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Coupled hydro-thermal analysis of underground coal gasification reactor cool down for subsequent CO_2 storage

Vasilis Sarhosis[a]*, Dongmin Yang[b], Yong Sheng[b], Thomas Kempka[c]

[a]*Geoenvironmental Research Centre, School of Engineering, Cardiff University, Queen's Building, CF24 3AA,UK*
[b]*Institute for Resilient Infrastructure, School of Civil Engineering, University of Leeds, LS2 9JT, UK*
[c]*GFZ German Research Centre for Geociences, Section 5.3 – Hydrogeology, Telegrafenberg, 14473 Potsdam, Germany*

Abstract

The present study investigates the time dependency of a UCG (Underground Coal Gasification) reactor cool down process by comparing natural cool down with forced cooling driven by water flushing. The convective heat transport out of the UCG reactor was calculated using an analytical approach coupled to a numerical heat flow model of the geology surrounding the UCG reactor. Our results show that forced cooling by water flushing at flow velocities of 1 m/s can decrease the required time to retain initial in-situ temperature conditions by a factor of more than 300.

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Keywords: *Underground coal gasification; reactor cool down; numerical simulations; CO_2 storage*

1. Introduction

1.1. Background

Despite advances in the so called clean coal technology, coal-fired power plants still have a sizeable carbon footprint. By 2020, power plants across Europe will have to incorporate carbon capture and storage (CCS) to comply with EU regulations and meet the targets on greenhouse gas emissions [1]. In addition, many of the world's coal reserves cannot be mined by conventional mining methods as seams

* Corresponding author. Tel.: +44 (0) 29 2087 4004; fax: +44 (0) 29 2087 4004.
E-mail address: SarhosisV@cardiff.ac.uk

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are often too deep and geological conditions too complex. In-situ coal gasification, generally addressed as underground coal gasification (UCG), may provide an efficient approach for the conversion of these unmineable coal resources into a synthesis gas that can be used as fuel for power generation. The process involves the injection of an oxidant, coal gasification underground and production of the generated synthesis gas to the surface using wells. During the gasification process, underground cavities are generated by coal consumption. Such cavities can be used for permanent CO_2 storage involving the benefit of sorptive linkage between CO_2 and coal increasing storage capacities and safety [2]. By combining UCG with CCS, a cost effective, low carbon emission energy source can be implemented as illustrated in Figure 1.

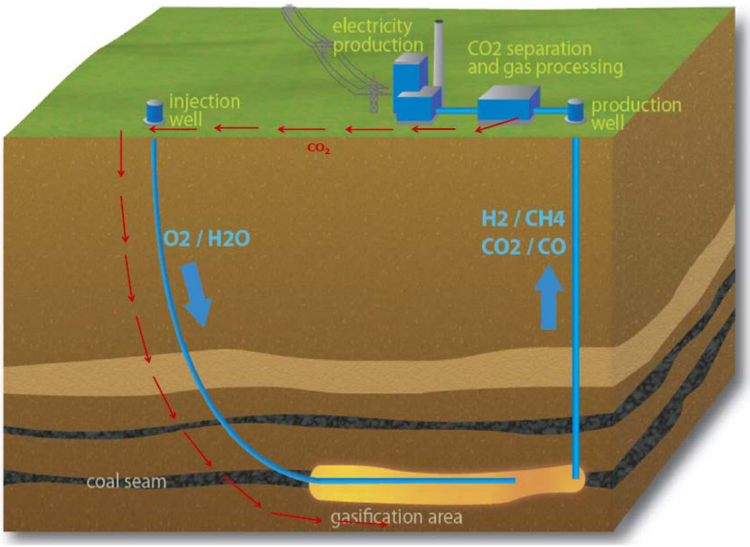


Fig. 1. Conceptual scheme of the combined UCG-CCS process modified from Kempka et al. [3].

