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Factors Affecting Hot Spot Development in Bulk Coal and Associated Gas Evolution

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ABSTRACT

There are many physical factors that can affect the self-heating rate of coal. The presence of seam gas has often been referred to as inhibiting coal self-heating due to the limited access of oxidation sites created by the presence of the gas adsorbed on the coal pores. Similarly, the presence of bed moisture in the coal also acts as an inhibitor of oxidation by blocking access of air into the pores. Gas drainage of a coal seam prior to mining removes both gas and moisture from the seam. Bulk coal self-heating tests in a two-metre column on both gassy, as-mined and gas-drained, dried high volatile bituminous coal show that removal of gas and moisture from the coal accelerates the rate of self-heating to thermal runaway from 8.5 days to 4.25 days, from a start temperature of 30°C, with an airflow of 0.25 L/min. The corresponding gas evolution pattern for each of these situations is different. Therefore, it is necessary to take this change in coal condition into consideration when developing a spontaneous combustion management plan.

INTRODUCTION

Self-heating leading to spontaneous combustion continues to pose a significant hazard during the mining of coal. A recent example of this is Southland Colliery in December 2003, where a heating progressed to ignition forcing the mine to be closed. Unfortunately, the heterogenous nature of coal and the contributing factors that control whether heat is gained or lost from the coal/oxygen system make it difficult to predict the onset of a heating with any confidence.

Bulk coal self-heating tests have been limited due to the expense and time taken to obtain results. Some success has been obtained with various column-testing arrangements (Li and Skinner, 1986; Stott and Chen, 1992; Akgun and Arisoy, 1994; Arief, 1997), but the equipment used has not gained wide acceptance.

A new laboratory has been established within the School of Engineering at The University of Queensland (UQ) that uses a two-metre column to conduct a practical test capable of providing reliable data on coal self-heating (Beamish *et al*, 2002). This can be used to predict the onset of coal self-heating with acceptable engineering certainty for risk management purposes. Preliminary results from this new work are providing definitive insights into hot spot development (Beamish and Daly, 2004; Beamish, in press). This paper presents some examples, which show the effects of gas and moisture removal from coal.

COLUMN SELF-HEATING

Equipment

Beamish *et al* (2002) describe the basic operation of the UQ two-metre column, which has a 62 L capacity, equating to 40 - 70 kg of coal depending upon the packing density used. The coal self-heating is monitored using eight evenly spaced thermocouples along the length of the column that are inserted into the centre of the coal at each location (Figure 1). Eight independent heaters correspond to each of these thermocouples and are set to switch off at 0.5°C below the coal temperature at each location so that heat losses are minimised and semi-adiabatic conditions are maintained radially.

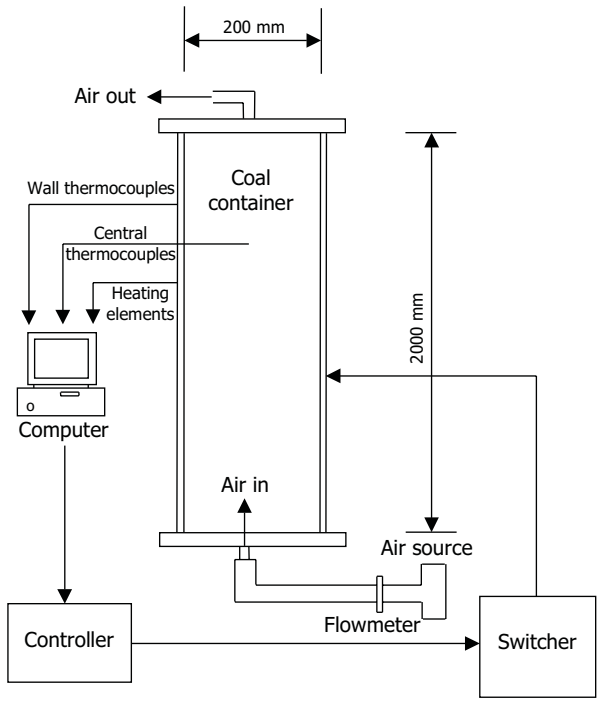

FIG 1 - Schematic of UQ two-metre column self-heating apparatus (modified from Arief, 1997).

