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Experimental study on application of high temperature reactor excess heat in the process of coal and biomass co-gasification to hydrogen-rich gas

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ABSTRACT

The paper presents the results of the experimental study on the simulated application of HTR (High Temperature Reactor) excess heat in the process of allothermal co-gasification of coal and biomass. The laboratory scale installation with a fixed bed gasifier and auxiliary gasification agents pre-heating system, simulating the utilization of the HTR excess heat, were applied in the study. Steam and oxygen were the gasification media employed, and the process was focused on hydrogen-rich gas production. The results of the co-gasification of fuel blends of various biomass content at 800 °C and in various system configurations proved that the application of the simulated HTR excess heat in pre-heating of the gasification agents leads to the increase in the gaseous product yield. Furthermore, the HCA (Hierarchical Clustering Analysis) employed in the experimental data analysis revealed that the gasification of fuel blends of 20 and 40%w/w of biomass content results in higher volumes of the total gas, hydrogen, carbon monoxide and carbon dioxide than gasification of fuel blends of higher biomass content.

1. Introduction

The economic development is inherently combined with the increasing energy demand. This challenge need to be addressed by an adequate energy supply architecture. Considering the primary energy resources reserves to production ratio, the numbers for uranium and thorium ores may be considered quite competitive when compared to those of fossil fuels [1–3]. However, in view of the questions related to the social, economic and waste management aspects of the nuclear energy systems as well as the country-specific energy balances, coal is expected to remain the dominant fossil fuel securing the world energy supplies, but also contributing significantly to the world CO_2 emission [1]. Measures of coal-based energy sector CO_2 emission mitigation include primarily application of highly efficient, low-emission gasification systems, generation and utilization of hydrogen-rich gas and co-processing of coal with “zero-emission” fuels, like waste biomass. These may also be complemented with a technically viable, but still economically ineffective utilization of the excess heat from nuclear plant replacing the carbon-intensive combustion as a source of heat for endothermic reactions of the processes of thermochemical conversion of coal [3]. When production of hydrogen (hydrogen-rich gas), as the energy carrier, is considered in such a system, the CO_2 reduction might be achieved not only at the manufacturing step, but also at the end user step. Here, the carbon footprint of gasification process, which is already of higher efficiency and lower emissions than the most advanced combustion systems applied today [4–6], may be further mitigated by the utilization of the excess heat from nuclear plants within a so-called coal-nuclear synergy system [7]. The idea of hydrogen production with nuclear heat application is not new, especially when the electrolysis process is considered [8,9]. The thermochemical process of methane steam reforming with utilization of a nuclear plant heat is also mentioned in the literature [7,10,11]. In the paper the idea of combining the excess heat from nuclear plant with the process of solid fuel gasification to hydrogen-rich gas is examined. The nuclear reactors considered in such application are the HTRs (High Temperature Reactors) consisting of spherical fuel elements i.e. graphite balls with a diameter of 60 mm, containing small grains composed of uranium dioxide and thorium dioxide or uranium carbide and thorium carbide [12]. A reactor core cooling medium,

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helium, is heated from 700 to 950 °C flowing through a HTR [12,13]. The final product considered in the theoretical studies on coal gasification with application of a nuclear heat for endothermic reactions include ammonia, liquid fuels [14,15] and hydrogen [16,17]. Biomass has also been recently considered as a raw material for the process [18]. The research studies on High Temperature Reactors applications were performed in Germany in 1970s and 1980s, including among the others, the KVK (Component Experimental Loop), NFE (Nuclear Long-Distance Energy Transportation), EVA and EVAII installations [19–21]. The study presented in the paper contributes to the research area concerned in several principal aspects. These include the recognition of the co-gasification process as a thermochemical part of the synergistic fossil fuel-nuclear system, utilization of a "zero-emission" solid fuel, focus on hydrogen production as an environment friendly energy carrier in the system concerned and providing the experimental data complementing the variety of theoretical studies in the field of coal-nuclear synergy.

In the paper the results of the experimental study on the effects of simulated HTR excess heat application on the efficiency of the allothermal coal gasification to hydrogen-rich gas are presented, including the selection of the optimal biomass content in a fuel blend. Three options of a pre-heating system were tested. The results proved the feasibility of the utilization of the external excess heat in the pre-heating of gasification agents in the process of coal and biomass co-gasification to hydrogen-rich gas.

2. Methods and materials

The co-gasification study was performed in the fixed-bed reactor installation adopted for the purposes of the simulated HTR excess heat utilization. Fuel blends of two types of hard coal and two species of energy crops were processed with steam and oxygen at 800 °C and with the application of various system configurations described below.

