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Experimental and numerical investigation of injection of coal washery waste into longwall goaf

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EXPERIMENTAL AND NUMERICAL INVESTIGATION OF INJECTION OF COAL WASHERY WASTE INTO LONGWALL GOAF

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ABSTRACT: Mining, preparation and consumption of coal produce large amounts of waste, of which the coal washery rejects account for a major part. Currently emplacement of coal washery waste not only requires large land, but also pollutes the air, soils and underground water. A number of methods have been developed to make use of coal wastes to fill the voids and strata gaps formed from coal extraction, including dry material backfill, paste backfill and overburden slurry injection. Without the need of underground transport system and interference with coal production, the overburden injection technology is considered a cost-effective method in which the coal washery slurry is injected from the surface down to the caved zone of the longwall goaf and fill the voids. In order to understand the mechanism and behaviour of the grout flowing in the caved zone, laboratory experimental and numerical studies were conducted. The laboratory experiment visually simulated the process of coal washery flowing in the caved zone. The process was also numerically simulated by developing a Computational Fluid Dynamics (CFD) model. These studies provide better understanding of the injection and flow mechanism of the grout in the broken medium. The agreement between the experimental and numerical models indicates that the CFD model is able to simulate the complicated flow and can be used to optimise the injection system design and operation parameters.

INTRODUCTION

Coal production produces a large amount of coal washery rejects. Management of these coal rejects has becomes a challenging issue which affects the mining industry, local communities and governments. Disposal of coal washery rejects is a challenge due to their large volume and the possibility of the waste containing contaminating materials. Currently emplacement of coal washery rejects on the surface not only requires large land, but also causes environmental concerns. The industry needs alternatives to dispose of the large quantity of coal washery rejects. To stimulate improved environmental management of coal washery waste, NSW has introduced the coal washery rejects levy since 2009 with an initial rate of $15 per tonne. On other hand, extraction of coal underground creates voids including stopes, and goafs and gateroads. These voids can induce instability and subsidence hazards (Sheshpari 2015). Making use of these voids to dispose of coal rejects not only reduces the occupied land and surface pollution but also reduce the subsidence induced by mining.

The voids in the fracture networks of the caved zone of longwall goaf formed by coal mining have the potential to store coal washery rejects. A number of methods have been developed that use coal wastes to fill the voids and strata gaps formed from underground coal extraction, including dry material backfill, paste backfill and overburden slurry injection (Belem and Benzaazoua 2008; Huang *et al*. 2010; Lokhande *et al*. 2005; Mez and Schauenberg 1998). The recently developed Overburden Grout Injection (OGI) technology (Shen *et al* 2010; 2011) is believed to be a more cost-effective method than the dry backfill systems as there is no need for an underground transport system and no interference with coal production.

Overburden grout injection has been successfully used in China to reduce longwall mine subsidence by 40-60% (Shen *et al* 2010). Two previous ACARP projects (Guo *et al* 2005; Shen *et al* 2010) had been carried out to investigate the feasibility of this technology for application in Australian mines. In

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two of the three mines studied in Australia, the OGI technology is expected to reduce subsidence by about 50%. However, before conducting any full scale trial, the practicality of injecting the coal washery rejects into the goaf needs to be investigated. Some key hurdles include interaction between the injection activity and coal production, interaction between gas emission and grout filling, the influence of injection on gas management, and the influence of borehole instability on coal wash injection. In connection with the OGI technology, a concept being considered is to inject the grout directly into the goaf to fill the voids there. This can be considered to be a method mainly for waste disposal but it could also help stabilizing the goaf and reduce surface subsidence. In this case the details of the grout flowing within the caved zone of the goaf and many quantitative parameters about the injection flows are still unknown. For example, how much of the materials can be stored, what injection flow rate is appropriate, what range can the injection borehole cover, what space of boreholes should be designed, These unknowns and lack of documented procedures for design and optimisation of injection parameters have hindered coal mine operators from conducting field trials and implement this technology for coal washery rejects treatment.

