the Central Mining Institute with application of wavelength dispersive X-ray fluorescence according to PN-EN ISO 12677. The results are given in Table 1.

The composition of coal and biomass differed significantly in terms of fixed carbon, sulfur and ash contents (higher for coal), and volatiles, oxygen and hydrogen contents (higher for biomass) (see Table 1). Coal derived ash was rich in aluminum and iron oxides, and included substantially less alkali and alkali earth metals than biomass ash.

2.2. Test stand

The experimental study on steam co-gasification of coal and biomass was executed with application of a laboratory scale installation of the Laboratory of Advanced Energy Technologies of the Department of Energy Saving and Air Protection, Central Mining Institute (see Fig. 1). The main elements of the test stand are: a fixed bed reactor of a volume of 0.8 L, heated with a resistance furnace, gasification agents supply system, and product gas treatment and measurement system. For further details see [37].

2.3. Methods

Steam co-gasification tests were performed on fuel samples composed of coal and biomass of the total mass of 10 g. Selected fuels were dried, grinded and sieved to the fractions of particle size below 0.2 mm for coal and below 3 mm for biomass. Next, a fuel sample of a biomass content of 0%w/w, 20%w/w, 40%w/w, 60%w/w, 80%w/w or 100%w/w was put into the reactor on a layer of quartz wool, and heated up in nitrogen to the required process temperature of 700, 800 or 900 °C. Then steam as a gasification agent was injected into the reactor with a flow rate of 3.2 mL/min. The selected process variables adopted in the experimental campaign were: process temperature, biomass content in a fuel blend and kinds of fuels tested: steam coal and biomass of selected energy crops: SV, AG, SP, MXG, HT and SH.