2.1. Materials

Hard coal samples were provided by Janina Mining Plant and Lubelski Wegiel Bogdanka S.A., Poland. The biomass of energy crops, *Salix Viminalis* and *Andropogon Gerardi*, was supplied by M&D Farms Sp. z o.o. in Świerczów and the Department of Agricultural Sciences in Zamość of University of Life Sciences in Lublin, Poland, respectively. The samples were hereinafter called JC (Janina Coal), BC (Bogdanka Coal), SV (Salix Viminalis biomass) and AG (Andropogon Gerardi biomass). The co-gasification tests were preceded with the analyses of the selected physical and chemical parameters of tested fuels (see Table 1) performed in the accredited laboratory of the Department of Solid Fuel Quality Assessment of the Central Mining Institute. These were made with the application of the relevant standards, testing procedures and the following apparatuses: 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). The fixed carbon was calculated according to the formula: 100% − W − A − V (PN-G-04516:1998).

Table 1
Physical and chemical parameters of studied fuel samples.

No.	Parameter, unit	Fuel samples			
		JC	BC	SV	AG
1	Moisture W, %	10.21	3.29	4.74	9.72
2	Ash A, %	9.46	11.61	1.51	3.87
3	Volatiles V, %	32.41	32.38	73.16	70.26
4	Heat of combustion Q_s, kJ/kg	25,114	28,667	18,171	16,132
5	Calorific value Q_i, kJ/kg	23,917	24,582	16,697	14,242
6	Total sulfur S, %	1.45	1.3	0.05	0.06
7	Carbon C_t, %	62.73	68.4	52.19	53.3
8	Hydrogen H_t, %	3.94	4.42	6.22	7.57
9	Nitrogen N, %	0.84	1.53	<LD	<LD
10	Fixed carbon, %	47.92	52.72	20.59	16.15

2.2. Test stand

The experimental verification of the simulated HTR excess heat application in gasification process was performed with the application of the experimental set-up of the Laboratory of Advanced Energy Technologies, the Department of Energy Saving and Air Protection of the Central Mining Institute. The main elements of the test stand include fixed bed reactor of a volume of approximately 0.8 L, the gasification agents supply and pre-heating system, simulating the utilization of the HTR excess heat, and the product gas treatment and measurement system (see Fig. 1). The fixed bed reactor and the gasification agents pre-heating unit are heated with computer-controlled electric resistance furnaces. The process temperature and pressure are monitored with thermocouples and manometer, respectively, and controlled with temperature and pressure controllers.

2.3. Experimental procedure

The allothermal co-gasification tests with the application of a pre-heated oxygen/steam mixture as the gasification agent were

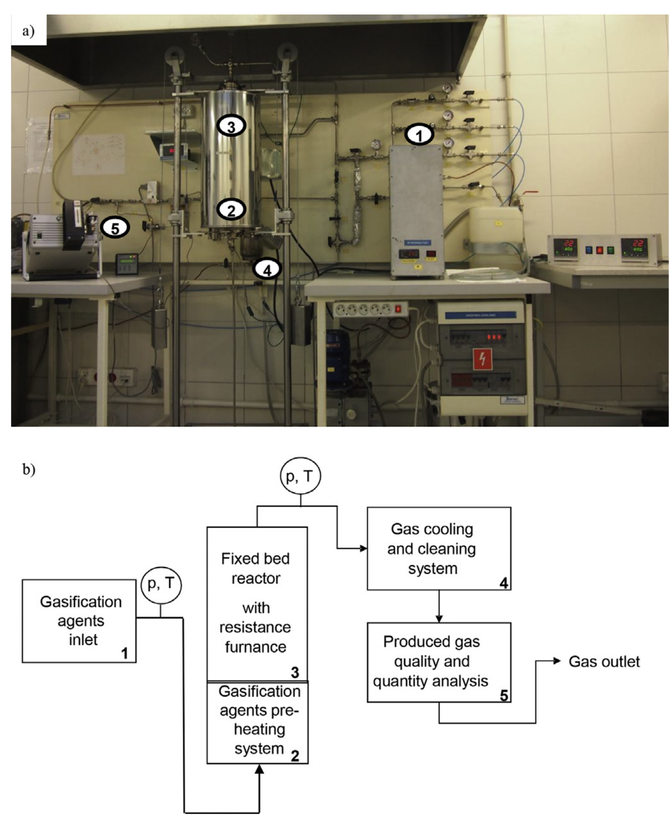

Fig. 1. The laboratory scale fixed-bed reactor installation coupled with the gasification agents pre-heating system, simulating the utilization of the HTR excess heat: (a) view and (b) schematic diagram.