The paper describes part of the works conducted recently at CSIRO on developing the goaf injection technology, focusing on the laboratory and numerical modelling to visually showing the filling process of the grout in the inaccessible goaf area. Laboratory simulations and Computational Fluid Dynamics (CFD) are combined to investigate the grout injection flow within the longwall goaf. This study consists of three major steps. Firstly a lab scaled transparent injection test system was built up and a series of tests were carried out to visually observe the coal reject grout flowing in the pebble bed which represents the cave zone of the longwall goaf and obtain data for calibration of the CFD model. Secondly, a CFD model was developed based on the lab scaled system to simulate the process of injection. After calibration, the CFD model was further developed to simulate the injection into a large model, based on a real scale of a longwall goaf to understand the process of the coal rejects grout flowing and filling in the longwall goaf.

LABORATORY SCALE INJECTION TEST

It is commonly accepted that a longwall goaf can be divided into three major zones, namely caved zone, fractured zone and separation zone (Shen and Poulsen 2014; Qu *et al* 2015), as illustrated in Figure 1. In this study, a laboratory scaled physical model simulating the caved zone and fractured zone of the longwall goaf was built up, and extensive injection tests was conducted to study the grout flow behaviours within the broken medium using materials provided by the coal industry. The major part of the physical model is a rectangular transparent tank with glass for side walls. The tank dimension is 1200 mm long, 400 mm wide and 400 mm high. On the bottom of the tank a layer of 110 mm of pebble stones are laid. This layer is to simulate the caved zone of the longwall goaf. Snow white pebbles are used for the purpose of easy observation. Above the pebble layer are a number of layers of broken beams made of a mixture of plaster and fly ash, representing the fracture zone of the longwall goaf. The top layer without fracture represents higher overburden strata as shown in Figure 2(d).

Figure 2 shows the apparatus and materials used in this experimental study. The coal washery rejects were provided by South 32 Illawarra Coal. By adding a small amount of water a thick grout was made as shown in Figure 2a. The viscosity of the grout was measured using the Haake Viscometer VT-550 as shown in Figure 2b. The peristaltic hose pump, VF 32, as shown in Figure 2C, with continuously variable speed controller is used to inject the grout into the tank. In running the injection test, an injection flow rate of about 0.035 kg/s was applied by adjusting the speed of the pump. The tank packed with pebbles and brick of plaster and fly ash is shown Figure 2d. A pipe 55 mm in diameter is installed close to one end of the tank. The bottom of the pipe touches the top of the pebble layer. A hose of 15 mm is connected to the pump at one end and the other end of the hose is put inside the pipe