Sample preparation

A fresh run-of-mine high volatile bituminous coal sample was obtained from a Newcastle Region longwall mine for testing in the UQ two-metre column. The coal particle size was kept below 150 mm and a size distribution of the sample was determined prior to loading into the column. The average particle size of the coal was 8.19 mm, based on the procedure described by Kunii and Levenspiel (1991) for estimating the surface-volume average particle size from the size distribution of the coal. Three subsamples were taken at this stage to obtain data on the as-received moisture of the coal, which was determined to be 3.1 per cent.

Test procedure

A standard test procedure has been developed for UQ two-metre column coal self-heating tests. The coal was loaded into the column with three 20 L plastic buckets. Once all the coal was in the column it was sealed and the heaters used to set the starting coal temperature, which in this case was 30°C. This was achieved overnight. Air was then introduced to the coal at 0.25 L/min. A computer records all data at ten-minute increments. The column has several safety devices including computer-controlled trips on the external heaters and a temperature trip on the air inlet line. These were set to ensure maximum safety during operation of the column.

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Following the successful completion of this test, which developed a 220°C hot spot, the coal was allowed to cool and equilibrate at 30°C. In this state, the coal in the column resembles a gas-drained situation, as both seam gas and moisture have been removed from the coal. An airflow of 0.25 L/min was again applied to the column.

As each column test progressed regular gasbag samples were collected from the outlet. These were analysed by Simtars using standard gas chromatography.

RESULTS OF COLUMN TESTING

Hot spot development in gassy, as-mined coal at 30°C

Figure 2 shows the temperature profile changes that take place with time in the column. In the initial stages of self-heating, a warm spot appears at 127 cm from the air inlet and progresses slightly downwind as the coal temperature continues to rise in this region. At around 85°C, the rise in the coal temperature in this region begins to slow and plateaus just below 100°C. Meanwhile, coal closer to the air inlet has been continually drying out and shortly after day eight a definite hot spot appears at 73 cm from the air inlet. Closer inspection of Figure 2 reveals that visible signs of the hot spot forming lower in the column begin as early as day six. The hot spot then begins to migrate towards the air source as the coal on the leading edge of the hot spot dries out and the hot spot chases the air to sustain the oxidation reaction. By day 11 a large hot spot in excess of 220°C is present 55 cm from the air inlet. At this stage the hot spot continues to migrate upwind as the coal dries out and also expands downwind due to convection.

Hot spot development in gas-drained, dry coal at 30°C

The methane content of the outlet gas for this test at 30°C was 0.8 per cent, compared with 2.1 per cent for the previous test at the same temperature. Similarly, the coal moisture content had reduced to less than 2.5 per cent (from a simple mass balance check and coal sample checks). Hence, there had been significant methane desorption and moisture losses during the hot spot development of the initial test, particularly in the region of highest coal temperature.

Hot spot development in the column for the non-gassy, dry coal test is summarised in Figure 3. While some warming appears in the upper half of the column, it is immediately overshadowed by a rapidly forming hot spot 55 cm from the air inlet (Figure 3). In this state there is no stepped rise in maximum coal temperature as the coal nearest the inlet is already predisposed to allow the air to reach oxidation sites in the coal. In other words the inhibiting effects of the seam gas and coal moisture in the pores of the coal have been removed.

Gas evolution in response to coal oxidation and hot spot development

The coal sample contained seam gas rich in methane with a subordinate amount of carbon dioxide and traces of ethane. Consequently, there are some noticeable differences between the gas evolution patterns of the gassy, as-mined and non-gassy, dried coal self-heating tests. Methane evolution is shown in Figure 4. The initial gasbag for both tests shows elevated levels of methane due to the gas desorbing in a static air environment during temperature equilibration to 30°C. In the as-mined coal, there is a significant rise in the methane concentration due to gas desorption up until the coal reaches a temperature of 83°C. Beyond this temperature the methane concentration drops rapidly. No such feature is evident for the drier coal.

