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Monitoring of spontaneous combustion at a lignite stockpile

Spontaneous combustion of coal causes substantial material damage and endangers the safety of workers both in the actual extraction of coal and during its transportation, preparation and storage. For these reasons, great attention is paid to the prevention and early detection of early-stage spontaneous combustion. The issue of early detection of spontaneous combustion at coal stockpiles was addressed by the research project TA01020351 solved in the Czech Republic in 2011-2014. The project was focused on spontaneous combustion of lignite, on laboratory tests of indicator gases of spontaneous combustion, and on the verification of the laboratory tested gaseous products and the development of temperature changes at lignite stockpiles. Brief information about the project have been published in the JMMF in September 2012, pp. 193-196.

1. Introduction

Despite continuous research efforts in all developed countries, a completely reliable method of early detection of the spontaneous combustion process has not been found yet. The most common methods of early detection and evaluation of spontaneous combustion include air composition assessment and monitoring so called indicator gases of spontaneous combustion of coal. The origins of this technology can be traced back to the author (Graham, 1920-21). The method of using gaseous hydrocarbons for the early detection of spontaneous combustion was designed in the 1950s by the author (Kittagowa, 1959). The research was followed by a number of international authors, e.g. (Pursall, Banerjee, 1961). A lot of related informations are also mentioned by the author (Banerjee, 2000). Research of gases indicating spontaneous combustion of coal also took place in several stages in the Czech Republic (Lanková, 1975), (Schreiber, 1987), (Adamus, 2002).

It should, however, be noted that even after more than a hundred years of research in the area of interpretation of indicator gases, no reliable and versatile temperature indicator was found for the initial stage of spontaneous combustion of coal. Nevertheless, in laboratory conditions, a number of beneficial findings were discovered, both in relation to values of developing a large amount of indicator gases with increasing temperature, and, in particular, to the sequence of their occurrence with increasing temperature (Adamus, 2011). In practical terms, however, evaluation based on laboratory results is often distorted due to specific influences (the impact of reverse desorption of gases to coal and rock mass, diluting the concentrations of gases below the limit of detection, the choice of the sampling site, accuracy of gas analysis, etc.). Another way to monitor developing the spontaneous combustion process is measuring temperature (Dušák 1989) (Zhang, 2007). Thermometric methods are based on the identification of sites in the monitored area (coal seam, stockpiles, etc.) with elevated level of temperature compared to the surrounding mass, or the identification of sites with otherwise unexplained higher temperature.

The above mentioned project aimed at using both these methods related to early detection of the spontaneous combustion process and develop a comprehensive method that makes it possible to locate places at a critical heating stage in time. Within the project, other factors affecting the formation and progress of the spontaneous combustion process were also monitored and taken into account, for example the influence of climatic conditions (temperature, humidity, pressure, wind, etc.), physical and mechanical properties (grain size, porosity, density, etc.), petrological composition of coal mass, coal susceptibility to oxidation, etc.

2. Sampling and determining basic physical and chemical properties

Within the project, a total of 10 lignite samples were collected for laboratory tests from various locations in the North Bohemian and Sokolov brown coal basin. Samples were taken either directly from the coal seams, from a conveyor belt, or from freshly heaped stockpiles. Proximate analysis of all collected coal samples was performed, including an ultimate analysis. A particle size analysis of samples taken from stockpiles was also conducted.

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Table 1: List of coal samples

Coal sample no.	Location	Proximate analysis (%)			
		A^d	S_t^d	W_t^r	V^{daf}
1	Hrabak Quarry	26.22	1.13	26.54	-
2	Centrum Colliery	19.02	0.38	25.35	48.80
3	CSA Quarry	13.42	1.62	26.52	53.40
4	Hrabak Quarry	29.78	0.93	24.46	55.96
5	Jiri Quarry	5.56	0.36	39.35	52.64
6	Hrabak Quarry	47.59	0.63	25.49	-
7	Bilina Quarry	5.67	0.95	29.98	49.35
8	Jiri Quarry	35.54	3.60	37.18	50.77
9	Jiri Quarry	35.54	3.60	37.18	50.77
10	Jiri Quarry	35.54	3.60	37.18	50.77

