Investigation of cavity formation in lump coal in the context of underground coal gasification

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Synopsis

Underground coal gasification (UCG) is becoming more popular as the reserves of good quality, mineable coal are starting to diminish, and yet the global energy demand from coal is still increasing. The purpose of this research project was to investigate cavity formation within a coal block due to the combustion reactions in the context of UCG. The cavity plays a pivotal role in the UCG process, as it is essentially the gasification reactor. Cavity formation in an *in situ* gasification process using the forward combustion linking method (FCL) had been investigated, and a laboratory model was created to simulate the process.

The experiment was performed by drilling a U-shaped tunnel into a coal block, which was then combusted internally with air that was fed through an injection hole. A heating element (at approximately 500°C) was used to supply the required heat for combustion at the base of the injection well. The coal blocks were analysed using micro-focus X-ray tomography.

The tomography results showed that the coal tended to crack along the bedding plane after a short duration of combustion, due to either the formation of clinker or the expansion of swelling vitrinite along the horizontal tunnel. The deposit was thicker at the base of the injection well compared to the base of the production well; this may have been caused by the turbulence of the air flow and the relatively high oxygen concentration at the base of the injection well. A comparison of the results with work by Daggupati *et al.* (2010) showed the same trend, despite the slightly different methodology applied.

Keywords

underground coal gasification, cavity formation, gasification reactor, forward combustion linking method (FCL), clinker, vitrinite, micro-focus X-ray tomography.

Introduction

Underground coal gasification (UCG) creates an opportunity to access coal that is deemed un-mineable due to its depth, the low quality of the coal, and unsafe mining conditions. In addition, it is considered to be more environmentally friendly than conventional mining and the process is less capital- and labour-intensive (Self, Reddy, and Rosen, 2012). The produced syngas can be used by a host of technologies, but it is used mainly for the production of liquid fuels, power generation, industrial heating, or fertilizers (Seddon and Clarke, 2011).

UCG is an *in situ* gasification process. There are many methods for the gasification of coal seams and the extraction of syngas; the utilization of an injection and production well is investigated in this report. The injection well allows for the feed flow of air/oxygen/oxygen-enriched air and steam, and the produced syngas is extracted to the surface via the production well. However, a linkage is required between the two wells as the coal seams are not sufficiently permeable to allow for the dispersion of air/steam across the horizontal length. There are several methods for creating this linkage path, namely: reverse combustion linking (RCL), forward combustion linking (FCL), hydro-fracking, electro-linking, and in-seam linking (Abdul, Aqeel, and Gholamreza, 2013). The experiment was based on *in situ* gasification using the injection and production well with the FCL method.

FCL involves the use of directional drilling, which offers the least damage to the existing ground structure (Directional Drill Pty Ltd, 2011) and improves the feasibility, design, and operation of a UCG plant.

The purpose of this research was to investigate cavity formation in a coal block in the context of UCG. The work of Daggupati *et al.* (2010) was used as a guide for the experimental investigation and X-ray tomography was used to confirm and analyse the cavity formation.

Materials and methods

Experimental setup

The experimental setup was based on that of Daggupati *et al.* (2010), with the main

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difference being the use of a heating element as the heat source in place of the LPG used by Daggupati *et al.* A U-shaped tunnel was drilled into a 15 cm × 11 cm × 12 cm coal block; the vertical injection and production wells were 5 mm in diameter and the horizontal tunnel connecting the two was 8 mm diameter. Stainless steel pipes were inserted into the vertical wells, one of which was connected to a gas rotameter and the air cylinder, and the other allowed the venting of the product gases into the fume hood. A Type K thermocouple was used inserted into the coal block to monitor the temperature throughout the experiment. Cutile refractory bricks were clamped together and surrounded the experiment in order to minimize heat loss and to keep the high-temperature zone separated from the external surroundings. The heat source was provided by a heating element made of 2 m of Kanthal D wire with 8.25 Ω/m resistance; the wire was wound into a spiral around a 3 mm rod. This wire was connected to a Variac (POWERSTAT® Variable Autotransformer) to control the voltage applied to the element and hence the temperature. The experimental setup is shown in Figure 1.

Experimental procedure

An inlet air flow was set and maintained at 25 mL/s; this was fed into the injection well and monitored by a rotameter. The heating element was switched on using the Variac and the temperature was measured using a thermocouple. The experiment was allowed to run for 3 hours and the resulting coal block was analysed using the Nikon XTH 225 ST micro-focus X-ray tomography system at South African Nuclear Energy Corporation (NECSA) (Hoffman and De Beer, 2013). This produced 3D images of the coal samples and allowed the mapping of the cavity based on density differences.