1.2. Preparation of UCG cavities for the subsequent storage of CO_2

When a UCG operation is shut down and CO_2 storage in the remaining cavities scheduled to start, it is essential to carry out the necessary procedures to prepare the cavities for an efficient CO_2 storage, while preventing contamination of adjacent groundwater aquifers. Hereby, one focus is to prevent the escape of UCG by-products (tars, phenol, benzene, etc.) to avoid a potential contamination of adjacent aquifers. Furthermore, during the UCG process, the temperature in the UCG reactor generally reaches more than 1000 ºC [2-5]. However, at the time of CO_2 injection, the temperature in and around the reactor must have already cooled down to a level where significant CO_2 volume expansion due to the difference between in-situ and injection temperature is avoided. The cooling of the cavity can be achieved either naturally (without any specific measures) or supported by flushing the UCG reactor with water. Consequently, understanding the reactor cool down process is essential for the preparation of UCG cavities for the subsequent CO_2 storage.

1.3. Aim of the study

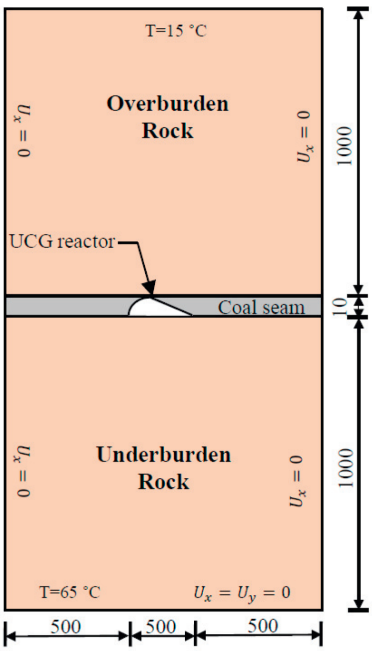
We discuss the development of a computational model to study the preparation of UCG cavities for subsequent CO_2 storage. Using an analytical approach to determine convective heat flow in the cavity coupled to a finite element method for thermal analysis, we developed a two dimensional hydro-thermal model which was applied to study the time dependency of the UCG reactor cool down process. Two cases have been considered: a) the natural cool down; and b) the cool down process supported by water flushing. The commercial finite element software ABAQUS [6] has been used in this study using the convective heat transport calculated by the analytical model as input.

2. Development of the model

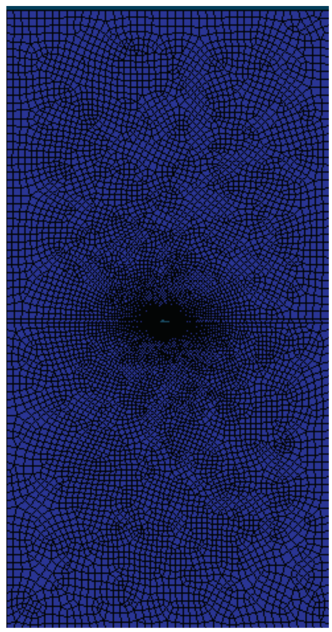
2.1. Model geometry

A geometric model has been created using the ABAQUS software package to represent the geological cross section of a synthetic UCG reactor in a coal seam of 10 m thickness located at a depth of 1,000 m below ground. A teardrop-like cavity shape has been created (Figure 2a) with dimensions of 50 m in the horizontal and 10 m in the vertical direction [12].

The finite element mesh generated shown in Figure 2b. Since high temperature gradients will occur close to the UCG reactor, a finer mesh has been assigned there growing coarser in direction of the model boundaries. Mesh convergence tests have been carried out to ensure that the solution does not change significantly upon further mesh refinements.



(a)



(b)

Fig. 2. (a) Geometry of the model, dimensions in meters, not to scale; (b) finite element mesh of the model.`

2.2. Analytical convective heat transport model

Based on the cavity geometry (cf. Fig. 2a), the length of the cavity outline can be calculated to 106.93 m resulting in a cavity wall surface equal to 106.93 m^2 for a 2D model with an extent of 1 m in z-direction. Also, the cavity volume is 278.54 m^3 and the average cavity diameter considering a cavity length of 50 m equals to 2.66 m. The average cavity diameter was applied for calculation of convective heat transport forced by the water flushed through the cavity while assuming the cavity to have the shape of a pipe for analytical model simplification. We also assumed that water inflow temperature into the cavity is constant at 25 °C and estimated the film temperature for UCG cavity wall temperatures from 1,000 °C to 100 °C in 100 K steps to determine the water (vapour) properties. These are then used to calculate the forced convective heat transport out of the UCG cavity serving as input for the numerical model. Thermo-physical properties of water (vapour) were derived from [7], [8], [9], [10] and [11].