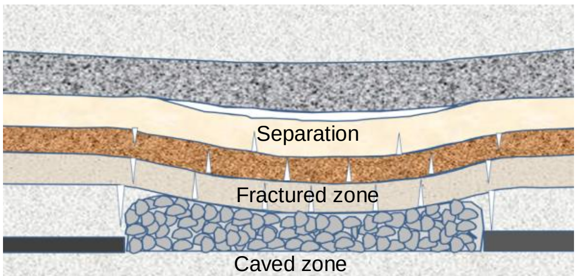

Figure 1: Schematics of structures of longwall goaf overburden strata

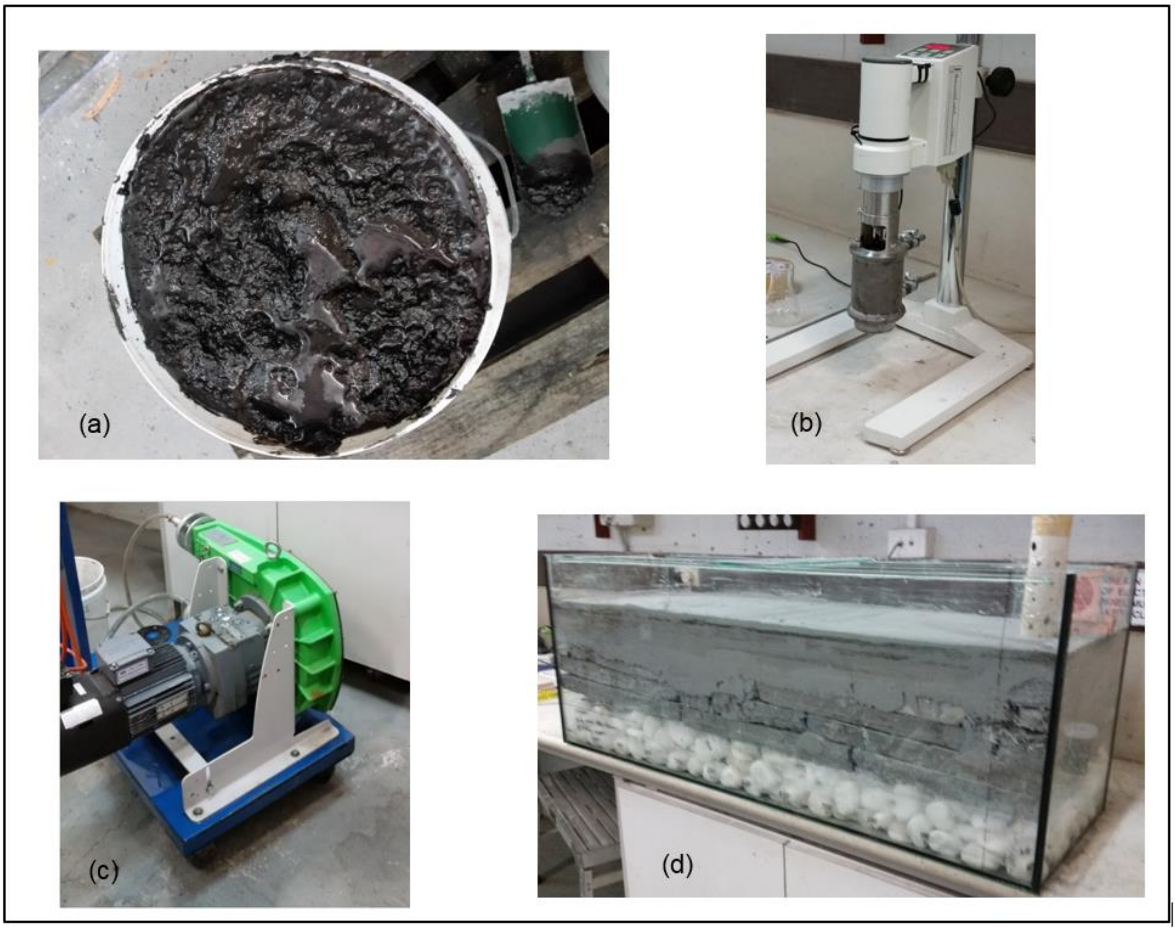

Figure 2: Experimental apparatus and materials (a) coal washery grout; (b) viscometer; (c) injection pump; (d) injection tank

The viscosity of the grout varies very much when the coal washery rejects are mixed with different amounts of water. Figure 3 shows the viscosity when the fine coal rejects were mixed with water to reach a density of 1309 kg/m^3. It is seen from the viscosity measurement results that the grout behaves like Bingham fluids with viscosity increasing nonlinearly when the shear rate decreases. Figure 4 shows the connected injection system in operation. During the test, it was observed that the grout cannot be seen reaching the front side wall of the tank until one minute passed. As injection continues the grout gradually fills the voids of the pebble layer from one end of the tank towards the other end. After injecting for about eight minutes, the grout in the pipe raised to the top of the pipe and spilled out, marking the final finish of the injection. As the tank sides are transparent the process of grout flow in the pebble layer can be observed and recorded. The data of the position of the flow front at different times was obtained for calibration of the CFD model as will be described below.

