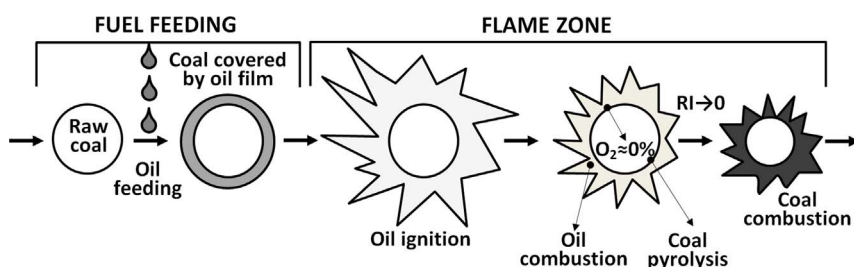Full Length Article

Adaptation of hard coal with high sinterability for solid fuel boilers in residential heating systems

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GRAPHICAL ABSTRACT

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ABSTRACT

Solid fuels boilers with low emission and modern construction, which are used for residential heating, require coal fuel with low sinterability (RI < 15). This paper presents a process for adapting coal with high sinterability for use in small boilers in residential heating systems. This solution allows for the combustion of coals with an RI of 50 without causing negative effects (in terms of combustion stability) in typical burners used in heating devices. The proposed solution involves the delivery of fuel particles coated with an oil film (waste oil and canola oil) to the combustion chamber. Tests were performed using a commercial-scale boiler with a 17–23 kW output, equipped with a retort burner and a dosing device, which applied oil to the coal in the boiler. Tests were performed during the combustion of hard coals characterized by different sinterability, with and without various streams of oils. Emission issues are also analysed. Impregnation of the coal by canola oil caused slightly lower NOx emissions, but higher CO and dust emissions. Analyses of the basic quality parameters (i.e., coal structure after thermal treatment) show that changes in the coal properties also occurred. Based on these studies, a mechanism that explains the beneficial effect of oil presence on high sinterable coal (HSC) combustion is proposed.

1. Introduction

The application of small, domestic-scale boilers and stoves (< 50 kW) as a heat source for daily activities (i.e., house and water heating, cooking etc.) is widespread all over the world. Depending on regions, social issues and fuel resources, different fuel types are used, such as gaseous fuels (mainly natural gas) [1], coal [2–4], fossil and bioliquid fuels [5], and solid biomass (e.g., wood, agricultural products and residues) [6–9]. The use of coal in domestic applications is

problematical in most EU countries. However, coal-fired boilers and stoves are still used in domestic applications. For example, in the Czech Republic in 2011, out of a total of 3.6 million households, 9.2% were heated by coal and 7.8% were heated by wood. Moreover, the problem of air pollution is enhanced due to the illegal combustion of municipal solid waste in domestic furnaces [10]. In Poland, as of 2015, the share of hard coal in total energy consumption in households was 32.11% [11]. In China, residential coal stoves are commonly used for cooking and heating, especially in the winter [2]. In some regions (e.g., Jingxian

and Xinmi), the total share of coal per capita in rural household energy consumption is more than 25% [12]. The use of coal for residential heating around the world was analysed by Kerimray et al. [13], who noticed that certain counties have higher per capita residential coal consumption (in kilograms of oil equivalent per capita (kg OE/cap), 2014): i.e., Poland (165 kg OE/cap), Kazakhstan (157 kg OE/cap), Mongolia (104 kg OE/cap), Ireland (87 kg OE/cap), South Africa (69 kg OE/cap), the Czech Republic (49 kg OE/cap), China (36 kg OE/cap), the Republic of Korea (14 kg OE/cap) and Hungary (10 kg OE/cap). Ryfa et al. [14] reported that about 203 million households in Europe are mostly equipped with a single heating system (boilers). The residential heating sector in Poland consumes approximately 12 million tons of coal annually. Due to the price competitiveness of this fuel, compared to other fossil fuels or biomass used in this sector, the situation will not change in the near future. It is estimated that approximately 80% of the heating infrastructure is outdated, negatively affecting air quality and requiring frequent cyclic operation and supervision. Boilers with modern, low-emission construction, which meet the standard PN-EN 303-5: 2012, require the use of fuel with low sinterability (Roga index, RI < 15). Automatic coal-fired boilers (ABs), in contrast to traditional manually operated boilers (TBs), are recognized as environmentally friendly with regard to domestic applications. The total emission of gaseous pollutants (e.g., CO, VOCs) from these boilers is several times lower than that for TBs [3,15]. However, NO_x emissions are approximately 40% higher (or more) from ABs than from TBs [3]. Small-scale commercial boilers (automatic or manually operated) were previously investigated with respect to efficiency, particulate matter (PM) and gaseous pollutant emissions (including NO_x), and other parameters [3,14–23]. Due to the increase in demand for energy and environmentally friendly combustion systems, different variations of fuel blends have been investigated. The change in heat source (fuel switch) in a short period of time is very difficult to manage. Thus, some transition solutions to coal firing and other energy sources have been suggested. The combustion performance of a mixture of different liquid fuels [5], a mixture of coal and process gas [3], a mixture of coal or lignite and biomass [4,24], and a mixture of different solid biomass [6,7,25,26] has been investigated in terms of efficiency and PM emissions. Xu et al. [4] observed that pelletized biomass and coal blends can significantly decrease emissions. Hrycko et al. [3] proposed the application of gas from the gasification process as a reburning agent. Moreover, they obtained high fuel flexibility because of the reburning fuel heat input of 63%. Buczynski et al. [18,19] and Ryfa et al. [14] performed experimental and mathematical modelling of small-scale countercurrent fixed-bed automatic boilers. The computations included the combustion of coal and heat transfer from the flue gas into heated water. Thus, a computational fluid dynamics-based model of the whole boiler was taken into account. Rabacal et al. [20] found that the type of fuel significantly affected boiler emission characteristics (i.e., CO, NO_x and hydrocarbons). The fuel-NO mechanism is the main source of NO_x emissions in this type of boiler. A computational fluid dynamics analysis of a small-scale commercial biomass pellet boiler was also presented by Porteiro et al. [27]. The fuel type and its blends have also been investigated in order to obtain an efficient multifuel boiler. For example, González-González et al. [5] presented a study involving the combustion of different mixtures of biodiesel/gasoil under different operating conditions using a 26.7 kW domestic heating boiler. Schönnenbeck et al. [6] analysed the energy recovery of grape marc in a 30–40 kW multifuel domestic-scale boiler. Different blends of grape marc and other biomasses (i.e., wood pellets and Miscanthus) were tested in terms of combustion performance and emission issues. Leyssens et al. [7] presented a study on the combustion performance of pellets made from sawdust and reused cardboard.