For the calculation of the Reynolds number water (vapour) flow velocities of 0.1 m/s and 1 m/s were taken into account, both resulting in turbulent flow in the UCG cavity. The Nusselt number Nu calculated according to the Dittus-Boelter correlation given in Equation 1.

$$Nu = 0.023 \cdot \mathrm{Re}^{0.8} \cdot \left(\frac{\nu}{\alpha}\right)^n \tag{1}$$

whereby Re is the Reynolds number, ν the kinematic viscosity and α the thermal diffusivity with n equal to 0.4 for the fluid being heated. The heat transfer coefficient h determined by the Equation 2.

$$h = \frac{\lambda \cdot Nu}{D_H} \tag{2}$$

whereas λ is the thermal conductivity and D_H the hydraulic (average cavity) diameter. Subsequently, we calculated the convective heat transport out of the 2D cavity for the water (vapour) flow velocities discussed above and cavity temperatures decreasing with time for implementation as boundary condition into the numerical model by Equation 3.

$$q = A \cdot T_f \cdot h \tag{3}$$

with q representing the convective heat transport out of the UCG cavity and T_f the film temperature defined as average temperature between the cavity wall and the flushing fluid.

2.3. Rock and coal properties

Material properties for rock and coal were obtained from existing literature [13] (cf. Table 1).

Table 1. Material properties used for coal and rock in the numerical model.

Coal			Rock		
Density (kg/m^3)	Thermal conductivity (W/m K)	Specific heat capacity (J/kg K)	Density (kg/m^3)	Thermal conductivity (W/m K)	Specific heat capacity (J/kg K)
1,500	0.81	2,500	2,500	0.4	1,100

2.4. Boundary conditions

The boundaries of the numerical model were fixed normal to the vertical and horizontal directions. A geothermal gradient of 25 K per 1,000 m from 15 °C at the surface has been assigned [14]. The analytical model for convective heat transport discussed before was coupled with the numerical model for thermal conduction by using the calculated heat convective transport as boundary condition in the latter one. The cavity was heated to a temperature of about 1,000 ºC using an adaptive heat flux to achieve these representative UCG temperature conditions at the end of the gasification process.

Natural cool down has been simulated by assigning zero heat flux at the cavity boundary. Also, the heat flux values for the forced cool down by water flushing velocities derived from the analytical heat transfer model. From Equation 3, the average convective heat flux to represent water (vapour) flushing velocities of 1 m/s and 0.1 m/s are equal to -1.15 MW/m^3 and -0.18 MW/m^3, respectively.

3. Results and discussion

Figure 3 shows the temperature distribution around the UCG cavity at the end of the gasification process as predicted from the coupled numerical simulation. The maximum temperature at this time is 946 ºC. Temperature changes are observed up to approximately 5 m away from the cavity.

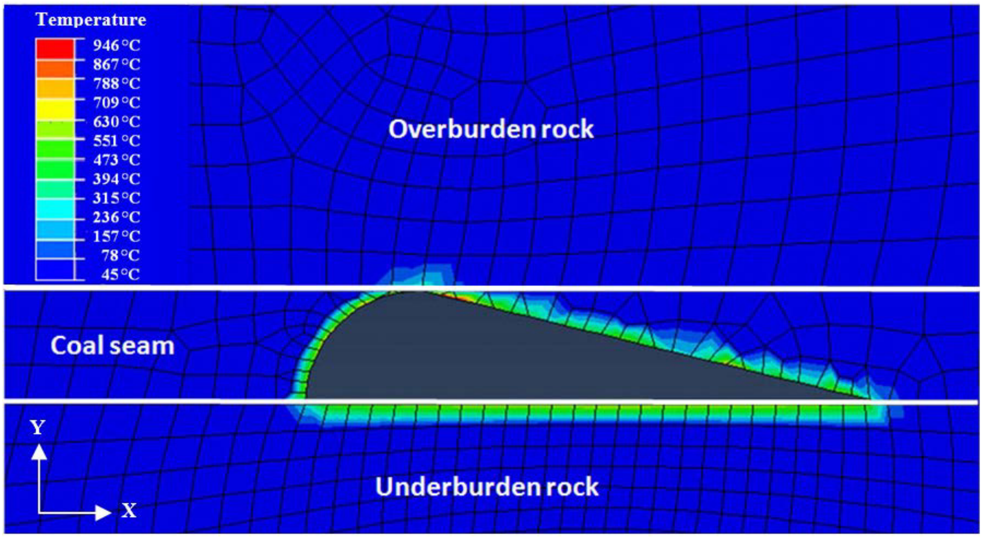


Fig. 3. Temperature distribution at the end of the UCG process.

