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Evaluation of Measured Digital Output of Gas Sensors During Spontaneous Heating of Coal

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ABSTRACT
Spontaneous heating is the major cause of unintentional coal burning in the underground coal mine. It is responsible for releasing a number of combustible gases. For measuring the concentration of these gases, the role of gas sensors becomes very important to plan efficient preventive measures. In general, the outputs of sensor produced in digital format after processing through the microcontroller platform. However, the sensor data need to be displayed in a standard format. Therefore, a tool is needed to convert the digital output of the sensors to the standard format (PPM or %) in actual environmental condition. Hence, in the present paper, mathematical expressions have been deduced for each sensor to produce the output in a standard format for test environmental condition and the same were compared simultaneously with the handheld gas analyzer. The results were found in agreement.

KEYWORDS
Spontaneous heating; Gases; Sensors; Underground coal mine

1. INTRODUCTION

Spontaneous heating induces a temperature rise in a material under ambient conditions, where the heating results from some physical and/or chemical processes occurring within the material. Spontaneous heating has a long history as a potential problem in the coal industry. It can pose a number of problems for coal producers. Fires due to spontaneous heating in underground mines put major safety concerns [1]. In surface mining, spontaneous heating in reject materials such as tailings and spoil piles cause long-term environmental problems as large areas may not be able to be rehabilitated due to excessive heat and/or contamination [2]. Safety of vessels may be affected due to the transportation of coal over large distances due to spontaneous heating. Exploitation of low-rank, low-sulfur coals also poses issues concerned with spontaneous heating during drying, storage, and transportation of coal [3]. As a result, spontaneous heating of coal needs to be controlled or averted. Hence, monitoring the different stages of spontaneous heating and its responsible factors would help to plan effective preventive measures [4]. The scale of spontaneous heating is, in general, measured by the fire indices globally as depicted in Table 1 [5]. It is obvious from Table 1 that the percentage of different gases released during spontaneous heating is very important. Furthermore, evaluation of the analog/digital output of various gas sensor, *i.e.* carbon dioxide (CO_2), carbon monoxide (CO), hydrogen (H_2), hydrogen sulfide (H_2S), methane (CH_4) and higher hydrocarbons in terms of ppm/percentage (%), is equally important for determining the state of fire.

However, the outputs of the gas sensor, in general, produced in digital format after processing through the microcontroller platform [6].

Therefore, in the present paper, attempts have been made to deduce the mathematical expressions for each sensor to produce the output in standard format *i.e.* in ppm or % for test environmental condition and the same were compared simultaneously with the handheld gas analyzer.

2. EXPERIMENTAL SET-UP AND MATHEMATICAL DERIVATION

The mathematical derivation for measuring the concentration of gases using the output of the gas sensor is the process of forcing the sensor output to a given mathematical tool to conform the digital input into standard output. This is often done by adjusting the sensor internally but can equivalently and easily be done externally by passing its output through a conversion function that converts the actual response to the desired value [7]. Here, the focus is on the development of mathematical function for conversion for all gas sensors mentioned in Table 2. The type of gas sensors is analogous in nature, *i.e.*

Table 1: Fire indices for spontaneous heating assessment

Graham's ratio $= \frac{CO}{\Delta O_2} \times 100$	Young's ratio $= \frac{CO_2}{\Delta O_2} \times 100$	C/H ratio $= \frac{6(CO + CO_2 + CH_4 + 2C_2H_4)}{2(0.265N_2 - O_2 - CO_2 + CH_4 + C_2H_4) + H_2 - CO} \times 100$	CO/CO_2 ratio	State of fire
$GR \leq 0.4\%$	$YR \leq 25\%$	$C/H \leq 2.0\%$	$CO/CO_2 \leq 3.0\%$	Normal value
$0.4 < GR \leq 1.0\%$	$25 < YR \leq 35\%$	$3.0 < C/H \leq 4.0\%$	$3.0 < CO/CO_2 \leq 7.0\%$	Existence of heating
$1.0 < GR \leq 3.0\%$	$35 < YR \leq 45\%$	–	$7.0 < CO/CO_2 \leq 9.0\%$	Heating about to be active fire
$3.0 < GR \leq 7.0\%$	$45 < YR \leq 55\%$	$C/H > 5.0\%$	$10.0 < CO/CO_2 \leq 13.0\%$	Active fire
$GR > 7.0\%$	$YR > 55\%$	$C/H > 20.0\%$	$CO/CO_2 > 13.0\%$	Blazing fire