Appreciable quantities of hydrogen are evolved as the coal self-heats from 30°C to 120°C (Figure 5). This pattern is present for both the gassy and non-gassy coal and occurs in similar amounts. Consequently, the hydrogen is not being produced from seam gas desorption. At higher temperatures the hydrogen evolution appears to level off. Grossman, Davidi and Cohen (1993) and Nehemia, Davidi and Cohen (1999) have reported research into the mechanisms responsible for hydrogen production from low temperature coal oxidation. Their findings will be discussed later in this paper.

Ethane evolution shows a prolonged increase in concentration (Figure 6), which unlike methane extends beyond 83°C. The non-gassy coal shows a roughly linear increase in ethane concentration from 60°C onwards. This tends to suggest that ethane is being produced predominantly from low temperature coal oxidation of the non-gassy coal. However, in the case of the gassy coal ethane from both gas desorption and oxidation mechanisms appears to coexist.

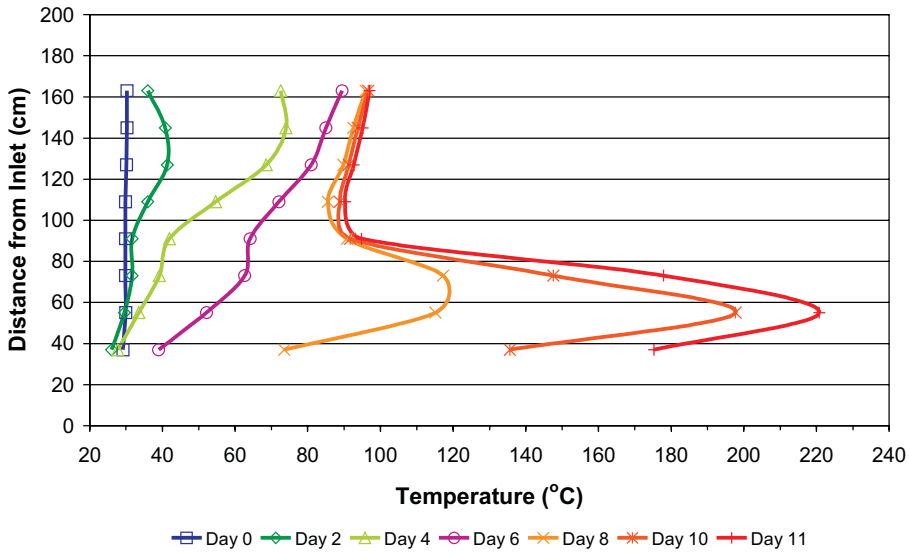

FIG 2 - UQ two-metre column temperature profile showing hot spot development in gassy, as-mined coal.

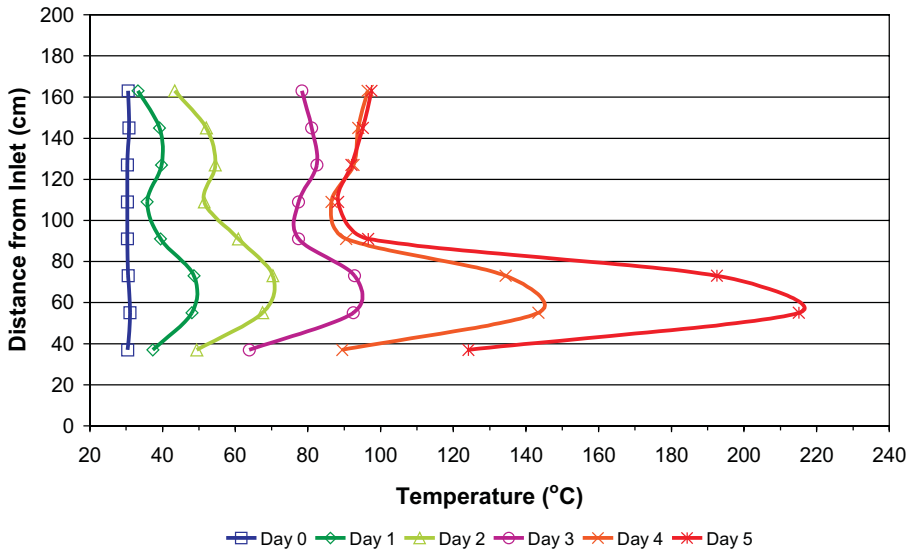

FIG 3 - UQ two-metre column temperature profile showing hot spot development in non-gassy, dry coal.