It is worth emphasizing that the co-combustion of coal and liquid fuels in domestic-scale boilers has not been investigated before. However, co-combustion of coal and glycerol (1 wt%) in industrial pulverised fuel boiler (180 MW_{th}) was reported by Topolnicka et al.

[28]. Some liquid fuels also have the status of renewable sources of energy. If canola oil cannot be used in the food industry (due to insufficient parameters), it can be employed as a fuel. Bhimani et al. [29] noticed that canola oil has a negligible ash content and can be used in boilers as an almost foul-free fuel.

The combustion of HSC is problematic in modern ABs. The main negative phenomenon involves the effect of AB burner blocking. Thus, it is necessary to find a solution to this problem, as it has not been previously investigated. Another novelty of this work is the extended fuel flexibility of a solid fuel-fired domestic-scale boiler using a liquid fuel as a secondary fuel. The objective of this work is to demonstrate that the stable combustion of HSCs in a domestic automatic boiler is possible after coal impregnation by liquid fuels. Combustion tests are also performed, along with an analysis of combustion parameters (flame stability, boiler efficiency) and the emissions of particles and gaseous pollutants.

2. Experimental

2.1. Fuels analysis

The proximate analyses of the examined coal samples were performed according to the technical procedure Q/LP/06/A:2011 for the determination of ash content and Q/LP/05/A:2011 for the determination of moisture content. The volatile matter analysis was conducted in accordance with the technical procedure Q/LP/07/A:2011. The ultimate analysis was performed using a LECO TrueSpec (LECO, USA) CHN analyser and a LECO SC 632 analyser (LECO, USA). The heating values were analysed using LECO AC500 (LECO, USA) apparatus. The oil ignition temperature was determined by Marcusson method. The liquid fuel sample was placed in an open vessel and it was heated up (rate of 3 °C/min). The gaseous fuel flame was approaching the liquid fuel sample within the temperature increase of 1 °C until ignition of liquid fuel volatiles appeared. The viscosity of liquid fuels samples were determined using Engler viscometer.

Fuel samples were also observed using an Axio Imager M1m (Carl Zeiss, Germany) optical light microscope. Samples of coal were processed before the microscopic observation. The coal samples were cut in order to obtain 2 cm cubes, then combusted in a flame. After combustion, the samples were embedded in acrylic resin, which was cut to obtain cross sections and then polished. Sample cross sections were observed using reflected polarized light. The results of the analyses of the applied fuels are presented in Tables 1 and 2. HSC was used in the tests. Usually, this type of coal is applied to the coking process. However, this type of coal was used to evaluate whether the proposed coal

Table 1
Proximate and ultimate analysis results of low sinterable coals and HSCs.

Parameter	Unit	Low sinterable coal	High sinterable coal
M_t^r	%	10.1 ± 0.3	2.4 ± 0.3
M^a	%	4.3 ± 0.1	1.0 ± 0.1
A^a	%	4.1 ± 0.1	7.0 ± 0.1
V^a	%	34.16 ± 0.12	30.16 ± 0.12
V^{daf}	%	37.29 ± 0.14	32.78 ± 0.14
C_t^a	%	75.8 ± 0.4	79.6 ± 0.4
H_t^a	%	4.56 ± 0.16	4.5 ± 0.16
N^a	%	1.22 ± 0.10	1.29 ± 0.10
O_d^a	%	9.63 ± 0.31	6.07 ± 0.31
S_t^a	%	0.56 ± 0.03	0.65 ± 0.03
S_C^a	%	0.39 ± 0.03	0.11 ± 0.03
S_A^a	%	0.17 ± 0.03	0.54 ± 0.03
HHV^a	kJ/kg	30345 ± 68	32700 ± 68
LHV^a	kJ/kg	29244 ± 70	31693 ± 70
LHV^r	kJ/kg	27324 ± 94	31210 ± 94
RI	–	11 ± 2	57 ± 2

a – analytic basis, r – as received basis, daf – dry ash free basis, M – moisture content, A – ash content, V – volatile matter content.