3.1. Natural cool down process

The temperature distribution after the cavity has been left to naturally cool down for a year is shown in Figure 4. The maximum temperature around the cavity is 181 ºC. Here, the temperature change can be observed up to 15 m away from the cavity.

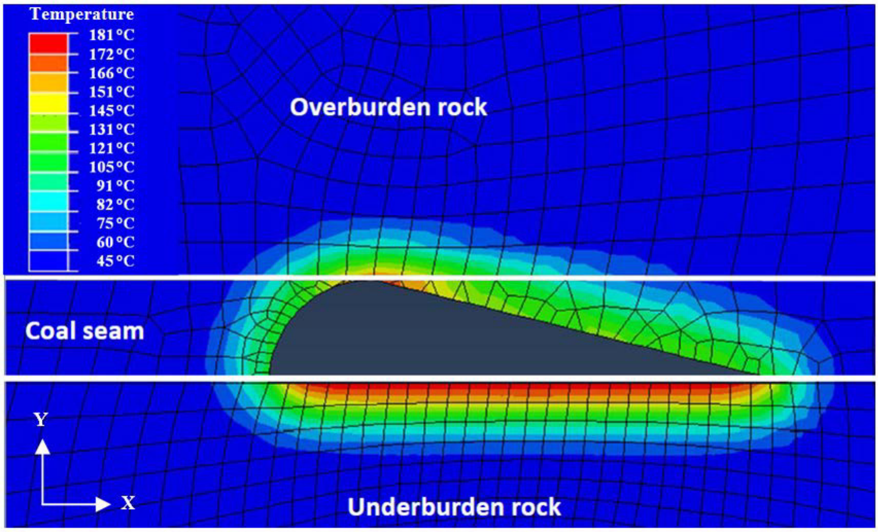


Fig. 4. Temperature distribution after one year of natural cool down.

Figure 5 shows the drop in the maximum temperature around the UCG cavity with time for the natural cool down process. For the first two weeks, the temperature is decreasing significantly at an average rate of -18.6 K/day. Thereafter, the average rate of temperature decrease is -1.2 K/day.

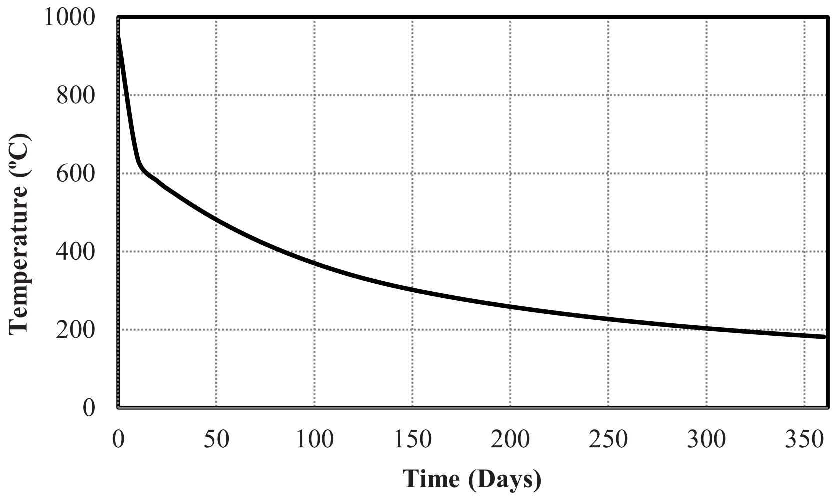


Fig. 5. Drop in maximum temperature around the UCG cavity with time during natural cooling.