3. Laboratory tests

Under laboratory conditions, coal samples taken directly from the mining sites at lignite quarries in North Bohemian and Sokolov brown coal basin were analysed (Table 1). Apart from the basic analytical and chemical (elementary) composition, coal was further tested for susceptibility to spontaneous combustion and with respect to the determination of characteristic gaseous products using the TEPOX method, for more details, see the references (Snopek, 2012). The concerned method was used to simulate thermal stress of the coal sample in laboratory conditions, during which samples of gases were periodically taken for chromatographic analysis. For this method, PC controlled air thermostat was used. The temperature of the apparatus and the coal sample was checked by thermocouples. The oxidizing medium (technical air) with volume flow of 20 ml/min was fed from the pressure vessel to the input of the apparatus by means of reduction and control valves. Air was fed to the reactor with a volume of 200 ml, which was placed in the heating furnace, where a thermal oxidation of the coal sample occurred. The reactor was gradually artificially heated to the temperatures of 40, 60, 80, 100, 120, 140, 160, 180 and 200°C. After reaching the above mentioned temperatures, the concentrations of the majority indicator gases CO_2, CO, CH_4 were measured by infra-analysers and the released gases were collected in a glass bottle for a chromatographic analysis of gaseous hydrocarbons C1-C4 and hydrogen. The achieved partial results were published in the literature (Adamus, 2014-1, 2014-2).

4. Susceptibility of coal to spontaneous combustion

Susceptibility of coal mass to spontaneous combustion was tested by two methods: specifically, the method of adiabatic oxidation, carried out at the workplace of the Faculty of Mining and Geology at VŠB–Technical University of Ostrava, Institute of Mining Engineering and Safety, and the method of pulse calorimetry applied at the University of Ostrava, the Department of Chemistry. Both workplaces confirmed that lignite from North Bohemian and Sokolov brown coal basin is prone to spontaneous combustion and can be categorized as highly reactive coal (Cat. I) or reactive coal (Cat II).

5. Measuring and sampling probe

For the purpose of monitoring subsurface temperature and taking gas samples on the monitored coal stockpile, a 5 m long steel probe was designed with a diameter of approximately 50 mm, with specifically covered tapping point, equipped with tubes for taking gas samples and with thermocouples for measuring the temperature (Fig. 1).

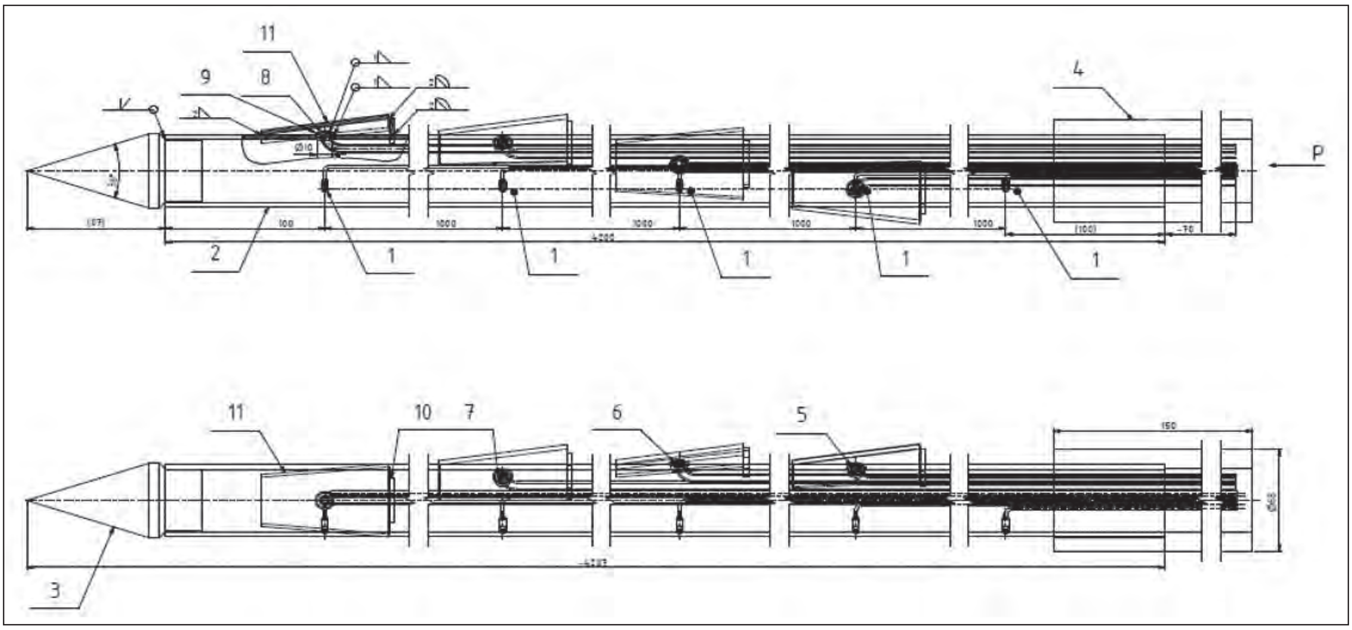

Fig. 1: A probe for taking gas samples and temperature measurements (author Rucky)

Spacing between the probes placed in the stockpile was 1-3 m. Thermocouples connected to the measuring and evaluation panel with wireless data transmission were used for the continuous measurement of the internal temperature, i.e. for detecting the thermal state of stored objects and their dynamic changes. The sampling probe was equipped with a special hook for easy insertion and extraction of the sampling probe from the stockpile at the site of outlet of the thermocouple connectors and sampling tubes. The location system usually consisted in several horizons in chess-like layout scheme so as to cover the largest possible area of the monitored stockpile (Fig. 2). The surface temperature of the coal stockpile was also monitored by a thermal camera.

