Applied Thermal Engineering 122 (2017) 27–38

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

An integrated methodology for monitoring spontaneous combustion of coal waste dumps based on surface temperature detection

Zhenqi Hu *,[1], Qing Xia [1]

China University of Mining and Technology (Beijing), Beijing 100083, China

HIGHLIGHTS

- A new methodology for constructing surface temperature distribution is proposed.
- The procedure of data collection and data processing is studied.
- The model obtained presents spatial coordinates and temperature information.
- This research is capable of giving an early warning for preventing fire disasters.

ARTICLE INFO

Article history:
Received 29 August 2016
Revised 19 April 2017
Accepted 5 May 2017
Available online 6 May 2017

Keywords:
Spontaneous combustion
Coal waste dumps
Close-range photogrammetry
Infrared thermography
Fire disaster

ABSTRACT

Coal mining wastes are prone to spontaneous combustion, causing burning environmental issues and a threat to human safety. To warn about such spontaneous combustion, mapping surface temperature distribution and locating surface anomalous zones is needed. The new methodology developed in this study was achieved following four primary steps, including field investigation procedures, data pre-processing procedures, data coupling, and 3D visualization. Eventually, a 3D temperature distribution model was presented, and the observed zones were classified into three categories basing on different temperature levels. This new methodology may be useful in monitoring and locating the potential risk zones in advance and making an early warning and allowing to prevent spontaneous combustion.

1. Introduction

Since China has currently become the world's largest coal production and consumption country [1–3], coal wastes generated from coal mining have turned into one of the primary pollution factors in China. So far, approximately150 km^2 of land has been abandoned due to accumulation of 4.5 billion tons of coal wastes. These coal wastes are commonly deposited in the vicinity of mining areas, forming 1700 coal waste dumps [4–7]. Coal wastes consist of claystones (40–98%), coal shales (2–40%), mudstones (2–40%), and sandstones (<33%). Carbonaceous rocks and conlomerates are rarely present within their mass. In terms of mineralogical composition, typical coal wastes are composed of clay minerals (50–70%), quartz (20–30%), other minerals (10–20%), and carbonaceous matter [8–10]. In ambient conditions, organic matter, which is represented by all three groups of macerals, i.e., huminite, liptinite, and intertinite, of coal waste may react with atmospheric oxygen and spontaneous combustion is more likely to occur when heat generated by the exothermic oxidation of the organic matter is larger than the dissipated one [6,11–13]. This spontaneous combustion poses a serious threat to the environment by releasing toxic gases and chemicals, e.g., carbon monoxide, hydrogen sulfide, sulfur dioxide, sulphate, liquid hydrocarbons, and heavy metal materials, to surrounding soils and ground waters [14]. In addition, it can also lead to coal-mining-related geological disasters, such as landslides, large collapses, rock bursts, and gas explosions, which endangers miners' and nearby people's safety and property [15]. Therefore, finding and locating surface anomalous zones is important, as it enables taking preventive measures before spontaneous combustion incidents, which then leads to avoidance of the occurrence of geological disasters and loss of lives and property.

In the early days, thermometers have been used to measure surface temperature of coal waste dumps with the temperature ranging from 40 °C to 1200 °C. However, this technique is time-consuming due to a point-to-point method, and it is dangerous for operators in burning zones with disadvantages of contact

---

* Corresponding author.
E-mail address: huzq1963@163.com (Z. Hu).

[1] Zhenqi Hu and Qing Xia contribute to this work equally.

http://dx.doi.org/10.1016/j.applthermaleng.2017.05.019

[16]. Many studies have been carried out to locate underground coal fires by analysing of remote sensing images, e.g., Priyom Roy used remote sensing images from ASTER and Landsat-8 to detect coal fires in Jharia coal field, India [17–22]. However, it is difficult to apply large-scale remote sensing images into monitoring the surface temperature in small-scale coal waste dumps due to relatively low spatial resolutions. Infrared thermography has gradually become the most common technique on a global scale for temperature detection with the advantages of non-contact, high accuracy and low cost. However, thermographic images can only display the surface temperature distribution without topographic information. Some attempts have been made to detect surface temperature in coal waste dumps using topographic surveying techniques and infrared thermography [15,16,23,24]. However, these studies mainly emphasized on presenting surface temperature distribution, resulting in difficulty concerning locating anomalous zones because of the lack of accurate spatial coordinates. Although topographic surveying techniques have been attempted to locate the regional anomalous zones by integrating with infrared thermography, the results are still unable to reconstruct 3D visualization models of entire coal waste dumps.