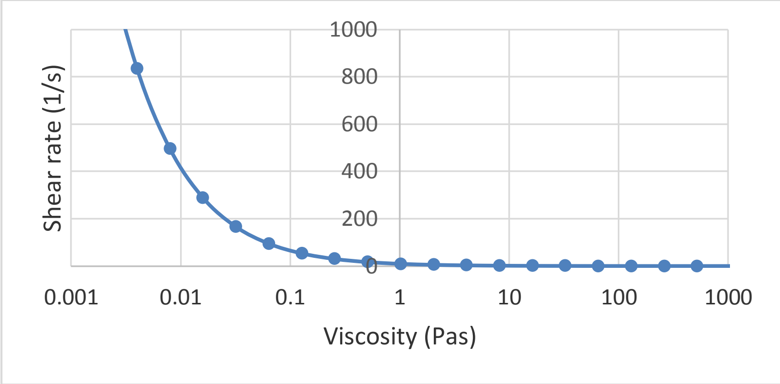

Figure 3: Measured relationship of viscosity and shear rate of coal reject grout

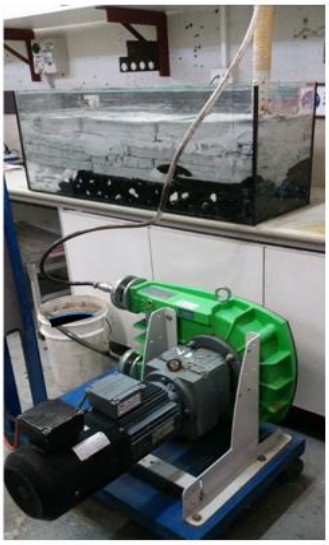

Figure 4: Connected laboratory scale injection system

CFD SIMULATION OF THE LAB SCALE INJECTION MODEL

CFD modelling is a useful approach in simulating the detail flow process in the inaccessible areas of the longwall goaf. CFD has been used to investigate the gas flow migration dynamics within longwall goaf areas with the objective of improving gas capture, minimising the risk of spontaneous combustion and developing effective goaf inertisation strategies (Ren and Balusu, 2009; Guo *et al*. 2012). The previous CFD modelling of goaf gas flows have provided better understandings of methane flow patterns in the longwall goaf and helped optimise longwall goaf gas drainage design. In this study, we first develop a CFD model to simulate the coal washery grout flows in the lab scaled injection system. After calibration of the CFD model with the laboratory model, the CFD model is developed further to simulate the real scale model of the longwall goaf to provide information for design and optimisation of the goaf injection system.

Geometry of the lab scale CFD model

The CFD model is based on the lab scaled injection tank. The dimensions are 1200mm x 400 mm x 400mm, exactly the same as the lab tank. A pipe of 55 mm in diameter is located at the right end of the tank to represent the borehole, and a hose of 15 mm in diameter is in the centre of the pipe representing the injection hose. The 3D domain is meshed into 180000 finite cells. The geometry and meshes are shown in Figure 5.

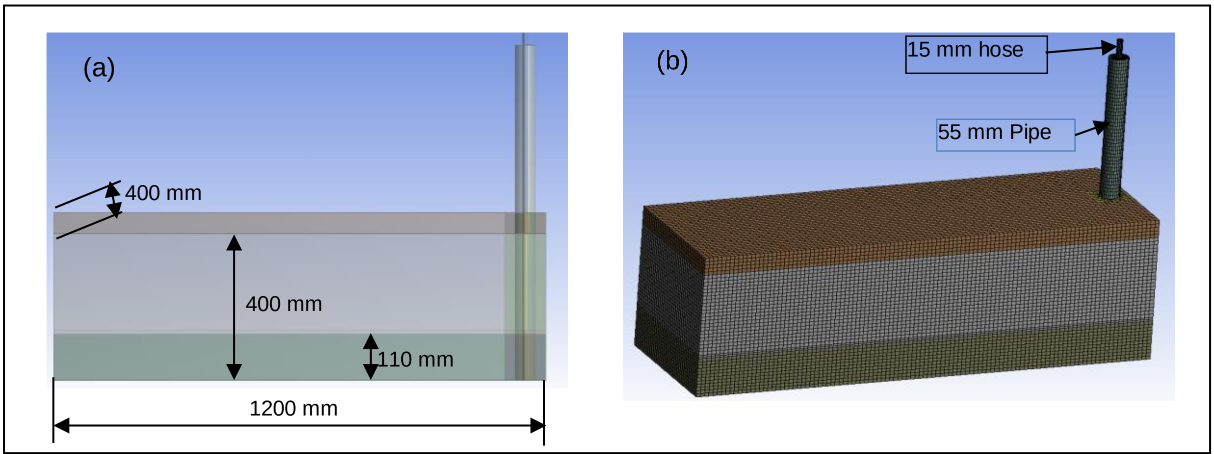

Figure 5: CFD modelling geometry (a) and meshes (b)