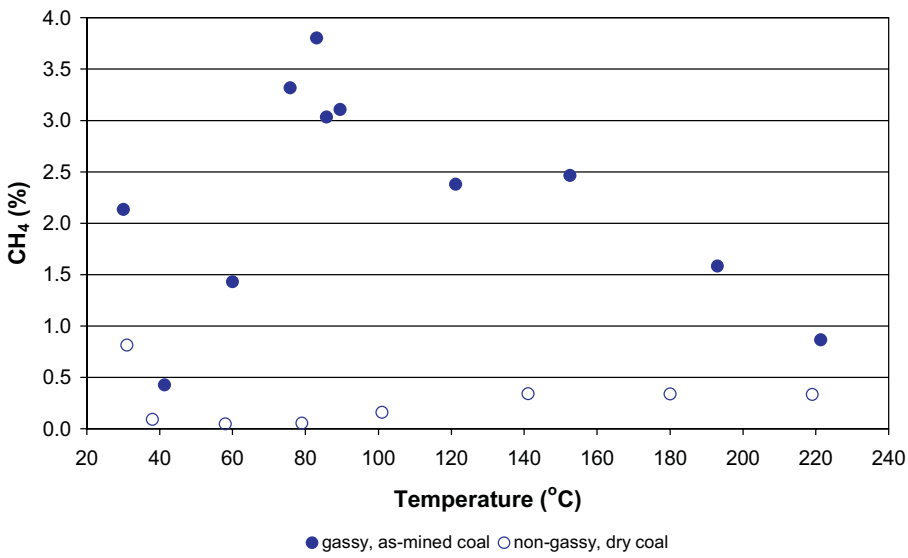

FIG 4 - Methane evolution as a function of maximum coal temperature.

Ethylene is not evolved in detectable quantities until the coal temperature exceeds 120°C (Figure 7). This temperature appears to be consistent for both gassy and non-gassy coals. The increase in ethylene concentration beyond this temperature is reasonably linear. There is a shift in the ethylene evolution trend above 180°C for the gassy coal, which also corresponds to a drop in ethane evolution. This tends to suggest these two gases are closely linked in terms of their evolution mechanism.

Gas indicator ratios in response to coal oxidation and hot spot development

One of the key gas indicators used by the coal industry is Graham's ratio. This is calculated as follows:

$$GR\ (\%) = (CO \times 100)/(\text{oxygen deficiency})$$

where:

Oxygen deficiency = $(20.93/78.11 \times N_2 - O_2)$

It should be noted that the factor for the nitrogen calculation is different to values quoted in most reference texts as the value used in these is for nitrogen plus inerts. However, the gas analyses provided by Simtars give the nitrogen as a separate value.

There is a noticeable difference between the Graham's ratio values of the gassy coal compared with the non-gassy coal (Figure 8). The non-gassy coal has a much higher Graham's ratio for a given temperature, presumably due to the ease of air access to oxidation sites. This finding has consequences for interpreting gas monitoring results in areas of a mine that has been gas-drained.