Results and discussion

A total of three experiments were performed, two of which yielded successful results, and which are referred to as Experiment 1 and Experiment 2.

Coal characterization

The characteristics of the coal that was used are summarized in Table I. The ash content was18.8%, and from the maceral analysis it was found that the coal was composed of 80.8% vitrinite by volume. It is important to note that all of the analyses were done using crushed coal samples, whereas the experimental work utilized large blocks of coal. However, the analysis can be assumed to be representative of the coal block as a whole.

Experiment 1

Expansion due to either the formation of clinker or the expansion of vitrinite caused a large crack to form along the length of the coal block during the first experiment. Clinker is a porous substance that forms during the combustion of coal that has a high ash content, non-combustible minerals, and a low gross calorific value (Mitra, 2011). The clinker is created by the fusion of non-combustible minerals (such as iron, calcium, and sodium) upon exposure to high temperatures (Afri Coal Investments Pty Ltd, 2013). Vitrinite is one of the organic substances found within coal and it is known to swell upon heating. Figures 2 and 3 show areas of darker grey which represent regions with a lower density material than coal. The low-density region is indicative of either clinker or plasticized vitrinite. For the purpose of this report, these regions will be referred to as 'clinker' as the material has not yet been analysed.

More clinker formed around the inlet gas well (the left well) than the production well (right well); this is also shown in Figures 4 and Figure 5, where the shape of the clinker zone is shown. A higher concentration of oxygen was available at the inlet well, and the extent of the combustion reactions as well as the temperature was therefore higher

Table I

Coal characteristics

Component	Standard	Composition (%)
Carbon	ASTM D 5373	71.05
Hydrogen	ASTM D 5373	4.29
Nitrogen	ASTM D 5373	1.78
Oxygen	ASTM D 5373	1.69
Sulphur	ASTM D 4239-05	0.99
Ash	ISO 1171:2010	18.8
Moisture	ISO 11722:1999	1.4

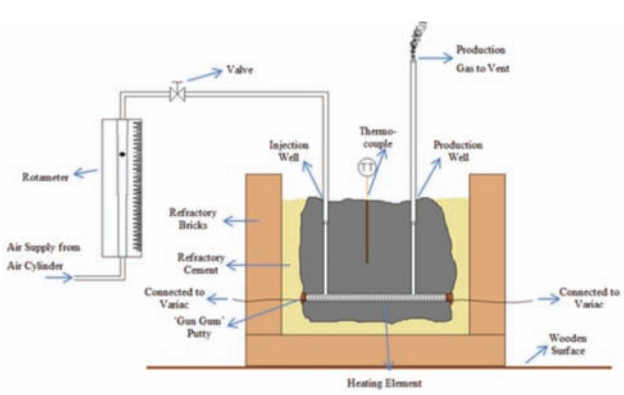

Figure 1—Diagrammatic representation of experimental setup (side view)