Two phase models selected

The Ansys software Fluent 15 is used to develop the CFD model. The injection process is considered time-dependent and the transient flow model was enabled. In addition, it is assumed that the pores of the domain are full of gas prior to grout injection, thus the two phase flow model was used, including air and grout. The volume of fluid (VOF) model was employed to track the interface between the phases. The continuity equation for the volume fraction of the q phase of a two phase model (p and q) is

$$\frac{1}{\rho_q}\left[\frac{\partial}{\partial t}\left(\alpha_q \rho_q\right) + \nabla \cdot \left(\alpha_q \rho_q \vec{v_q}\right)\right] = S_{\alpha_q} + \sum_1^2 \left(\dot{m}_{pq} - \dot{m}_{qp}\right) \tag{1}$$

where $\dot{m}_{pq}$ is the mass transfer from phase q to phase p, and $\dot{m}_{pq}$ is the mass transfer from phase p to phase q, and S_{α_q} is a source term.

The volume fraction of phase p is computed based on the following constraint:

$$\alpha_p + \alpha_q = 1 \tag{2}$$

The coal washery grout is considered to be a liquid phase whose density of 1309 kg/m^3 is measured from the lab test as mentioned previously. The viscosity of the grout was measured and shown in Figure 3. The other phase, air, is considered ideal gas, and the compressible gas law is used to describe the density of the gas.

Porosity and permeability and boundary conditions

The flow domain is a porous medium, and permeability and porosity are used to describe the porous domain. The porosity represents the volume fraction of the flows and the permeability represents the resistance of the medium to the flows. The porosity was determined in the lab through filling water into a certain volume of the packed pebble stones. The permeability is described by introducing the viscous resistance coefficient and the inertial resistance coefficient. To determine these two coefficients, the Ergun equation (Ergun 1952), a semi-empirical correlation applicable over a wide range of Reynolds numbers and for many types of packing are applied:

The viscous coefficient is

$$C_1 = \frac{1}{\alpha} = \frac{150}{D^2}\frac{(1-\varepsilon)^2}{\varepsilon^3} \tag{3}$$

where

$$\alpha = \frac{D^2}{150}\frac{\varepsilon^3}{(1-\varepsilon)^2} \tag{4}$$

The inertial coefficient C2 is

$$C_2 = \frac{3.5}{D}\frac{(1-\varepsilon)}{\varepsilon^3} \tag{5}$$

where D is the particle diameter, and ϵ is the porosity of the packed bed.

The top of the inject hose is defined as mass flow inlet of 0.035 kg/s of grout, as the same as the experiment. Other boundary conditions include boundary walls for the bottom, and the four sides, the top of the pipe and the top of the tank are defined as pressure outlets with atmospheric pressure applied.

CFD simulating results

Figure 6 compares the process of grout filling the voids of the pebble layer of the tank from experimental and CFD modelling. Both are observed from the front side of the tank. The CFD simulation shows that in about 1 minute the grout has reached the front side wall at the bottom right corner of the tank, and gradually moves towards the left. As the filling continues, the interface of the grout and air forms a line with a slope angle of about 40 degrees. This is consistent with the observation of the test. As the permeability of the pebble layer is much larger than the overlying fractured brick layers, almost all of the coal rejects grout flows into the caved zone. Little grout fills in the fractured zone.