3.2. Forced cool down process by water flushing

The time required for the cavity to cool to its initial in-situ temperature as a result of the forced cool down process depends on the water (vapour) flow velocity in the UCG cavity. Figure 6 compares the duration of the forced cool down process when water (vapour) is flushed at flow velocities of 1 m/s and 0.1 m/s. The results obtained from the coupled numerical simulations demonstrate that the time required for the cavity to cool down with a water flow velocity of 0.1 m/s is about 2.5 times higher than with a water flow velocity of 1 m/s, but more than 300 times lower compared to the natural cool down illustrated in Fig. 5.

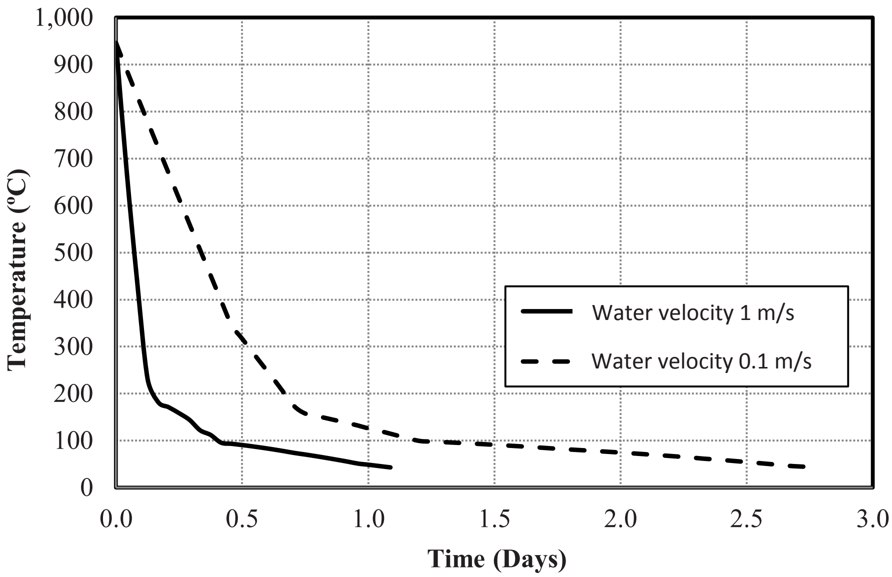


Fig. 6. Drop in maximum temperature around the UCG cavity versus time resulting from forced cool down by water flushing at two different flow velocities.

4. Conclusions

The present study investigates the cool down process of an UCG cavity as preparation for subsequent CO_2 storage. CO_2 volume expansion due to temperature differences during injection has to occur in a controlled manner to manage the in-situ pressure development, i.e. a factor of five in volume expansion is associated with a CO_2 temperature change from 25 °C to 200 °C at a pressure of 100 bar (e.g. at 1,000 m depth) [15]. An analytical convective heat transport model has been implemented to calculate the convective heat flux being used as input for a two dimensional numerical conductive heat flow model to simulate the UCG reactor cool down process with (forced cool down) and without water flushing (natural cool down). The model developed represents the cross section of a synthetic UCG site located at 1,000 m depth. Material properties for rock and coal have been obtained from literature. Both, the natural and the forced cool down process have been studied by a coupled analytical and numerical analysis. From the result analysis it was found that:

a) Forced cooling with water flushing can significantly decrease the duration of the cool down process by a factor of more than three hundred.
b) The higher the velocity of the water flushed through the cavity, the faster the time required for the cavity to cool down. However, frictional pressure losses in the wellbore limit the maximum water flushing velocities according to the inner liner diameter. This aspect was not investigated in the present study, and thus the assumed water flushing flow velocities may be overestimated. Nevertheless, we were able to clearly demonstrate that forced cooling may significantly decrease the cooling time, and consequently required CO_2 storage capacities can be provided at an earlier time regarding the entire coupled process of UCG and CCS. Water flushed through the cavity at a flow velocity of 1 m/s can reduce the duration of the cool down process by a factor of 2.5 compared to a water flushing velocity of 0.1 m/s.

Further work will consider the development of a 3D model involving a thermal, hydraulic and geomechanical coupling taking into account the remaining ash and rubble present at the bottom of the UCG cavity, verified water injection rates as well as a validation using field data from operating UCG sites.

Acknowledgements

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