Table 2: Characteristics of gas sensors

Gas	Sensor	Sensing technique	Range	Response time	Ref.
CO_2	TDS0054	Infrared	0–10%	< 30 s	[8]
CO	3MEF	Electro-chemical	0–20,000 PPM	< 30 s	[9]
H_2	3MHYE	Electro-chemical	0–20,000 PPM	< 30 s	[10]
H_2S	3MH	Electro-chemical	0–200 PPM	< 30 s	[11]
CH_4	TDS0068	Infrared	0–100% LEL	< 30 s	[12]
O_2	T7OXV	Electro-chemical	1–25%	< 15 s	[13]

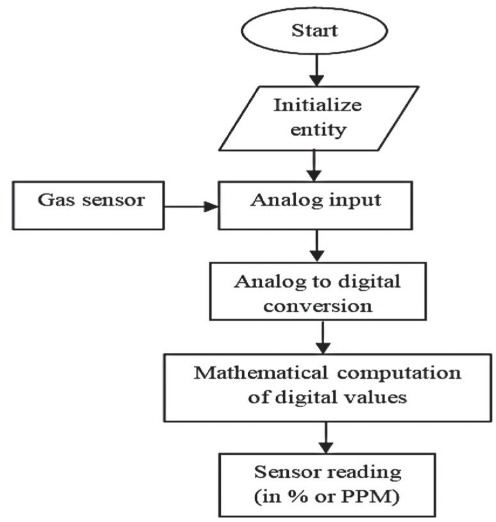

Figure 1: Sensor data reading flow diagram

sensors have analog voltage output with respect to change in the concentration of gases. In order to acquire point to point information of the spontaneous heating, atmega-based microcontroller board and a supported integrated development environment (IDE) software application [14] are needed which transfers the sensor data for display and further processing (Figure 1). The microcontroller platform which is used to access the sensor output converts them to digital level through an analog to digital converter. These digital values require to be changed in standard format either in percentage or PPM. The mathematical derivation involved in the study is derived from a number of laboratory and test environment analyses of sensors. During laboratory experiments, the sensor has been put in a gas tube and the test has been performed by supplying gases with standard gas canisters balanced with nitrogen as shown in Figure 2. The canister is 0.5-l water

