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Health effects engineering of coal and biomass combustion particulates: influence of zinc, sulfur and process changes on potential lung injury from inhaled ash

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Abstract

This paper is concerned with health effects of the ash aerosol formed from the co-combustion of municipal sewage sludge (a CO_2 neutral, ostensibly 'green' biomass fuel) with pulverized coal. To study, and mitigate, possible lung injury caused by inhalation of these ash particles, it is useful to employ 'Health Effects Engineering', which involves collaboration between combustion researchers and toxicologists. Health Effects Engineering attempts to build connections between mechanisms that form particulates during the combustion process and mechanisms that cause these ill health effects. By employing the methods of Health Effects Engineering, one can determine not only which fuel attributes are likely to contribute to lung injury, but also how tendencies of the ash to cause lung injury can be engineered out of the combustion process.

Initial results showed that inhalation of ash from the co-combustion of municipal sewage sludge (MSS) and pulverized coal caused much greater lung damage in mice, as measured by lung permeability increase, than that of coal ash, or MSS ash, alone. MSS contains substantial quantities of zinc but little sulfur, while coal contains sulfur but little zinc. Therefore, systematic experiments were conducted to determine the health effects of combustion generated zinc particles and zinc plus sulfur particles. Zinc without sulfur led to 'normal' behavior as far as lung permeability was concerned. Zinc with sulfur added led to the 'abnormal' behavior noted also in the coal+MSS experiments. Therefore, the bad actor was identified to be zinc together with sulfur, and that was why the co-combustion of coal and MSS caused greater lung injury than the combustion of either fuel alone. Health effects engineering can also be employed to diminish this health risk caused by burning fuels containing both zinc and sulfur. Injection of a kaolinite sorbent downstream of the flame, but above the Zn dew point, can sequester the Zn, and react it to form a new species which was shown to be relatively benign.

Keywords: Health effects; Municipal sewage sludge; Co-combustion; Ash aerosol; Zinc; Kaolinite

1. Introduction

Mixing dried human sewage sludge with pulverized coal has been evaluated as a way to reduce carbon dioxide emissions from traditionally coal-fired power plants, as well as to overcome sewage-disposal problems. Previous work [1] investigated the effects of inhaling particles emitted from the combustion of this mixture and found that these cause significantly more lung damage in mice than do particles from coal alone, probably because of their zinc content. Potential lung damage, in this case, was quantified by measurements comparing lung permeability of mice exposed to re-suspended ash particles to that of mice exposed only to room air. MSS had been processed (Swiss 'Combi' process) to produce 2–4-mm pellets, which were then pulverized and mixed (20% thermal, 50% mass load) with coal. Sampled particulate matter was re-suspended and diluted [2] to a sufficiently low concentration to allow the effects caused by different particle properties to be assessed

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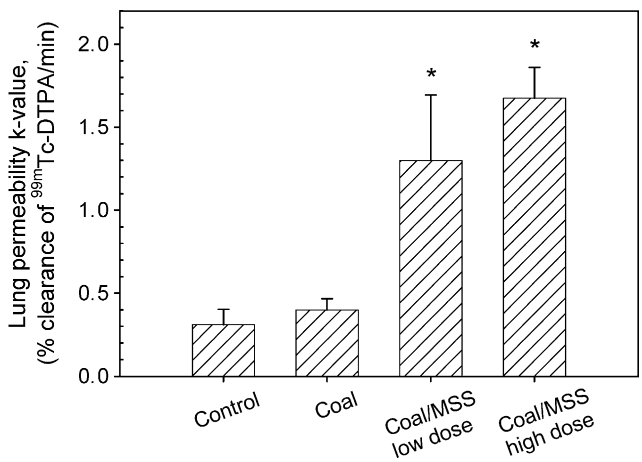

Fig. 1. Initial tests showing potential lung injury due to inhalation of ash aerosol from co-combustion of coal and MSS.

