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Research article

Optical microscopy as a new approach for characterising dust particulates in urban environment

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ABSTRACT

In urban environments airborne particulates (dust) must be managed to ensure that industry and community coexist in a mutually beneficial and sustainable manner. The composition of the dust is a function of the local environment and industry. In general, there is a view by many community members that a significant proportion of inhalable (PM_{10}) and respirable ($PM_{2.5}$) dust in these environments could be coal. Thus there is a need to have an analytical method that provides a quantitative analysis of the amount and size distribution of the different particulates that can be present in air samples.

Australia's national research body, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) has developed a Coal Grain Analysis (CGA) system that uses reflected light optical microscopy to provide a unique visual perspective, a qualitative feeling of the sample and quantitative information on the composition and size of the individual particles greater than 1 µm. Furthermore, semi-automated Optical Dust Marker software uses each individual particle's colour reflectance fingerprint to classify that particle. These markers can currently identify coal, combustion chars, iron, quartz/dark minerals, pyrite/bright materials and particulates of organic origin.

This paper presents a case study performed using CGA to evaluate the dust composition and proportion of coal and other particulates and also their size distribution in samples collected in an urban area along a coal rail corridor in Newcastle (Australia). In coastal environments a significant proportion of dust can be water soluble (salt) particulates; the proportion of soluble particulates in those samples varied from 46% to 52.3%. The concentration of insoluble particles in samples varied from 5.9 to 15.5 $\mu g\, m^{-3}$ in the $PM_{2.5\text{-}10}$ fraction and from 0.4 to 0.9 $\mu g\, m^{-3}$ in the $PM_{1\text{-}2.5}$ fraction. All samples consisted predominantly of particles of organic origin (mostly plant and insect remains) – 55.3%–85.3% by mass. Dark material particles of mainly inorganic origin (low reflecting material, mainly stone dust, clay, soot, rubber and soil), combustion char and metal particles (rust and iron oxides) were present in lower concentrations – 0.0% to 19.9% by mass. The amount of coal in the water insoluble fraction of the samples ranged from 5.3% to 19.7% by mass with 2.9%–13.5% by mass of coal particles in the thoracic (2.5–10 µm) and 0.3%–1.2% by mass in the respirable (1–2.5 µm) size fraction.

1. Introduction

For decades, the mining industry has remained a field of strong interest worldwide for academic and public policy research in terms of sustainable development (Hancock and Wolkersdorfer, 2012). Yu (2017) mention that some coal mines are positively moving towards sustainable development, but some challenges still persist, e.g., poor pollution control. As for the sustainable development of mineral resources, researchers in different countries focused their attention on different problems, as countries differ in development phases and mineral resources, thus there is need to develop a strategy to minimize the impact of this industry on the environment (Li et al., 2013). Globally, the industry employs millions of people; thus, it plays a significant role in economic growth (Lu and Lora-Wainwright, 2014) and poverty alleviation (Ge and Lei, 2013). However, in the process, it has caused long-lasting damage to the environment including land surface disturbance, the destruction of ecosystems and biodiversity, mine subsidence, soil erosion, and noise, air and water pollution. It is therefore necessary for the mining sector to turn their operations towards green practices (Sivakumar et al., 2015).

Coal and lignite production is a worldwide industry: over 7686 million tons of coal are produced per year with China, United States, India, Australia, Indonesia, Russia, South Africa, Germany, Poland and Kazakhstan being the top 10 producers (Enerdata, 2016). Australia is

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one of the world's major exporters of metallurgical and thermal coals; in excess of 376 million tonnes per annum is exported through coal terminals located in or near major coastal towns in the states of New South Wales (Newcastle and Wollongong) and Queensland (Brisbane, Mackay, Gladstone and Bowen) (Enerdata, 2016). Coal-related air pollution is not new. Since the late 17th century, coal-laden smog has influenced many cities in Europe, Australia, America and Asia, therefore it can be said that coal-related air pollution is a global concern. However, it seems that the big question today should not be whether coal can ever be "clean", but whether it can be clean enough to support sustainable development (Nijhuis, 2014). Partial substitution of fossil fuels with alternative solid fuels, such as biomass and waste-derived fuels has already been recognized as an advantageous method for greenhouse gas mitigation (Mikulčić et al., 2016a). However, due to the different properties of those fuels and their varying performances in existing combustion systems, their applications are still being studied both experimentally (Růžičková et al., 2016) and numerically (Mikulčić et al., 2016b).

Urban dust particulates are a complex mixture of particles of different sizes and chemical composition, which are dependent on the source of the particles, temporal and spatial variations and their formation process (García-Nieto, 2006). Thus, it is important to study chemical and physical properties of particulate matter and its relationship with sources, especially in industrialized areas as particulate matter emissions escape into the atmosphere from both ducted and fugitive sources (Štrbová et al., 2017). This means there is no single method that is able to quantify all the properties of particles and most often one or a number of properties of the particles are measured and used along with valid assumptions to quantify the particles (Keywood and Selleck, 2016).