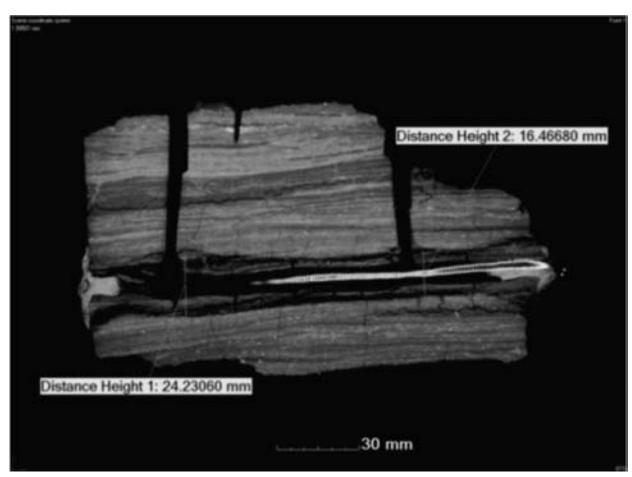

Figure 2—Cross-sectional front view of combusted coal

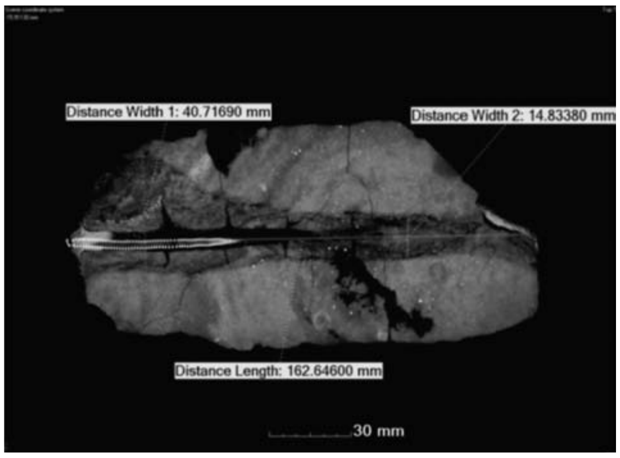

Figure 3—Cross-sectional top view of combusted coal

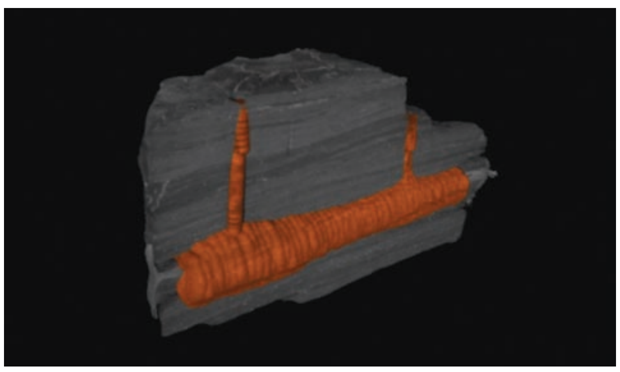

Figure 4—3D cross-sectional model of combusted coal with clinker formation

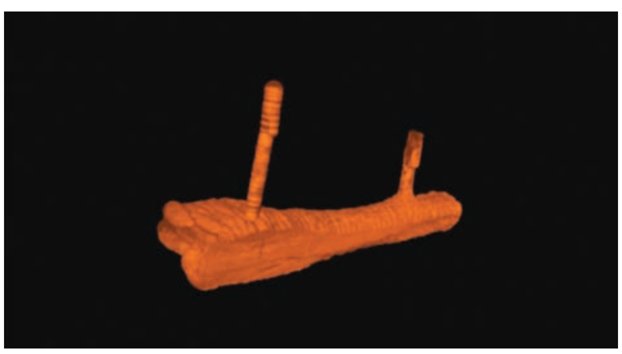

Figure 5—3D model of clinker formed in the coal after the duration of the experiment

than at the production well. The permeability of the clinker allowed oxygen to infiltrate deeper into and react with the coal (Wakatsuki, *et al.*, 2009); this was notable particularly at the base of the injection well where the air flow was turbulent. The height difference between the clinker layers at each of the two wells is 8 mm and the width difference is 26 mm due to the large crack that formed where the surface area of coal is in contact with air (see Figures 2 and 3). The teardrop shape of the clinker gives an indication of the air flow pattern in the coal.

Heat was provided to the coal for 30 minutes, but the air flow continued for a longer period. It was observed that the temperature continued to rise for a further 30 minutes until the self-heating system halted due to the eventual cooling of the coal surface by the air flow, which entered the coal at 23°C. When coal reaches temperatures of approximately 600°C, a self-sustaining heating will be established (Hoffman, 2008).

Experiment 2

The coal used for Experiment 2 was cemented into the refractory chamber, whereas the coal in Experiment 1 was only surrounded by refractory sand; this prevented the coal from cracking to such an extent. The shape of the clinker as shown in Figures 6 and 7 is similar to that seen in Experiment 1, however it is more cylindrical. Upon closer inspection (see Figures 8 and 9) it can be seen that the clinker layer is in fact slightly thicker at the base of the injection well (the well on the left of each photograph) than the production well (on the right).