on exposed mice. Mice were exposed for only 1 h each day for 24 consecutive days to a low dose of 1000 μg m^{-3} and to a high dose of 3000 μg m^{-3} (the atmospheric dose of particulate matter less than 10 μm in diameter currently allowed by the United States Environmental Protection Agency is 150 μg m^{-3} averaged over 24 h). These results are shown in Fig. 1, and show that inhalation of coal ash alone yields results similar to those tests with room air, while inhalation of ash from co-combustion of coal and MSS, led to greatly increased lung permeability where the increase was dependent on dose. One concludes from this that the use of dried municipal sewage sludge as a 'green' (CO_2-neutral) replacement fuel should be considered with caution.

Airborne particulate matter is associated with acute respiratory distress in humans [3]. Suggested causes [4] of the lung damage caused by these particles include their composition—for example, they may contain soluble transition metals such as copper, iron, vanadium, nickel or zinc—their acidity, and their ultra-fine size (some particles are less than 0.1 μm in diameter). These properties are all features of airborne particulate matter resulting from the co-combustion of pulverized coal and biomass, including dried municipal sewage sludge (MSS). Therefore, it was of interest to determine if and why the combustion of MSS in general might lead to increased risk to human health, and if so, how that risk could be diminished through changes in the combustion process. To this end, the methods of Health Effects Engineering were employed, as described in Section 2.

Elemental analysis of the re-suspended coal/MSS ash particles revealed that Zn was more concentrated in those ash particles with sizes in the respirable particle size range. Since these studies indicated that Zn plays an important role in the toxic effects in ambient aerosols, another goal of this study was to investigate the inhalation response to systematically generated combustion ash particles containing Zn. The Health Effects Engineering component of the work was to determine the lung injury due to inhalation of *systematically* generated ash particles from two different fuels, namely distilled fuel oil doped with Zn only, and distillate oil doped with both Zn and sulfur, and from two different combustion configurations, namely with and without sorbent injection.

Health effects of zinc enriched particles have been studied in the literature. The formation of sulfated compounds on the surface of ash particles is of great importance. Zn is considered a trace metal in coal, accounting for approximately 2% of the total aerosol mass [5]. However, since Zn condenses on the surface of ash particles (presumably as zinc oxide which reacts with sulfur dioxide to from zinc sulfate), the higher concentration of this salt on the ash particle surface can have a significant impact on its bioavailability. It has been shown in several in vitro studies that bioavailable metals can significantly contribute to cell toxicity and pulmonary hypertension [6–9]. The chemical and surface composition of combustion generated ash particles can have a complex impact on lung function and properties. An in vivo inhalation experiment conducted by Amdur and Chen [10] brought to light the possibility that zinc oxide (ZnO) particles coated with sulfuric acid cause a significant change in lung mechanical functions and increase the protein and neutrophils in the pulmonary lavage fluid. More recently, Adamson [11] published findings from intratracheal installation of an atmospheric dust sample (EHC-93), which contained several metals. Adamson's findings indicated that the soluble Zn had induced an inflammatory response with some necrosis of alveolar Type I cells, an increase in protein concentration, and the total number of cells in the bronchoalveolar lavage fluid (BALF).

2. Health effects engineering—methods and materials

This section describes in detail just how closely Health Effects Engineering requires collaboration between combustion engineers and health effects scientists. Engineers determine the fuel compositions and process configurations to be tested while health effects scientists determine the consequences that these process changes will wreak on human health, upon inhalation of components in the exhaust. Health Effects Engineering therefore attempts to build a direct connection between the engineering facets of a process and the consequent effects on human health of any constituents produced. From engineering and toxicological points of view, the current work addresses the following, heretofore unresolved, issues: (1) Is fly ash from MSS alone (with natural gas assist) likely to cause more lung damage than fly ash from coal alone, or are there synergistic effects found in the co-combustion of coal and MSS together? (2) Does time resolution of exposures uncover some effects that perhaps were missed by the previous study? (3) Can