Young's ratio is another key indicator of coal self-heating progression. This ratio is calculated as follows:

$$YR = CO_2\ /(\text{oxygen deficiency})$$

where:

Oxygen deficiency = $(20.93/78.11 \times N_2 - O_2)$

$CO_2 = CO_2 - 0.035/78.11 \times N_2$

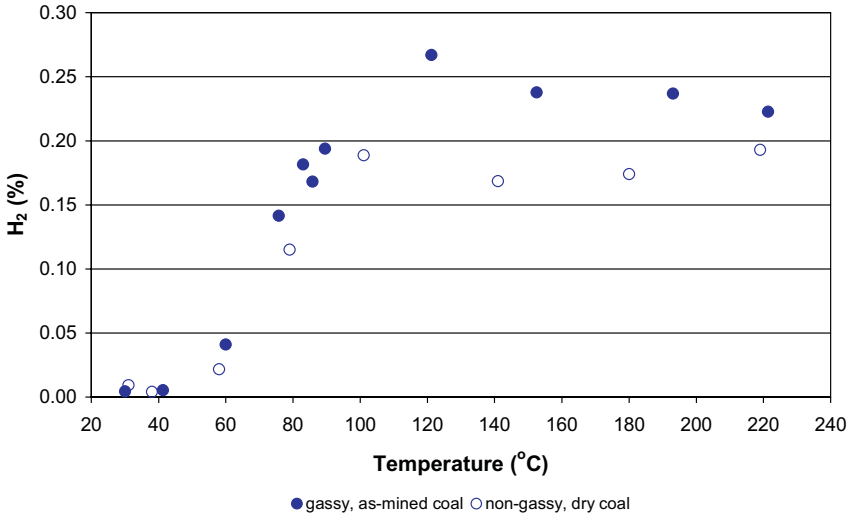

FIG 5 - Hydrogen evolution as a function of maximum coal temperature.

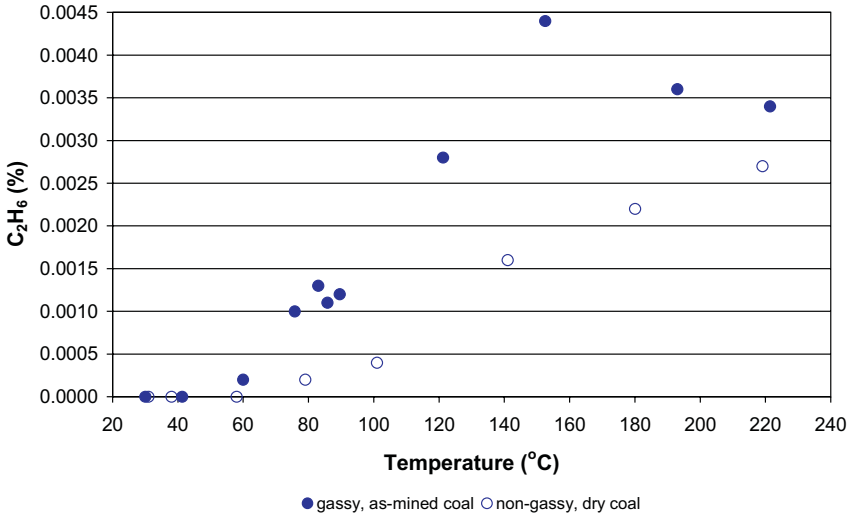

FIG 6 - Ethane evolution as a function of maximum coal temperature.

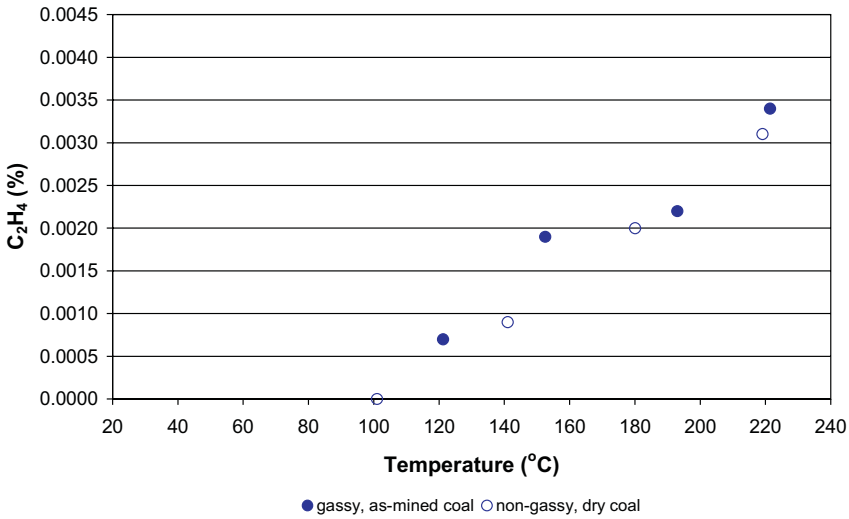

FIG 7 - Ethylene evolution as a function of maximum coal temperature.