Fig. 2: Location of probes in the coal stockpile (photo VUHU Most)

6. Apparatus for collecting and analysing gases

Samples of gases were collected and analysed in two ways. Basic (major) indicator gases (O_2, CO_2, CO, CH_4) were immediately analysed using the portable analyser Dräger X-AM 5600, which was equipped with its own sampling pump. At high CO_2 concentrations (over 5%), the instrument Geotech G 110 was used (Fig. 3). Minor indicator gases C1-C4 (mainly light saturated and unsaturated hydrocarbons) were collected to tedlar bags (sample bags) with a volume of $1dm^3$ using a special sampling pump SKC PCXR4, and transported to a special analytical department for chromatographic analysis.

Fig. 3: Measurement of CO_2 using the infrared analyser Geotech G110

7. Temperature monitoring

The surface temperature of the coal stockpile was scanned cyclically according to the plan by a non-contact thermometer. The thermal imaging set Therma CAMTM PM 45 made by the company FLIR systems was used, together with producer software (Therma CAM Reporter 2000 Professional) and software created by VÚHU, a.s. Most (Research Institute for Lignite). A thermal camera Fluke TiS and a simpler thermal camera Flir E4 were used as well. A sample image captured by the thermal camera at the coal stockpile with the manifestation of the spontaneous combustion process is shown in Fig. 4. To assess the influence of atmospheric conditions (the length of a solar exposure, aeration, precipitation, barometric pressure, temperature) on the processes leading to spontaneous combustion of lignite at stockpiles, the professional weather station WMR 200 was established to provide required meteorological information.

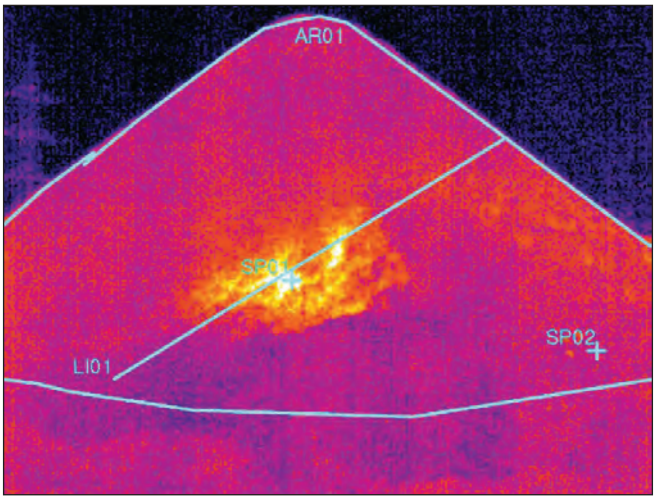

Fig. 4: The thermal image of the coal stockpile with the manifestation of spontaneous combustion (photo VUHU Most)

The internal temperatures of the stockpile were measured using the probes described above. Fig. 5 shows an example of the maximum internal temperature of the coal stockpile monitored for 52 days. An increase in temperature over time is clearly seen in the course. The highest temperatures (of spontaneous heating) were usually observed at depths of about 2-3 m below the surface. The reason can be seen in the amount of oxygen, which usually occurred in minimal concentrations at greater depths. In contrast, in the vicinity of the surface, the stockpile was cooled by wind. The internal temperature was also verified by thermal imaging technology, when the surface temperature of the metal rods driven into the stockpile was measured (i.e. thermal imaging probes). Application of this method again confirmed that the highest temperature in the initial heating stage usually ranged from 2 to 3 m below the surface of the stockpile. However, when the temperature reached about 80°C, it usually began to balance out throughout the whole depth profile, which was followed by a sharp increase in temperature at more shallow depths below the surface of the stockpile until ignition occurred.

