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Biowaste utilization in the process of co-gasification with bituminous coal and lignite

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ABSTRACT

Biowaste utilization in co-gasification with bituminous coal and lignite gives the benefits of stable supplies of a primary energy source – coal and utilization of a zero-emission, waste material (i.e. agriculture waste, sewage sludge, etc.) with higher process efficiency and lower negative environmental impact than biomass or coal gasification, respectively. The main focus of the study presented is co-gasification of bituminous coal or lignite with biowaste to hydrogen-rich gas. The experiments were performed in the laboratory scale fixed-bed reactor installation at 700 and 900 °C. The Hierarchical Clustering Analysis complemented with a color map of studied data were applied in the selection of the optimal operating parameters for biowaste utilization in the co-gasification process based on the experimental data of gasification/co-gasification process as well as physical and chemical properties of fuels tested. The experimental results showed that the carbon conversion rate in co-gasification increased with increasing biomass content in a fuel. The total gas volume and hydrogen volume in co-gasification were higher than the values expected based on the results of the gasification process of the fuels analyzed.

1. Introduction

Waste biomass represents considerable energy reserves, which need to be utilized in the present-day world facing the challenges of increasing energy demand, fossil fuels market constraints and high loads of waste. Carbonaceous materials, such as bio-waste, should be rather processed, with the highest possible efficiency, than deposited. This means that the technologies of gasification and co-gasification should be adopted to address the needs of energy and waste management systems and to replace, or at least complement, the combustion and co-combustion methods [1,2]. Biomass gasification systems are mainly based on relatively small scale gasifiers which is caused principally by the locally limited supplies of a bio-fuel and which results in higher unit energy costs and lower system efficiency than in fossil fuels gasification. Lower calorific value, high contamination of raw gas (tars, alkali metal compounds, sulfur, ammonia, chlorine) and operating problems resulting from a specific ash characteristics make biomass less attractive than fossil fuels [3–7]. Nevertheless, in the world of depleting reserves of traditional primary energy sources and concerns related to the more sustainable management of raw materials the bio-waste is considered to be of quite reasonable value. The raw gas generated in bio-waste gasification is still predominantly utilized in combustion for power generation in steam turbines [4,7]. Gas after cleaning may be also applied in electricity generation in gas turbines, but this is still problematic since it demands complex gas treatment systems. The technology of coal and biomass co-gasification represents a new approach to the thermochemical conversion of coal and waste utilization, addressing at least some of the energy safety and waste management concerns [9–13]. Co-gasification secures reliable supplies of a high-energy content solid fuel, allowing for utilization of biomass with higher efficiency and at lower specific operating costs than in conventional biomass gasification plants, though up to now the industrial scale experience with such systems is limited [3,4,8,14,15]. There is, however, a vast amount of research studies available investigating theoretical and practical issues related to the utilization of fuel blends of quite different characteristics in heat and/or power generation [8,11–13,16–21]. The great variety of experimental set-ups, operating parameters, gasification agents and fuel blends applied in these studies gives complementary insights into different aspects of the process. The study presented in the paper contributes to the

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more specific area of the research focused on generation of hydrogen-rich gas, as a clean energy carrier, in steam co-gasification [11–15,17]. It also presents a practical implementation of the advanced method of data exploration, the Hierarchical Clustering Analysis (HCA), in the analysis of the experimental results. In particularly, it enabled the determination of the process parameters optimal in terms of hydrogen-rich gas production, within the range of parameters values tested. In this aspect the work also contributes to the presentation of useful tools of data analysis applicable in various experimental studies.

2. Materials and methods

2.1. Experimental set-up

The experimental study on co-gasification of bituminous coal or lignite with agriculture biowaste in analytical state was performed with the application of the updraft fixed bed gasifier installation (see Fig. 1). The working volume of the reactor is 0.8 L and it is heated with a resistance furnace. The installation is equipped with gasification agents supply system, including gases like oxygen, air, carbon dioxide, and also steam which is produced in a steam generator. The amount of cooled and dried gas is determined with a flow meter. The composition of the product gas is analyzed on-line with the use of a gas chromatograph Agilent 3000A. In the first channel a column PLOT U (8 m × 0.32 mm) with a TCD detector is applied for separation of CO_2 and C_2-C_5. In the second channel, a backflush injector module with a pre-column PLOT U (3 m × 0.32 mm) and an analytical column MS5A PLOT (10 m × 0.32 mm) with a TCD detector (for separation of H_2, N_2, CO and CH_4) are used. Helium and argon are applied as carrier gasses in the PLOT U and MS5A PLOT columns, respectively. Samples of 10 g of bituminous coal (C), lignite (L), agriculture biowaste (B) or fuel blends of 20 or 40%w/w of biomass content, respectively, were tested. A fuel sample was placed at the bottom of the reactor between thin layers of a quartz wool applied to improve the temperature distribution and to prevent the entrainment of fuel grains by the gaseous media passing through the reactor. It was then heated, under the atmospheric pressure, with a heating rate of approximately 1.3 °C/s, to the final temperature of 700 or 900 °C, in an inert gas (nitrogen) atmosphere. Next, steam was injected to the gasifier with a flow rate of $5.3 \cdot 10^{-2}$ cm^3/s for one hour.