In this study, a new methodology for constructing a surface temperature distribution model of a coal-mining waste dump by integrating infrared thermography and close-range photogrammetry, was proposed. The close-range photogrammetry is a surveying technique using image capture to obtain topographic information and this operation is normally performed without any contact with the object under scope [25–27]. For the field data collection, some key issues on how to (1) set control points, temperature-marked points (TMPs), location of an infrared thermographic camera, location of a close-range photogrammetry camera, and (2) capture thermographic images and close-range photogrammetry images, were addressed in detail. Data pre-processing procedures for two different kinds of images, data coupling, and 3D visualization were also discussed. This study emphasized on providing a feasible procedure for detecting and locating thermally anomalous zones in coal waste dumps. This methodology was applied in a small test coal waste dump in northern China to verify its feasibility and applicability. The integrated method with two techniques involved is capable of easily monitoring and locating potential risk zones, especially for small-scale coal waste dumps, compared with the previous studies.

2. Field investigation procedure

2.1. An overview of the technology used

Infrared thermography allows to detect surface temperature of an object by measuring its emitted electromagnetic radiation. This goal is achieved without the need of a physical contact. The radiation detected is converted into electrical signals. Then a thermographic image or a visible image is displayed on a screen of an infrared thermographic camera [28–31]. A thermographic image represents a map of relative temperature variation where the highest and the lowest temperature is identified by hot colors (reds) and cold colors (blues), respectively. The TH9100MV/WV thermographic camera used in this study has a resolution of 320 (H) × 240 (V) pixels and operates in the 8 to 14 μm wavelength band range. The device has adjustable temperature measuring ranges from 0 °C to +500 °C with an accuracy of ±0.06 °C. It is equipped with a commercial MikroSpec4 software for thermographic images processing [32].

Close-range photogrammetry is a technique used to determine position, size and shape of an object by using images; by applying it one can metrically reconstruct objects in 3D by using accurate imaging techniques [25,33]. The close range refers to an object distance of up to about 300 m [34]. For the purpose of this study's close-range photogrammetry, we have applied a digital camera and the lensphoto 2.0 software [25,35–38]. A Canon EOS 5D Mark digital camera with a 28 mm focal length lens was used to capture images, and then these images are processed with the lensphoto 2.0 software to provide topography information for an area. This software can provide lens calibration before image processing.

2.2. Investigation methods

The experiment site was situated at a discarded coal waste dump in the Changping District of Beijing, China. The test coal waste dump was formed as a cone with a base diameter of 2.5 m and a height of 1.8 m, weighing approximately 2767 kg. The coal wastes consist of subbituminous coal, sandstone, clay, quartzite, sulfide mineralization, and solid wastes. Field investigations reveal some potential high temperature points at the coal waste dump surface and lack of vegetation. The location of the study area is shown in Fig. 1.

The first step of the experiment involved setting control points for the close-range photogrammetry. It is necessary to carry out an investigation of the test site (such as area, topography, elevation, presence of vegetation, and so on). In order to make the identification of control points easier, the points were marked with white crosses. First, the test site was divided into four different flanks (Fig. 2). For each flank, at least four control points were established and were evenly distributed at each corner (points a, b, c, and d in the Fig. 2). Additional control points were widely and uniformly distributed over each flank (points e, f, and g in the Fig. 2) to improve the accuracy during data processing. In the Fig. 2, numbers 1–4 represent close-range photogrammetry camera station. Each camera station captures an image, which is equal to each dashed frame. 1 & 2 is the overlapping region between image 1 and image 2, and 3 & 4 is the overlapping region between image 3 and image 4. For two adjacent flanks, both flanks must share at least three control points in the overlapping region because the theory of matching two adjacent flanks is based on the collinearity equations used as observation equations in a least-squares adjustment according to the Gauss-Markov model [39].

The second step involves setting the temperature-marked points (TMPs) for infrared thermography. Since the captured images (from the infrared thermographic camera) were too small to cover a single flank, a single chosen flank was vertically divided into multiple subareas, defined as 1st, 2nd… Nth, as shown in Fig. 3. In general, the quality of image stitching depends on the number of subareas. The more subareas distinguished, the lower accuracy. It is necessary to share at least three TMPs between two vertically adjacent subareas (black stars in the Fig. 3). For a single chosen subarea, it is necessary to share more than two points and the extent of the overlap should be higher than 10% between two adjacent thermographic images (black rectangles in the Fig. 3). The reason why we used two points was that the theory of image stitching between two adjacent thermographic images is based on a rigid transformation [40,41]. The transformation equation is described below.

$$\begin{pmatrix} x_2 \\ y_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} x_1 \\ y_1 \end{pmatrix} + \begin{pmatrix} t_x \\ t_y \end{pmatrix} \tag{1}$$

where (x_1,y_1) is pixel coordinates before image stitching, (x_2,y_2) is pixel coordinates after image stitching. (θ, t_x, t_y) is three unknown parameters. In order to calculate these three parameters, two points are needed. 10% overlapping is an empirical value taken from the MikroSpec4 software instruction after many field tests. It is difficult to distinguish TMPs in the thermographic image, so hot metal coils