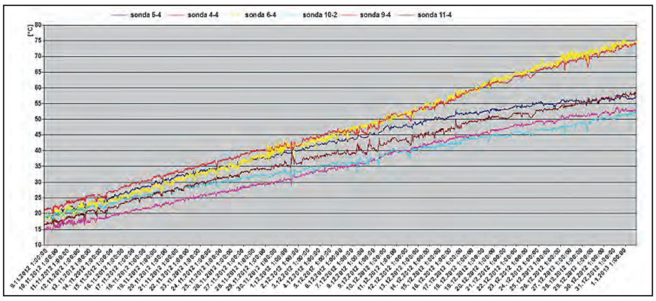

Fig. 5: Development of maximum temperatures monitored at the stockpile for 52 days. Legend: sonda – probe, (VUHU Most)

8. Gas monitoring

As mentioned above, for simultaneous measurement of the composition of gases and temperatures inside coal stockpiles, the special penetration probe was developed. In total, 15 probes were available, and they were distributed in a chess-like layout on the monitored stockpile so that data from different directions and heights could be evaluated. Monitoring of indicator gases confirmed the effect of the wind. On the windward sides, high concentrations of oxygen and low concentrations of indicator gases were measured, and vice versa. It was also possible to observe that after an initial increase in temperatures accompanied by a decrease in the O_2 concentration and an increase in the concentration of carbon oxides, a slight attenuation occurred. The repeated dynamic temperature increase occurred after the temperature reached approximately 70°C (which, according to laboratory research corresponds to the critical temperature of lignite).

Samples taken for chromatographic analysis confirmed the experience that hydrocarbons typically occur at temperatures of up to about 60°C. In the gas image, unsaturated hydrocarbons (ethylene and propylene) appeared first (besides methane) and were accompanied by saturated hydrocarbons (ethane, propane, butane) in a lesser intensity. Concentrations of measured gases gradually increased with increasing temperature. A short stretch before ignition of coal mass was characterized by high concentrations of CO – up to 35,000 ppm, and the occurrence of saturated and unsaturated hydrocarbons in concentrations of hundreds to thousands ppm. Shortly before an ignition, an increase in the concentration of indicator gases was exponential. The sharp rise in the amount of indicator gases usually with a lag of 2 days was accompanied by a sharp rise in temperatures until the ignition occurred.

An example of graphical evaluation of the development of minority gases is shown in Fig. 6. The graph shows that unsaturated hydrocarbons (ethylene and propylene) were released in the incubation period more intensively than saturated ones (ethane, propane).

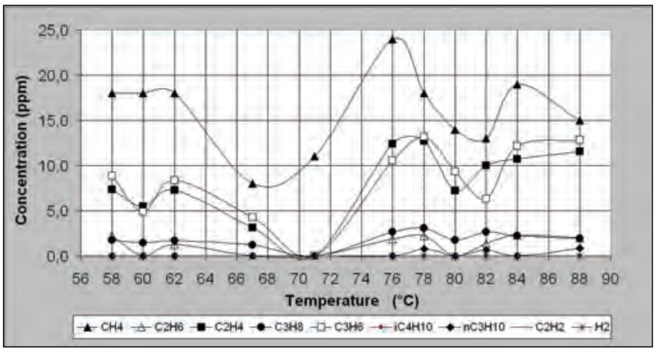

Fig. 6: Example of minority indicator gases at a lignite stockpile

9. Conclusions

The aim of the article was to acquaint the readers with the results of the research project of the Technology Agency of the Czech Republic no. TA01020351. It is apparent from the article that the investigators were trying to apply the currently available technology to address the issue of early detection of spontaneous combustion of lignite at stockpiles.

The results of in situ measurements confirmed the previous findings that emerged from previous research. Unlike most research conducted mainly in laboratory conditions, it was also focused to a practical measurement in operations. The data from these measurements are useful and can serve as verification for various calculations and software, which are intended for prediction and modelling of spontaneous combustion processes at coal stockpiles.

Within the project, a total of six lignite stockpiles were monitored; the first two stockpiles were used to develop and validate the design of the probes and the measurement procedure. At the remaining four, systematic measurements during different seasons were conducted. Temperature measurements confirmed that the temperature rise in the initial stage is the most dynamic 2-3 m below the surface, however, as the temperature rises, the centre gradually moves towards the surface of the stockpile. The gas monitoring confirmed the occurrence of unsaturated gaseous hydrocarbons before saturated ones (a phenomenon typical of lignite, compared to hard coal). The realized monitoring also confirmed the effect of weather conditions, i.e. higher oxygen concentration and cooling on the windward side of the stockpile, and vice versa. Outbreaks of spontaneous combustion usually emerged on the leeward side of the stockpile when the temperature was gradually rising to critical threshold of about 70-80°C. The outbreak of open fire, however, mostly occurred after the critical temperature was reached and after the wind direction changed subsequently (the lee side became the windward side).

In conclusion, the investigators of the above-mentioned project elaborated a methodology for determining the degree of risk of the spontaneous combustion process, temperature estimate, and assessment of the dynamic state of the outbreak of spontaneous combustion. The conclusions of interpretation of gas products were presented in the final research report (Adamus, 2014-3).

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