Coal dust can be generated by air blowing over a surface containing coal. This can happen at any of the numerous stages of the whole coal supply chain, which involves extraction, processing, transporting (via train, truck or conveyor), storing and use or export of coal from the mine to a ship or power plant (Pandey et al., 2008). This mechanical formation process results in a particle mass size distribution dominated by coarse particles (greater than 2.5 μm in diameter) (Aneja et al., 2012). On the other hand, resuspended coal dust particles along rail corridors and at ports produce a particle mass that includes fine particles as well (less than 2.5 μm in diameter) (Keywood and Selleck, 2016). Whilst coal dust is a significant environmental and social responsibility issue for the coal industry at all parts of the coal chain, it is where mines are in close proximity to towns and in urban and industrial environments, such as along rail corridors and at ports, that public concern with coal dust is greatest. Although coal is often only one of the constituents present in the dust in these environments, there is a general perception that all black dust is coal, and that a significant proportion of the visible dust is respirable (Warren et al., 2013). Furthermore, dust particles are known to have a significant impact on climate, human health and surrounding fauna and flora (Huertas et al., 2014). Exposure to coal dust is often associated with increased mortality and can cause various respiratory diseases such as coal workers' pneumoconiosis (black lung disease) and silicosis (Patra et al., 2016).

Currently available technologies that are used routinely in atmospheric measurement programs and could be applied to determine emissions from the coal chain are: particle concentration methods (e.g. gravimetric methods; Beta attenuation monitor; Tapered Element Oscillating Microbalance and Light scattering devices), particle size distribution measurements (e.g. Scanning Mobility Particle Sizer, Aerosol Particle Sizer; Cascade impactor and Light Scattering devices – optical particle counters and photometers), absorption techniques (e.g. Multi-Angle Absorption Photometer and Aethalometer) and chemical composition analyses (specialized analytical methods and source apportionment modelling) (Li et al., 2017). Gravimetric methods are the only type that meet the United States Environmental Protection Agency (US EPA) Federal Reference Method (FRM) requirements and can be used for the reporting of National Environmental Protection Measure for Ambient Air Quality (NEPM) PM_{10} standards and $PM_{2.5}$ advisory standards (Huertas et al., 2012; Keywood and Selleck, 2016).

Recent advances in instrument and method developments show a high potential in evolving new techniques for dust monitoring. Adoption of these techniques to the monitoring of the coal chain could provide high quality data that would quantify the contribution of the different sources of emissions in urban environment to the total emissions. There is a need to have an analytical technique that not only provides a quantitative analysis of the amount and size distributions of the different particulates that can be present in air samples, but also provides this information in a way that is acceptable to all stake holders, including community, government and industry. A literature review found that there is currently no standard, or any agreed preparation techniques to quantitatively analyse dust for coal, with some trying wet chemistry techniques (Burns, 2014) and others a petrographic type approach using SEM and/or optical microscopes.

Reflected light microscopy is used to characterize coal for its rank and type. Coal petrographers determine coal rank (degree of coalification) by measuring vitrinite reflectance and type (amount and category of macerals). Coal petrography is performed on grain mount samples set in suitable mounting resin (polyester, epoxy, and acrylic) and polished to a mirror surface (Diessel, 1999). There are a limited number of analysts who will undertake a petrographic analysis of dust samples for coal commercially in Australia, with most providing only general observational or semi-quantitative data on the samples, or only information on the carbon component of the sample as the analysis is typically done using an oil immersion lens (Coal Terminal Action Group, 2013).

To try to fill the gap identified in available analysis techniques for coal identification in dust, CSIRO has adapted its optical microscopy imaging technique – the Coal Grain Analysis (CGA) method that uses an air lens to provide information on the coal and the other particulates present in urban dust samples, including size information of each individual particle. CGA is described in this paper in detail together with comparison to other available methods and a case study to highlight its uniqueness.

2. Comparison of methods for coal dust analysis

For urban dust characterisation there are only a limited number of methods that can be used for coal dust determination. These can be grouped into methods that collect samples for offline gravitational and chemical analysis, and methods that continuously determine particulate concentrations by measuring light scattering of the particle. In Australia, there are three main techniques used for coal dust determination: firstly, source apportionment; secondly stereomicroscopy combined with scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS); and thirdly optical microscopy techniques that involve either a manual pointing or a imaging method such as the CSIRO's Coal Grain Analysis (CGA) method (Hibberd et al., 2016).

2.1. Source apportionment

Recently in Australia, source apportionment modelling has been adopted to examine dust and aerosol samples. It determines the source of particles according to the chemical composition of particles and matches unique tracer components to the source. Currently the identification of coal particles by chemical analysis has proved difficult as there is no unique chemical tracer or clear ratio of elements to distinguish coal from other particles (Matysek et al., 2015). The tracer typically used for coal dust identification is black carbon (Hibberd et al., 2013). Light absorption (light-absorbing carbon) is routinely used to determine the BC concentration of atmospheric aerosol in air quality and climate research. The ability of a particle to absorb light however is affected by the size of the particle and the wavelength at which the