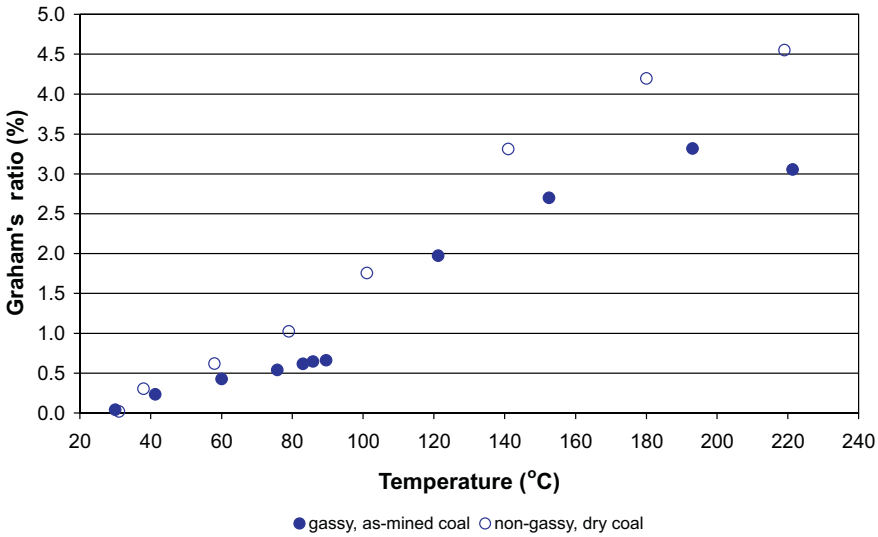

FIG 8 - Graham's ratio as a function of maximum coal temperature.

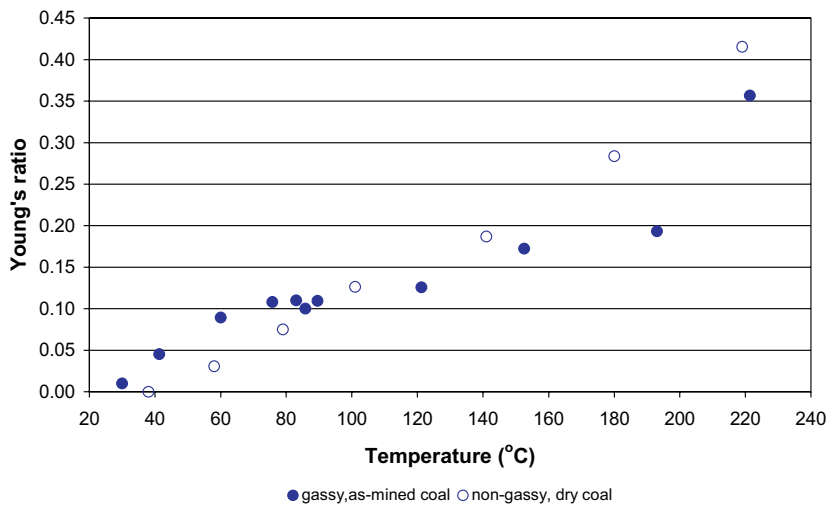

FIG 9 - Young's ratio as a function of maximum coal temperature.

At temperatures less than 90°C, the Young's ratio of the gassy coal is higher than for the non-gassy coal (Figure 9). The difference appears to be too great to be explained by the presence of additional carbon dioxide in the seam gas, which is present in only minor concentrations. Therefore, the additional carbon dioxide must be produced by another mechanism. At temperatures higher than 90°C, the Young's ratio of the non-gassy coal is higher than for the gassy coal, which is the equivalent trend to the Graham's ratio.

