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Review

Unburned carbon from coal combustion ash: An overview

Lucie Bartoňová *

VŠB-Technical University of Ostrava, Tř. 17. listopadu 15, 708 33 Ostrava-Poruba, Czech Republic

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ABSTRACT

Vast quantities of ash are produced in coal combustion power stations annually. Including aluminosilicate matrix, all ashes also contain unburned carbon (UC) of varying amounts; in some ashes it can exceed 10% (or even 45% in stoker boilers). High UC levels in ash does not only constitute an energy loss during combustion, it can also hinder technological utilization of such ashes (e.g., in cement industry). Thus, effective technological utilization of UC (e.g., in adsorption processes) will result in multiple benefits — it will not only convert the waste material into a valuable product, but it will also facilitate utilization of ash fractions, from which UC has been separated (which consequently help to solve ash disposal problem). For this reason, the main aim of this paper is to provide an overview of research related to UC from coal combustion ashes. It reviews factors affecting UC content in ash, methods of UC determination, UC separation techniques, different approaches in studying UC, and so on. Particular attention has been paid to feasible utilization options of this material in reference to its properties. Further research in the related areas is discussed as well.

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Abbreviations: UC, Unburned carbon; FBC, Fluidized bed combustion; PFC, Pulverized fuel combustion; PFBC, Pressurized fluidized bed combustion; LOI, Loss on ignition; FA, Fly ash; BA, Bottom ash; ESP, Electrostatic precipitator; 1 M NH_4OAc, Ammonium acetate (1 mol/L); HRTEM, High-resolution transmission electron microscopy; XRD, X-ray diffraction; FTIR spectroscopy, Fourier transform infrared spectrometry; MWCNT, Multi-walled carbon nanotubes; SSA, Specific surface area; BET, Brunauer–Emmett–Teller; AC, Activated carbon; MB, Methylene Blue; FGD, Flue gas desulphurization; XAFS spectroscopy, X-ray absorption fine structure spectroscopy.

* Tel.: +420 59 699 1514.
E-mail address: lucie.bartonova@vsb.cz.

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1. Introduction

According to the International Energy Agency and World Coal Association, coal currently provides about 30% of global primary energy needs. Total world coal production in 2012 reached 7830 Mt [1] and it has been estimated that current coal reserves are sufficient to meet at least 100 years of such global production [2].

The worldwide production of coal combustion products (in 2010) was approximately 780 million tons [3]. Unburned carbon (UC) levels in ash varies greatly; however, even if average unburned carbon content in all these ashes was as low as 1%, it would constitute about 8 million tons of this waste material produced annually. Since typical UC content in coal ash is generally higher, and the implementation of modern low-NO_x burners further complicates the effort to decrease it, annual production of UC in coal combustion units is estimated to be in the order of tens of millions of tons.

In addition to energy loss due to incomplete coal combustion, there are two main research areas attracting particular attention currently:

i) Higher level of UC in coal ashes hinders further utilization of these ashes in cement and construction material industry, increase transportation and/or landfilling costs, etc. From this point of view, UC in ashes is an undesirable component whose content should be reduced either by optimized combustion process or by efficient separation techniques.
ii) Due to some promising UC characteristics, there is a strong tendency to find some feasible utilization of this material, e.g., for preparation of effective adsorbents, graphite-like materials, fillers, and so on.

This paper has been written with the intention to provide (at least fundamental) overview of the current knowledge relating to UC present in coal ash, and to digest interesting observations, innovative approaches, stimulating ideas and practical conclusions in the field of UC levels in ash, UC characteristics, separation techniques, and its feasible utilization.

2. Unburned carbon levels in coal ash

2.1. Factors affecting UC content in ash

The factors affecting UC levels in ash fall within two major groups — the effect of coal characteristics and the effect of combustion system design and operating conditions. The most important ones are listed below.

2.1.1. Effect of combustion system design and operating conditions

The operating conditions in power stations can influence UC levels in ash predominantly through the following parameters:

- type of combustion unit — fluidized-bed combustion (FBC), pulverized fuel combustion (PFC), etc. [4,5]
- type and number of burners (especially installation of low-NO_x burners) [6–12]
- oxy-fuel combustion technology [13,14]
- post-combustion of carbon residues in ash [15]
- combustion temperature and pressure [16,17]
- residence time available for combustion in furnace, boiler output [9,18–20]
- oxygen availability (air/coal ratio, excess air at the burner, primary to secondary air ratios) [9,16,21–29]
- furnace heat loading, heat flow rates [24,26]
- even/uneven flame patterns [30]
- matching of operating conditions and raw-fuel quality [30].

2.1.2. Effect of coal characteristics

The most significant coal characteristics affecting UC content in coal-combustion ashes are summarized below:

- coal rank [31–33]
- maceral composition of coal [8,17,18,31,34–39]
- volatile matter content [26,40]
- moisture content in coal [10,41]
- particle-size effect [9,10,16,26,42–44]
- coal char properties (porosity, fragmentation, specific surface area, etc.) [8,26,45]
- effect of coal mineral matter [8,16,26,46]
- coal blending [32,39,44,47–49]
- co-combustion of coal with alternative fuels [50–54].

In the case of most factors listed above, the results reported in literature are consistent and the conclusions obtained are generally accepted. However, there are some factors requiring further discussion and detailed description of the nature and extent of the influence would be beneficial.

2.1.2.1 . Effect of inertinite content in coal. It is a traditionally accepted conclusion that higher inertinite content in coal produces ashes with higher UC content [35–37]. However, some studies have presented results where inertinite content in coal and coal burnout efficiency was not in exact positive relation [31,33].

Since inertinite classification can be applied to the organic matter from peat to meta-antracite [60], the range of inertinite reflectance can be rather broad. And this can be the very reason why inertinite-derived UC can be (in some cases) highly reactive and for some high volatile bituminous coals even more reactive than vitrinite-derived ones [61–63].

This is consistent with conclusions presented by Choudhury et al. [33] where inertinite showed even better reactivity than vitrinite (when various coals and their fractions were combusted). It was concluded that low-reflecting inertinite in the combusted coals contributed to the good burning behavior of these inertinite-rich Indian coals. Similar conclusions were found by Malumbazo et al. [64] for South African inertinite-rich coals where the distinction between reactive and inert macerals was made with regard to their reflectance under the microscope. Such detailed petrographic description fully explained the conversion performance of the studied coals [64].

2.1.2.2. Effect of volatile matter content. Although volatile matter content in coal is generally thought to have a positive effect on coal burnout,

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