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Review article

A review of the application of X-ray computed tomography to the study of coal

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ABSTRACT

There has been a long history of using X-rays to visualize coal and its transitions during various treatments. Advances and improved availability has allowed the application of X-ray computed tomography (CT) to create 3D images to aid rationalizing coal behavior. This non-destructive technique has been used in the determination of mineral dispersion for coal cleaning potential; swelling/shrinking and fracturing accompanying drying; transitions with devolatilization, combustion, and gasification; fracturing during handling; cleat system characterization; and cleat transitions during fluid-flow, gas uptake and degassing; fractures induced with microwave bursts; coal compression; particle classifying systems, coking; and solvent swelling among others. Here the application of X-ray computed tomography to rationalizing coal behavior is reviewed. Much of the initial work was informative simply by providing visualization of the internal complexity or allowing insight into the transformations. It is expected that this will increase with improved instrumental access. Recent technical advances have allowed submicron resolution, and this has resulted in increased challenges in capturing the range of structural information within such diverse samples. It is argued that the field is now mature enough that the X-ray CT technique is being more appropriately applied to solving select behavioral challenges through improved experimental design. It has particularly applicable to evaluating the swelling and contraction accompanying gas uptake and removal in coal under confining stresses. Also for fracture transitions due to the challenges in assessing coal when within stress fields. The use of 3D tomographic data in subsequent simulations such as fluid flow or compression of coke are examples of the technique advancing beyond pure visualization. The potential of X-ray CT informed 3D printing for both visualizations and mechanical measurements with perturbations are also an interesting future direction.

1. Introduction

Here the applicability of X-ray computed tomography (CT) to coal is examined, specifically the role in rationalizing the complex behavior accompanying handling, processing, drying, pyrolysis, combustion, gasification, and use as a gas storage medium. Reviews of the application of X-ray CT for geoscience applications are available [1,2] but applications to understand coal and coal behavior has yet to be reviewed. The application of X-rays to visualize coal dates to 1897, as cited in the 1929 paper of "X-ray examinations of coal sections" [3]. The then new medical technology for examining the body had a coal analog: the bones being similar to the inorganic material and the flesh the organic component [3]. The earliest coal work was generated in a hospital settings [3] a trend that has continued where there is limited instrumental X-ray CT accessibility. Those 2D X-ray shadowgrams of coal slices remained state-of-the-art until advances in the 1970's when computed tomography enabled 3D volumetric reconstructions and quantitative analysis. The earliest application to coal that we are aware of, was in 1983 when a furnace was placed within a medical scanner (again in the hospital) and the transitions accompanying pyrolysis were observed [4]. Since then many different applications have been explored, taking advantage of the non-destructive nature, increasing acquisition speed, resolution gains, and accessibility of increasingly capable instruments. The non-destructive nature is particularly useful as it permits exploration of transformations in 4D (time being the 4th dimension), something that is made inherently challenging due to the diversity of coal. Fig. 1 shows the increase in journal article publications utilizing X-ray CT for coal or coal-related research over the last

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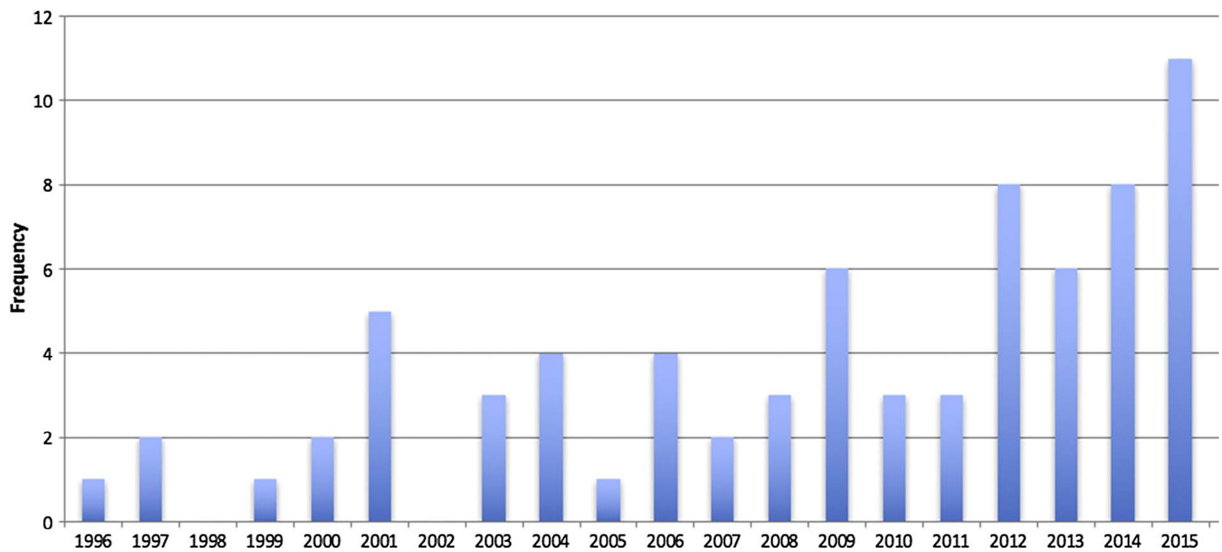

Fig. 1. Journal articles using X-ray CT to examine coal structure or coal-related behavior by year of publication (English language).