The H_2/CO ratio shows exactly the same trend for both gassy and non-gassy coal (Figure 10). This ratio appears to reach a maximum near 80°C. The gassy coal reaches a higher maximum, which is almost three times that of the non-gassy coal, primarily due to the greater amount of carbon monoxide generated by the non-gassy coal. From this ratio it is clear that at temperatures lower than 80°C, the bulk coal self-heating from low-temperature oxidation of the coal favours a hydrogen generating mechanism. Once the coal temperature exceeds this value the carbon monoxide generating mechanism is favoured.

Nehemia, Davidi and Cohen (1999) have suggested that the low-temperature oxidation mechanism for the hydrogen production is decomposition of formaldehyde catalysed by coal:

$$2CH_2O + O_2 \xrightarrow{\text{coal}} 2H_2 + 2CO_2$$

It is interesting to note that the by-product of this reaction is carbon dioxide. The imbalance shown by the Young's ratio for the gassy coal may be strong evidence to support this reaction mechanism. Chamberlain, Barrass and Thirlaway (1976) also noted reasonable quantities of aldehydes being evolved from coal oxidation in this temperature range, which would further support this mechanism as a likely source of the hydrogen.

HOT SPOT DEVELOPMENT FEATURES OF GASSY AND NON-GASSY COAL

The hot spot development features seen in the UQ two-metre column test are entirely consistent with the moist coal self-heating models of Schmal, Duyzer and van Heuven (1985), Arisoy and Akgun (1994), Portola (1996) and Monazam, Shadle and Shamsi (1998). In particular, the moist coal model of Schmal, Duyzer and van Heuven (1985) predicts the plateau effect of the initial hot spot development (Figure 11). They maintain heat effects due to evaporation and condensation of moisture is responsible for the coal reaching a constant maximum temperature of 80 - 90°C. This level continues until the coal becomes dry locally, after which a steep temperature rise occurs at the dried spot.

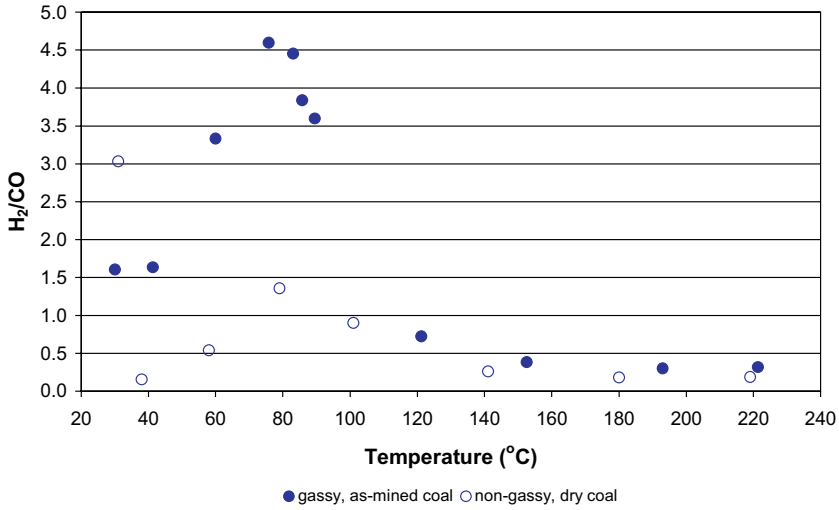

FIG 10 - H_2/CO ratio as a function of maximum coal temperature.