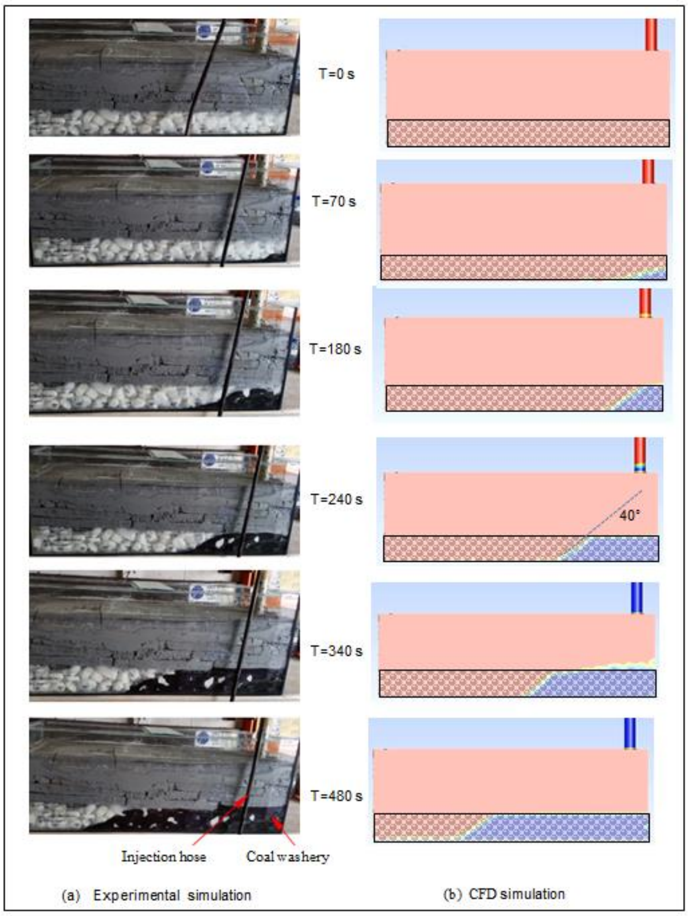

Figure 6: Comparisons of injection processes between lab test and CFD simulation

Figure 7 compares the filling distance from the experiment and the CFD modelling, indicating a good agreement between them. It is seen that from both the experiment and CFD modelling that although the injection flow rate keeps constant, the filling speed of the grout is not constant. After 300 seconds, the filling speed gradually slows down. This is because the flow resistance increases as the filling area becomes smaller, and more grout stays in the pipe rather than flows to the voids of the pebble layer.

Figure 8 shows the profiles of the grout fraction (left) and the correspondent pressure profiles at different times on the vertical section crossing the injection pipe and hose. It can be seen that both the grout level in the pipe and the pressure underneath the pipe increase with the injection time. Due to the top end of the pipe (borehole) being open to the atmosphere the driving force for filling is not from the injection hose, but from gravity. It is seen that, as the filling speed slows down, more and more grout is stored in the pipe and the level surface of grout gradually rises up, this in turn builds up pressure and drives the grout flowing further horizontally in the pebble layer. When the grout level in the borehole rises up to the top of the borehole, the pressure underneath the pipe is not able to increase, and the grout is eventually not able to flow further, and the filling process ceases.