2.2. Materials

The tested lignite and bituminous coal samples were supplied by the open cast Bełchatów (Poland) and Janina coal mine (Poland), respectively, whereas the agriculture biowaste (Salix Viminalis sawdust) was acquired from the experimental plantation in Poland. The ultimate and proximate analyses as well as heat of combustion and calorific value of tested materials are given in Table 1. The analytical characterization was performed by the accredited laboratory of the Central Mining Institute in accordance with the relevant standards: PN-G-04511:1980 (total moisture), PN-G-04560:1998 and PN-ISO 1171:2002 (ash), PN-G-04516:1998 and PN ISO-562:2000 (volatiles), PN-G-04513:1981 (heat of combustion, calorific value), PN-G-04571:1998 (carbon, hydrogen and nitrogen), and PN-G-04516:1998 (fixed carbon).

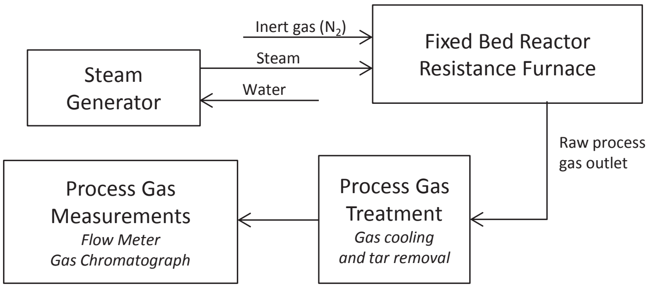

Fig. 1. Schematic diagram of the experimental set-up.

Table 1
Basic physical and chemical parameters of fuels tested (analytical state).

Parameter, Unit	Sample		
	B	C	L
Total moisture, %	7.13	11.60	14.50
Ash, %	4.03	6.96	8.60
Volatiles, %	76.16	20.44	42.80
Heat of combustion, kJ/kg	17,862	25,336	20,161
Calorific value, kJ/kg	16,411	24,092	18,955
Carbon, %	50.64	62.62	50.70
Hydrogen, %	5.95	3.30	3.90
Nitrogen, %	<0.01	0.88	1.30
Fixed carbon, %	12.68	61.00	34.10

2.3. Method of the exploratory analysis of the experimental data set

The Hierarchical Clustering Analysis was applied in the study of the relationships between the parameters characterizing fuel blends and the effects of co-gasification process. The analysis was focused on the determination of the optimal conditions for hydrogen-rich gas production. The HCA can be applied in the analysis of multidimensional data sets, in order to study similarities between studied objects (e.g. fuel blends) in the parameters' space (e.g. fuel blends properties or product gas composition), as well as between parameters in the objects' space [22–25]. The method is characterized by the similarity measure used and the way the resulting sub-clusters are linked (single linkage, complete linkage, average linkage, centroid linkage, or Ward linkage). The most commonly applied similarity measures (for continuous variables) are Euclidean distance or Manhattan distance which are the special cases of the Minkowski distance:

$$d_{ij} = \left[\sum_{k} (\mathbf{x}_i - \mathbf{x}_j)^q\right]^{1/q} \tag{1}$$

where k denotes the number of the variables, and if q = 2, then d_{ij} represents the Euclidean distance, whereas for q = 1, it represents the Manhattan distance. In the single linkage method the distance between two clusters A and B is defined as the smallest distance between a sample from cluster A and a sample from cluster B. In the complete linkage method the distance between clusters A and B is defined as the longest distance between two samples belonging to clusters A and B. In the average linkage method the distance between clusters A and B is defined as the average of the single linkage and complete linkage distances. In the centroid linkage method the distance between clusters A and B is based on the distance of the mass centers of each cluster, whereas in the Ward linkage method it is based on the inner squared distance of clusters, so that at each stage these two clusters are merged, for which the minimum increase in the total within-group error sums of squares is observed.

The results of the analysis are presented in the form of dendrograms in which the indices of clustered objects (or variables) are displayed on axis x, whereas the corresponding linkage distances are presented on axis y. The disadvantage of the method is that it does not allow for the interpretation of the observed objects'