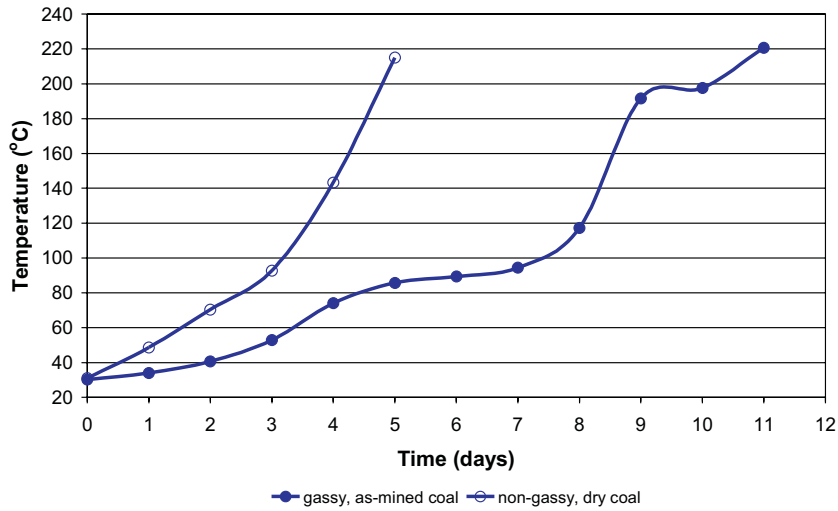

FIG 11 - Maximum coal temperature during bulk coal self-heating.

In all these models, it is clearly shown that the higher the moisture content of the coal, the longer it takes to reach dangerous temperatures. The difference between gas-drained, dried coal and the as-mined, moist coal illustrates this feature (Figure 11). In fact, the maximum temperature curve for the gas-drained, dry coal is a direct match of the dry model proposed by Schmal, Duyzer and van Heuven (1985). It took 4.25 days to reach temperatures in excess of 150°C for the dried coal condition and 8.5 days to reach the same stage in the moist coal. Equally important, is the fact that for the dried coal, the migration towards the air source is much faster as heat is not used up to evaporate moisture from the coal on the leading edge of the hot spot.

These findings have major implications for coal mines practising coal seam gas drainage. It is well known that gas-drained coal is dry and dusty when mined. Consequently, any Spontaneous Combustion Management Plan must consider the elevated risk of coal self-heating that results from gas drainage. Small-scale R_{70} testing by Beamish, Barakat and St George (2001), which is a dry coal test, shows that as rank decreases below medium volatile bituminous, the self-heating rate of the coal increases dramatically. Hence, gas drainage of coals in the low rank high volatile bituminous range will create a higher risk of self-heating than for the non-drained coal in the same mine.

To mitigate the elevated risk of self-heating from gas drainage there is a need to consider returning moisture to the coal. This could be achieved through water infusion. The difficulty encountered here is how efficient are the procedures for doing this. Future research into this area would be most beneficial to all underground coal mines, as the water infusion would also help with dust suppression during mining.

CONCLUSIONS

The UQ two-metre column is producing coal self-heating results that are consistent with both theory and practice. In particular the hot spot development matches closely with several published models for coal self-heating. Features of moisture transfer and hot spot migration are clearly visible in the column. Under the conditions used for testing a high volatile bituminous coal, a hot spot reached thermal runaway (>150°C) after 8.5 days from a gassy, as-mined state. The same coal in a gas-drained, dried state reached thermal runaway after only 4.25 days. These results indicate that it is sensible to consider some form of water infusion for coal that has been gas-drained.

There are significant differences in the gas evolution patterns of gassy, as-mined coal compared with non-gassy, dried coal. Removal of seam gas and moisture allows easier access of air to oxidation sites, with a resultant higher Graham's ratio for any given coal temperature. However, an increasing Graham's ratio is still a good indicator of coal self-heating in both cases. Substantial quantities of hydrogen are evolved at low temperatures during bulk coal self-heating. Hence, the old adage of hydrogen acting as an indicator of an advanced heating in its own right is a fallacy. The evolution of ethane from gassy coal appears to be a mix of gas desorption and low temperature oxidation, with both mechanisms responding to temperature increase. Measurable ethylene does not appear until the coal temperature has reached 120°C in both gassy and non-gassy coal, and continues to increase as the coal temperature increases beyond this value.

Further column testing is in progress on a range of Australian coals to look at hot spot development features in more detail and to provide the coal industry with a better means of assessing the risk of coal self-heating.

ACKNOWLEDGEMENTS

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