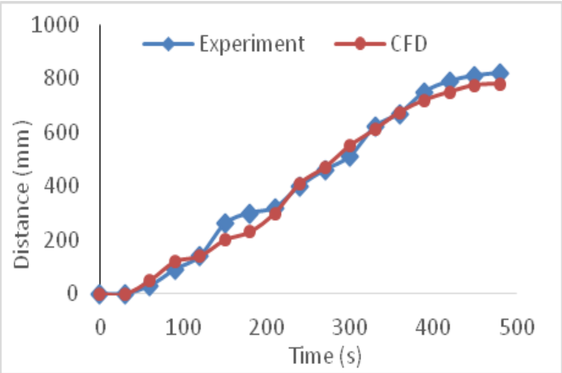

Figure 7: Comparison of flow distance of the flow front between test and CFD

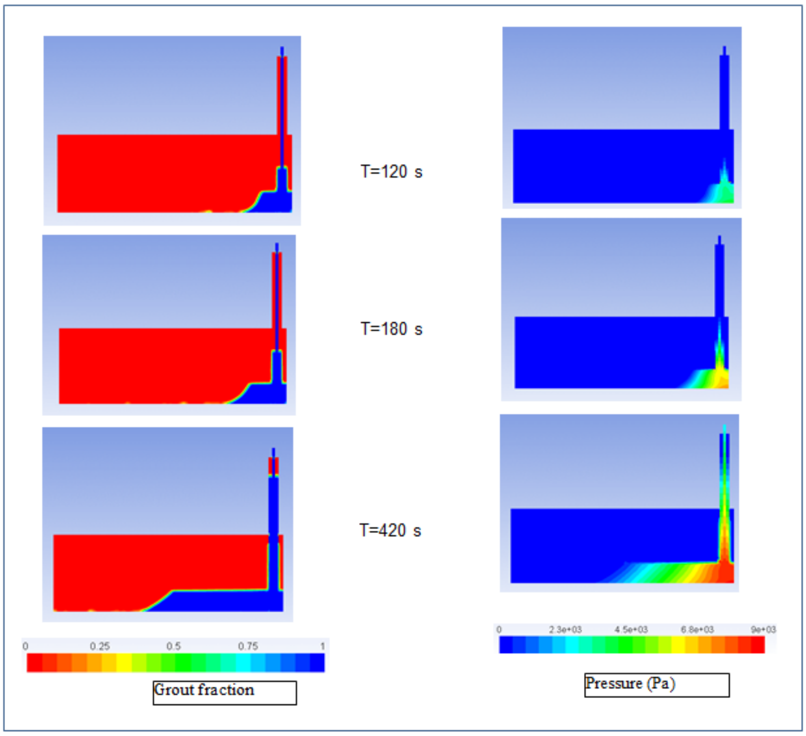

Figure 8: Contours of phase (coal washery) fraction (left) and pressure (right) on a vertical section when grout level rises to different positions

CFD SIMULATION OF INJECTION OF COAL REJECT GROUT INTO A LONGWALL GOAF

CFD geometry of the LW3 goaf model

After demonstrating that the developed CFD model is able to simulate the process of the injection of grout into the lab scaled injection model, the CFD model was developed further to simulate a large injection of a real longwall goaf. The longwall goaf is formed by mining a coal seam of thickness of 3 m. The dimensions of the model are 800 m long, 400 m wide and 110 m high. In this CFD model, one borehole located 170 m behind the working face and 50 m from the tailgate is selected as the injection hole. Figure 9 shows the geometry and the meshes of the model of the longwall goaf. The geometry and meshes are shown in Figure 9.

Unlike the lab scaled model where the permeability of the caved zone (pebble layer) can be calculated using the Ergun equation based on the measured porosity and average diameter of the stones, the permeability and porosity of the longwall goaf are not able to be obtained by simple test and calculation. In order to determine the permeability of longwall goaf, a series of site characterisation studies, field investigations, and numerical modelling studies, were previously conducted by researchers CSIRO to investigate longwall mining induced strata behaviours including stress change, strata displacement, and underground water pressure changes in many coal mines of Australia and China. Based on the mine site measurements, 3D models using the software, COSFLOW developed in CSIRO were developed to estimate the permeability changes of the surrounding strata of longwall goaf.

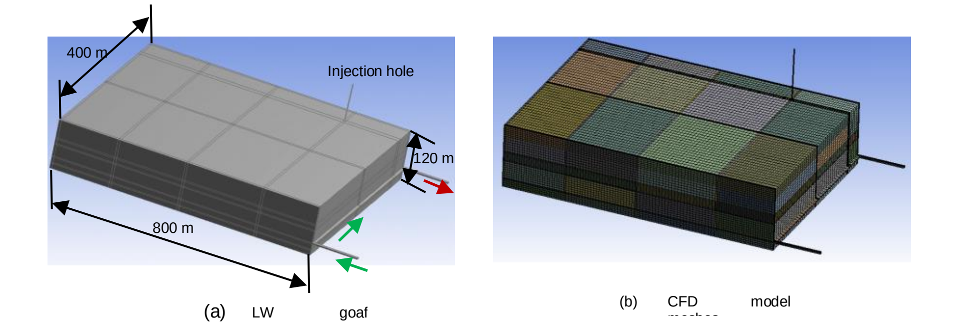

Figure 9: Geometry and meshes for CFD modelling a longwall goaf injection

Permeability of the longwall goaf

These results were used to construct a permeability model of the overlying and underlying strata of the mined coal seam areas for the CFD model. Details of site characterisation and permeability determination for longwall goaf are referred by Guo *et al* (2009; 2012; 2015), and Qin *et al* (2015).

Simulation results of the longwall goaf injection

The simulation of the injection into the longwall goaf can provide information about the grout flowing in the inaccessible caved areas. Different scenarios can be obtained by running this model with different injection parameters, such as injection flow rate, viscosity of the grout and the position of the injection borehole. The filling coverage area, the capacity of disposal of coal rejects in a certain size of goaf, the required injection flow rate and injection time, can be predicted and assessed by running the model. This is particularly useful in design and optimisation of an injection system, in considering the high cost of practising an injection operation.