Figure 2: Laboratory setup for sensor testing

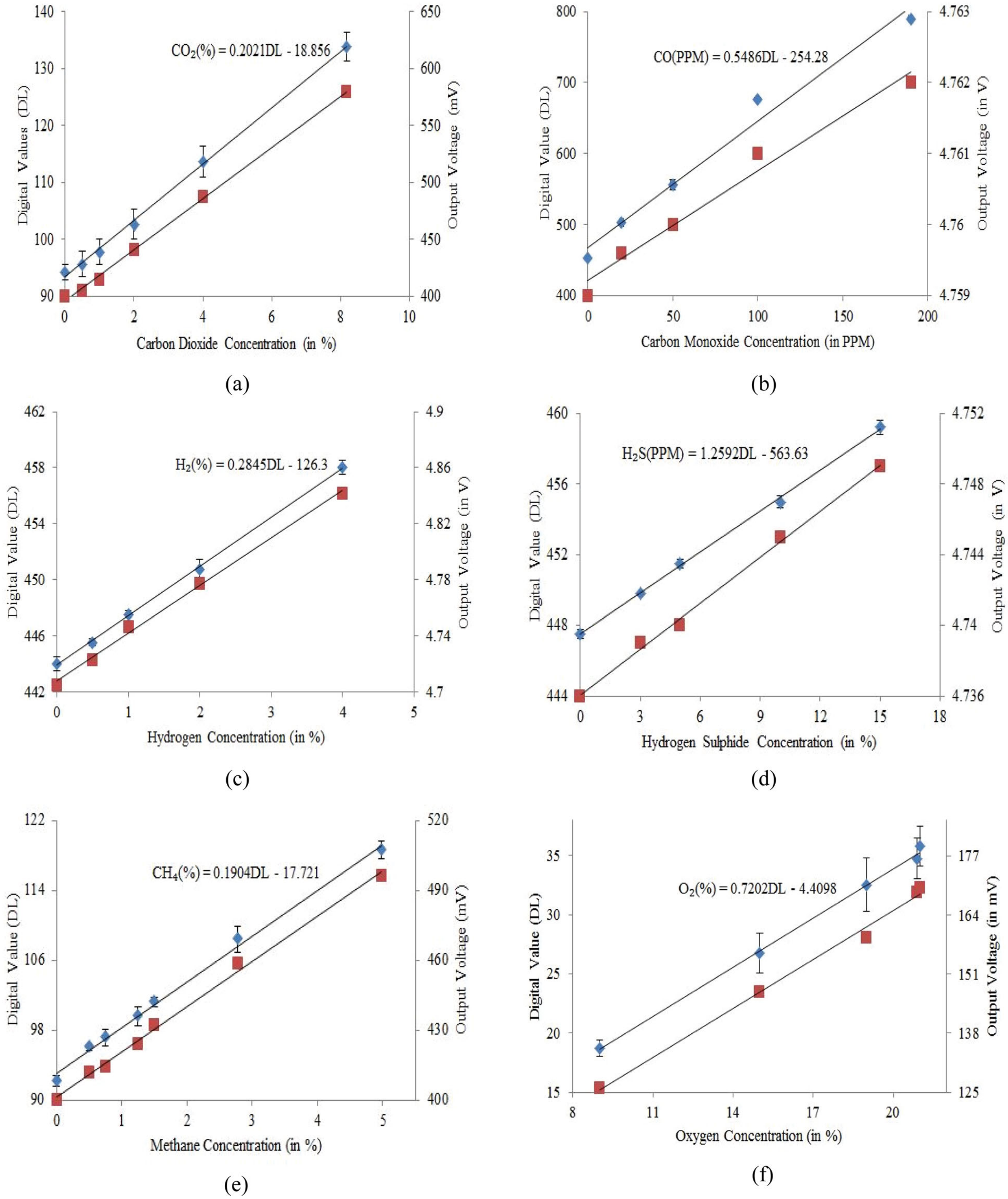

Figure 3: Digital value (DL) vs. output voltage vs. gas concentration curves for (a) CO_2, (b) CO, (c) H_2, (d) H_2S, (e) CH_4, and (f) O_2

size capacity having 10 l of standard gas stored at 20 bar pressure. There is a regulator valve which is used for the controlled supply of gas from the canister to tube via nylon gas channel. The purpose of this setup is to provide isolation to the sensor from the external environment such as the dissolution of gas to air, minimization of the effect of humidity and other environmental interference.

The derivation of the mathematical formula for gas sensors for measurement of the concentration level of gases in the atmosphere in terms of standard units requires accuracy, numerical stability and reliability [15,16]. For this purpose, a number of gas canisters for each gas have been used with different concentration levels for identifying the respective digital value (DL) of the output of the sensor. Those DLs were plotted with respect to the respective concentration of gases during various laboratory analyses as shown in Figure 3. With the help of the laboratory analysis and the graph, the mathematical functions have been deduced. Although a good approximation to the underlying situation was performed, one cannot assume that it is exactly correct. Therefore, the mathematical derivation should possess statistical procedure [17]. For this purpose, mean of the observations have been taken to eliminate the measuring deviation.

In addition, the analog output of the sensors at respective concentration levels of the gases has also been plotted in the same graph. The trend for both the readings, *i.e.* for DLs and analogue outputs is the same.

In general, the value of variable DL for the ith observation is denoted by DL_i. For a sample with n observations, the formula for the mean value is as follows:

$$\overline{DL} = \frac{\sum_{i=0}^{n} DL_i}{n} \quad (1)$$

Five number of sample data has been collected for each sensor at different gas concentration for each gas canisters over a period of one month. So, (1) can be deduced as

$$\overline{DL} = \frac{\sum_{i=1}^{5} DL_i}{5}$$

Furthermore, as shown in Figure 3, the fitting curve and standard deviation with mathematical expression have been drawn. The standard deviation 's' is the positive square root of the variance and is based on the difference between the value of each observation (DL_i) and the mean. Mathematically,

$$s = \left(\frac{\sum_{i=1}^{5} (\overline{DL} - DL_i)^2}{4} \right)^{1/2} \quad (2)$$

The aim of calculating the standard deviation is to check whether the fitting curve falls within the standard deviation range. The following subsection plot the experimental results conducted in the laboratory. The mathematical equation, thus, obtained from the above analysis for conversion from a digital value to standard reading has been summarized in Table 3.

Similar to DL, the analog voltage output of sensors for respective concentration levels have been analyzed using Fluke make digital multimeter. The voltage characteristics of sensors have also been plotted in Figure 3. The derived equation for measuring the concentration level of gases for each sensor has been shown in Table 3. The DL vs. gas concentration and output voltage vs. gas concentration curves show a similar trend which supports the mathematical analysis performed using digital values for measuring gas concentration.