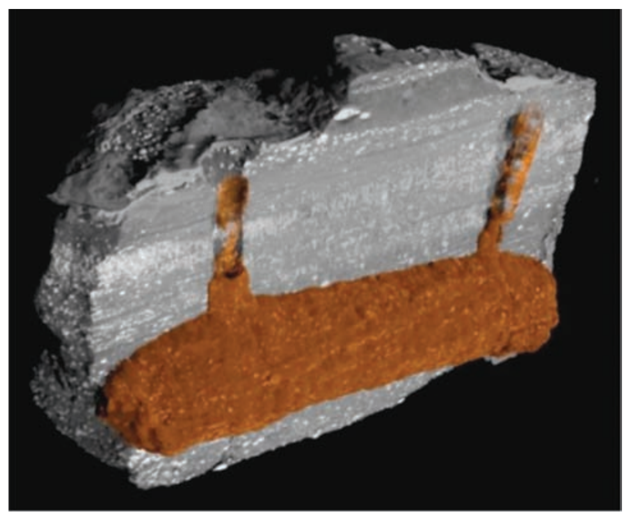

Figure 6—Cutaway section of the coal showing the clinker formation

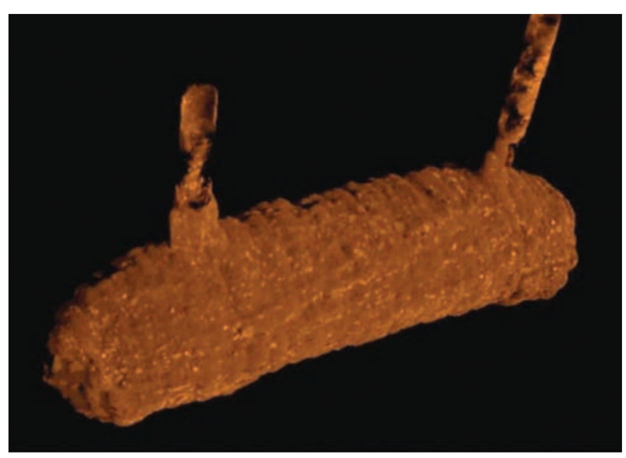

Figure 7—The shape of the clinker formation

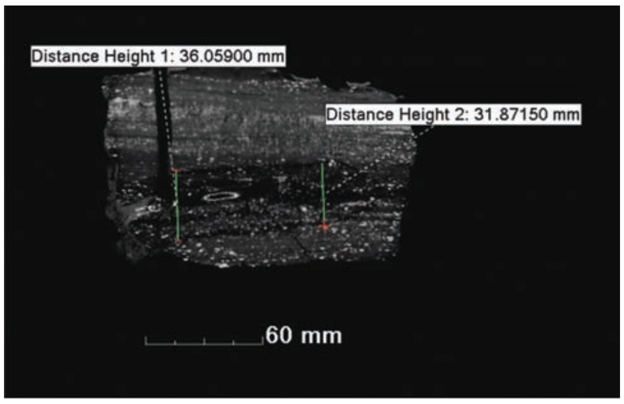

Figure 8—Cross-sectional front view of combusted coal with dimensions

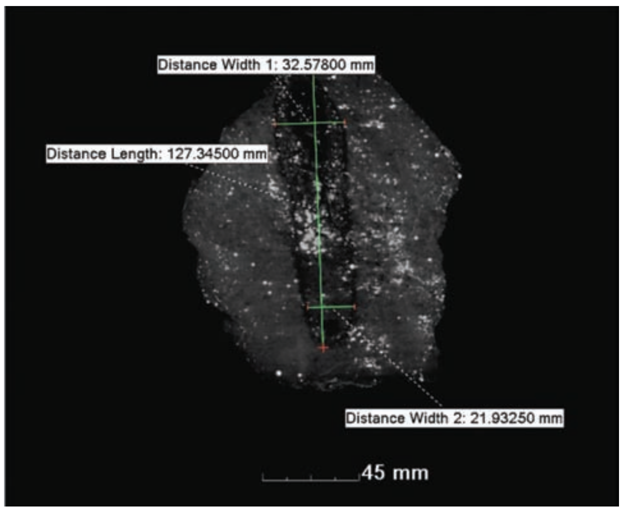

Figure 9—Cross-sectional top view of combusted coal

Comparison to the research by Daggupati *et al*

The current research was roughly based on the work done by Daggupati *et al.* (2010), the major differences between the two investigations being the type and size of the coal used, the heat source adopted, and the experimental duration. However, the general trends of cavity formation can still be compared.

Figures 10 and 11 compare the top views of the cavity formation in the experiment by Daggupati and Experiment 1 respectively. The injection well is indicated by the white circle on the left of each image and the production well is on the right.

It is clear that in both cases the cavity at the base of the injection well is larger than at the production well. This shape is not as obvious in Figure 11 due to the fact that a heating element was used across the entire length of the horizontal tunnel, causing clinker to form. It is also noteworthy that ash was formed in Daggupati's experiment, whereas clinker was formed in the current investigation. This can be attributed to the different coal characteristics and operating conditions.

Conclusions and recommendations

A laboratory-scale method was used successfully to simulate cavity formation during underground coal gasification. It was found that cracking tends to occur along the bedding plane of the coal due to the formation of clinker or expanded vitrinite, which forms in a thicker layer at the base of the injection well than at the base of the production well. This can be attributed to the turbulence of the air flow as well as the relatively high oxygen concentration at the base of the injection well. The air flow pattern has a great effect on cavity formation. The combustion products were not analysed, but should be in future work. It is recommended that further work be done on the heating source, such as using an alternative method. The use of Liquefied Petroleum Gas (LPG) is recommended as this method allows the experiment to mimic more of an industrial UCG process, in addition, if the temparature of the cavity could be controlled more effectively the clinker formation should be able to be minimized. Further investigations should take changes in the process variables into account; these variables include varying the injection air flow rate, the type of coal, duration of heating and the temperature of the heating source. Using steam together with the air would allow gasification reactions to occur in addition to combustion reactions, and thus mimic actual UCG processes more accurately.