Figure 10 displays some of the contours of grout fraction from the CFD simulation showing the process of the grout filling the caved zone of the longwall goaf on a longitudinal vertical section, and Figure 11 shows the filled area from the plane view at the working level. It is noted that because the permeability around the perimeter of the goaf is higher than the central area, and the borehole for injection is close to the Tailgate (TG) side, after injecting for 300 minutes, the grout has flowed to the boundary of the tailgate side. If there are no sealing walls between the caved zone and the tailgate, the grout will flow into the tailgate and may influence the mining production. This needs to be taken into consideration when designing and practising a real injection system. By sealing off the cut-throughs and gate roads or locating injection borehole in the central area of the goaf or controlling injection time, grout flowing into gate roads can be avoided.

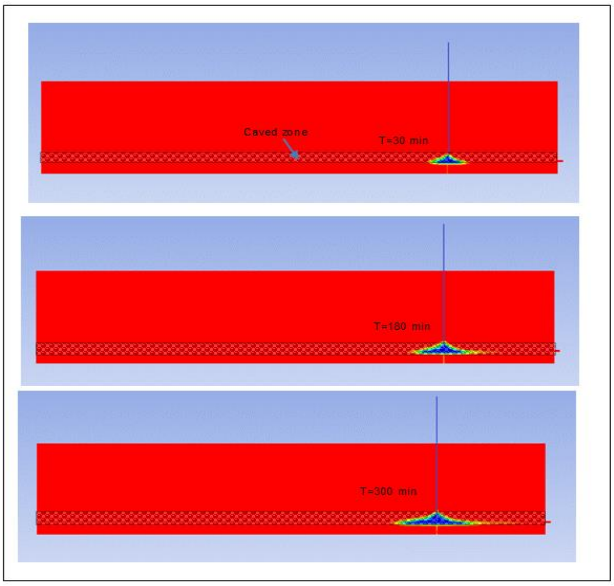

Figure 10: Coal washery filled area development on a longitudinal vertical section as injection time advances

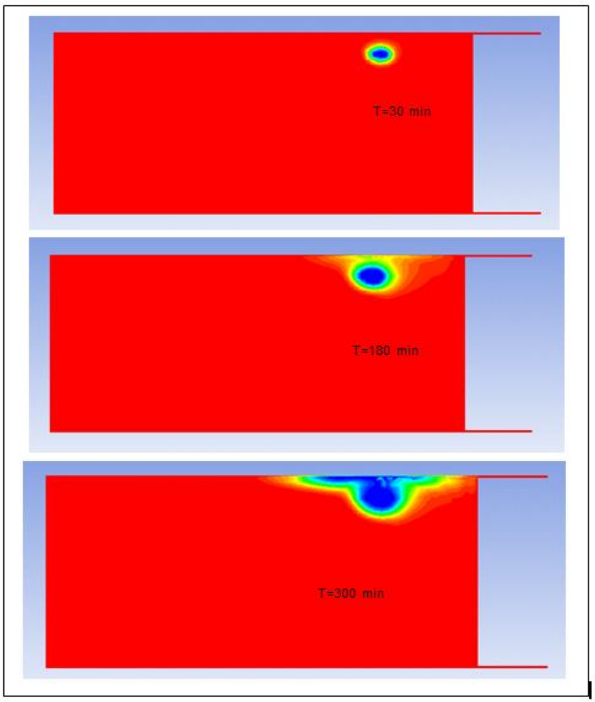

Figure 11: Coal washery filled area development on a plane section of the working level as injection time increases

CONCLUSION

For the purpose of coal washery disposal in underground coal mines, experimental and CFD simulation of overburden injection of coal washery grout into the caved zone of longwall goaf has been carried out. The lab scaled model uses packed bed of pebbles to simulate the caved zone. The transparent tank allows the filling process of the grout flow in the caved zone to be visible. The developed CFD model successively simulated the grout filling process in the lab scaled injection tank. The calibrated CFD model was then developed to simulate a large model of a real longwall goaf injection. The study not only helps improve our understanding on the mechanisms of grout flow and filling in the networks of the caved zone of longwall goaf, but also provides quantitative flow parameters to optimise the design of the injection system, and assess the capacity of waste disposal in a longwall goaf.

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