Table 3: Mathematical equation for different gas sensors

Sensors	Mathematical equation (in terms of DL)	Mathematical equation (in terms of voltage)	Unit
CO_2	0.2021DL – 18.856	4.4456×10^{-2}V – 17.6291	%
CO	0.5486DL – 254.28	5×10^{4}V – 2.3796×10^{5}	PPM
H_2	0.2845DL – 126.3	2.94117 V – 13.84588	%
H_2S	1.2592DL – 563.63	1.1111×10^{3}V – 5.2633×10^{3}	PPM
CH_4	0.1904DL – 17.721	5.5015×10^{-2}V – 20.70489	%
O_2	0.7202DL – 4.4098	0.27855 V – 25.97242	%

Table 4: Cross-sensitivity chart

Sensors	CO (%)	H_2 (%)	H_2S (%)
3MEF CO sensor	100	< 60	~ 7
3MHYE H_2 sensor	40	100	65
3HYE H_2S sensor	< 2	< 0.15	100

Ideally, an electrochemical gas sensor should only react with target gas to be monitored. However, cross-sensitivity does occur even if most of the sensors are somewhat specific. Cross-sensitivity is defined as sensor's reaction to an interfering gas available in the vicinity. This condition causes an error in the measurement of the target gas [18]. For example, in the present study, 3MEF carbon monoxide sensor has been used which is having the cross sensitivity of $\sim$60% against hydrogen. It means if the concentration of 20 PPM of hydrogen is present in the target region and if the target gas (CO) is absent, in spite of that the actual value of CO reading will be seen 20*(60/100), *i.e.* 12 PPM on the display of the analyzer due to sensor's reaction with hydrogen. A similar phenomenon takes place in case of other electrochemical-based gas sensors as mentioned in Table 4.

3. TRIAL ON TEST ENVIRONMENT

To study the dynamics of spontaneous heating of coal, there is an experimental facility at the authors' institute, known as mine fire gallery. The present sensor modules have been tested at the mine fire gallery and compared with GasTech make handheld gas analyzer calibrated with standard gas. Figures 4 show the comparative results of the scaled output of sensor modules CO_2, H_2, CH_4, CO, and O_2 to the actual values of sensor data installed in mine fire gallery. It has been observed that CO_2, H_2, CH_4, CO, and O_2 have 96.69%, 97.6%, 97.57%, 97.5%, and 98.85% accuracy, respectively. The test results thus obtained have a maximum$\pm$3.5% deviation from actual values measured in the analyzer.

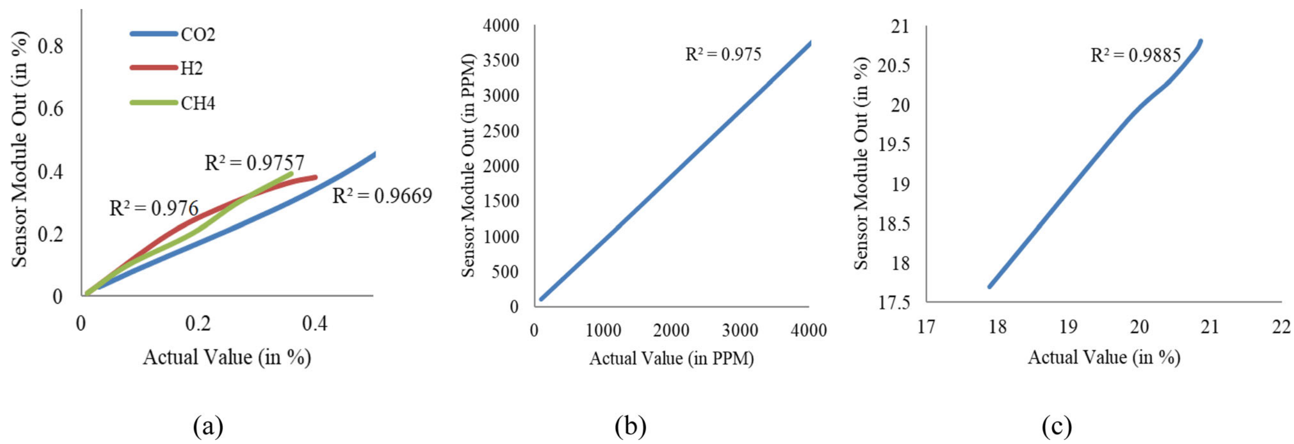

Figure 4: Actual vs. scaled sensor module reading for (a) CO_2, H_2, and CH_4, (b) CO and (c) O_2

4. CONCLUSIONS

The spontaneous heating of coal is highly nonlinear. To know its dynamics, fire indices based on the concentration of gases can play a significant role. Taking into account, gas sensors have been identified carrying out a number of physicochemical studies of coal samples collected from fiery seams of Indian underground coal mines [4,19]. In general, gas sensors are analogous in nature. However, for further processing of the analog output, microcontroller platform is used which changes it to the digital format. Therefore, in the present study, mathematical expressions have been deduced for each sensor to produce the digital values in standard format *i.e.* in ppm or % through numerous laboratory experiments and statistical analysis under various test environmental condition. Finally, the sensor modules have been tested in mine fire gallery and were compared simultaneously with the handheld gas analyzer. The respective results were found in agreement.

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