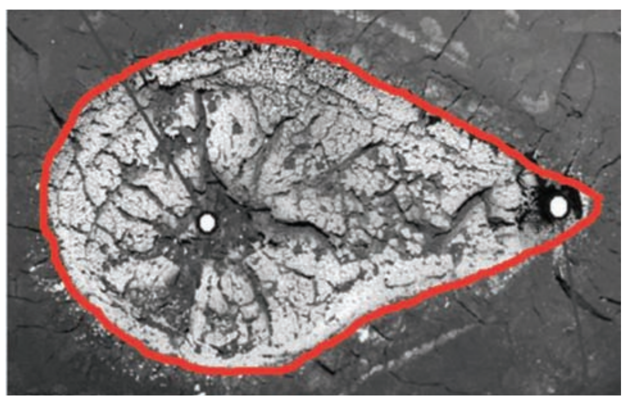

Figure 10—Plan view of the cavity obtained by Daggupati *et al.* (2010)

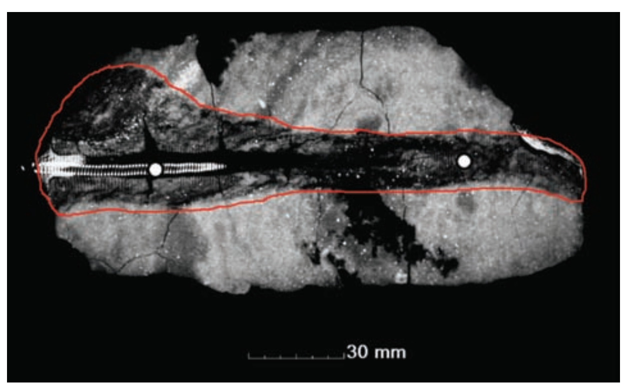

Figure 11—Tomogram showing the plan view of the cavity produced in Experiment 1

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References

ABDUL, W.B., AQEEL A.B., and GHOLAMREZA, Z. 2013. Underground coal gasification: From fundamentals to applications. *Progress in Energy and Combustion Science*, vol. 39. pp. 197–199.

AFRI COAL INVESTMENTS PTY LTD. 2013. What causes clinkers in coal fired boilers. http://www.africoal.co.za/what-causes-clinkers-in-coal-fired-boilers [Accessed 18 Oct. 2013].

DAGGUPATI, S., GANESH, A.,MANDAPATI, R.N., MAHAJANI, S.M., MATHUR, D.K., SHARMA, R.K., and AGHALAYAM, P. 2010. Laboratory studies on combustion cavity growth in lignite coal blocks in the context of underground coal gasification. *Energy*, vol. 35. pp. 2374–2386.

DIRECTIONAL DRILL PTY LTD. 2011. What is horizontal directional drilling. http://www.directional-drill.com/horizontal-directional-drilling.html [Accessed 26 Oct. 2013].

HOFFMAN, G. 2008. Natural clinker. http://geoinfo.nmt.edu/staff/hoffman/clinker.html [Accessed 18 Oct. 2013].

HOFFMAN, J.W. and DE BEER, F. 2013. Micro-focus X-ray tomography facility (MIXRAD) at NECSA. Personal communication.

MITRA, S.K. 2011. Coal testing and analysis. http://www.mitrask.com/coaltesting-analysis/index.html [Accessed 24 Oct. 2013].

SEDDON, D. and CLARKE, M. 2011. Underground coal gasification (UCG), its potential prospects and its challenges. http://www.duncanseddon.com/underground-coal-gasification-ucg-potential-prospects-and-challenges [Accessed 25 Apr. 2013].

SELF, S.J., REDDY, B.V., and ROSEN, M.A. 2012. Review of underground coal gasification technologies and carbon capture. *International Journal of Energy and Environmental Engineering*, vol. 3, no. 16. pp. 1–8

WAKATSUKI, Y., HYODO, M., YOSHIMOTO, N., NAKASHITA, A., and IKEDA, T. 2009. Material characteristics of clinker ash and examination of applicability for embankment. *Powders and grains 2009: Proceedings of The 6th International Conference on Micromechanics of Granular Media*, Golden, CO, 13–17 July 2009. http://scitation.aip.org/content/aip/proceeding/aipcp/10.1063/1.3179872 [Accessed 24 Oct. 2013]. ◆