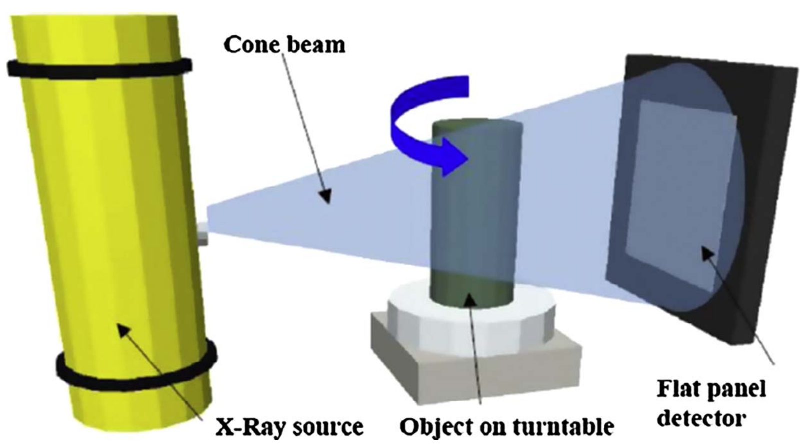

Fig. 2. X-ray CT basic principles (example showing a cone beam). Adapted from Hen et al. [7].

~20 years. While this is likely an underestimation of the work there has been significant activity since 2001. Including conference work would increase the sum (from 73 to > 100 papers). However, the instrumentation is becoming more widely available, and it is expected that this non-destructive technique will become more common for exploration of coal, coal-related exploration, and rationalization of behavior. Here the general theory of X-ray CT approaches are discussed (see Fig. 2 for the basic setup); along with applications in petrology and mineralogy; coal drying, cleaning, and handling; pyrolysis, combustion, and gasification; cleat determination and induced fractures; coalbed methane, carbon dioxide sequestration; coke quality, and coal solvent swelling behavior. The review finishes with recommendations and future directions for this enabling technology.

2. X-ray computed tomography theory and advances

X-ray CT analysis was introduced into the discipline of petrophysics by Withjack and Vinegar in 1988. For a more complete review see Mees et al. (2003) [2]. Medical application of X-ray images has traditionally been based on qualitative pattern recognition by physicians and pathologists. As with simple 2D X-ray images, features like tumors and bone fractures are recognized by their contrast with surrounding tissue and by their shapes. Calibrated digital radiographs and CT images can also be used to determine physical dimensions and volumes of such features in a technique referred to as metrology. These techniques are commonly used for fault detection and quality assurance in industrial applications. Geological and petro-physical use of X-ray data can also take advantages of these techniques where rock structure is course enough to be resolved. Even where individual features are smaller than the available resolution, quantitative analysis of the attenuation data in digital images can be further used to measure density, porosity, and, to a limited extent, composition of rock samples. In the following, we will briefly discuss the basis of X-ray CT analysis and how they are used, particularly in analysis of coal and its responses to chemical and physical stresses.

X-rays consist of short wavelength, high energy light photons typically obtained by bombarding a high-density target with a focused electron beam. The electron beam is obtained by accelerating electrons emitted from a filament cathode through an "excitation" voltage. The beam is focused onto a metallic cathode. Interaction of the fast-moving electrons with the high-density cathode decelerates them causing emission of "bremsstrahlung" radiation which consists of a spectrum of X-rays with maximum photon energy equal to the excitation voltage (usually stated in thousands of electron volts or keV). Unlike optical photons, these photons have sufficient energy to penetrate solid objects. The intensity of the radiation decreases with penetration depth according to exponential decay i.e. the Beer Lambert law. A simple 2D X-ray image (a shadowgraph or digital X-ray) is just a map of the total attenuation of the X-rays along different ray paths through an object. A chest X-ray for example records low attenuation where photons are passing though lungs since they are mostly air, but high attenuation where the ray path is through bone. But this approach yields only a projection, an average attenuation along the ray path. You can see that there is a bone along the ray path, but not where. Instead of this single-