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ORIGINAL ARTICLE

On the mitigating environmental aspects of a vertical well in underground coal gasification method

Mohammadreza Shahbazi[1] · **Mehdi Najafi**[1] · **Mohammad Fatehi Marji**[1]

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Abstract Underground coal gasification (UCG) is an energy production pathway in underground coal deposits with the potential advantage of decreasing the greenhouse gas emissions during the energy extraction process. The environmental benefits of UCG are mainly due to eliminating (i) conventional mining operations, (ii) the presence of coal miners in the underground, (iii) coal washing and fines disposal, and (iv) coal stockpiling and coal transportation activities. Furthermore, UCG has a capacity of great potential to provide a clean coal energy source by the implementing carbon capture and storage techniques as part of the energy extraction process. In this method, coal seams in the underground were converted into syngas including hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), and methane (CH_4) gasses with an advanced thermochemical process. UCG operation effected significant geomechanical changes to the overburden strata. In this process, the vertical well (especially the production well) was mainly affected by the mechanical stresses and the thermal stress, induced by the high syngas temperature. This high temperature changed the mechanical, thermal, and physical properties of the coal seam and its surrounding rocks (the host rocks), finally causing instability of the vertical well, while leading to serious production and environmental problems. One of these environmental issues is the possibility of syngas leakage in to the environment, resulting in water pollution and acidification. In addition, the released syngas could trigger global warming and air pollution. This research evaluated environmental aspects of UCG vertical well (production well) based on the stability analysis. Therefore, a flow sheet form was developed for three-dimensional

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✉ Mehdi Najafi
mehdinajafi1362@gmail.com; mehdinajafi@yazd.ac.ir

Mohammadreza Shahbazi
mohammadrezashahbazi66@gmail.com

Mohammad Fatehi Marji
mfatehi@yazd.ac.ir

[1] Department of Mining and Metallurgical Engineering, Yazd University, Safayieh, Yazd 89195-741, Iran

thermomechanical numerical modeling of an UCG vertical well by explicit Lagrangian finite difference method. In this model, a criterion was established based on normalized yielded zone area to assess the stability conditions. The methodology was able to capture all factors that influence the instability of UCG well while selecting suitable mud pressure and lining system during the well drilling process. Hence, when wellbore integrity issues arose during drilling, the mitigation strategies were applied to rectify these problems. The results demonstrated that the vertical well should be drilled at a constant mud pressure of 9 MPa (megapascal), thus causing minimum environmental problems. The thermomechanical modeling provided an opportunity to assess the potential environmental impacts and identify reliable global climate change mitigation strategies.

Keywords Underground coal gasification (UCG) · Vertical production well · Greenhouse gas emissions · Environmental aspects

1 Introduction

Coal is known as a carbon-intensive fossil fuel whose use in the global electrification will have implications for climate mitigation strategies if low emissions and high-efficiency technology are utilized in high proportions. According to surveys, if all of the world's oil, gas, and coal resources are considered as 100%, approximately 95.5% of the world's hydrocarbon resources are composed of coal (Couch 2009). This suggests that the investment and implementation of long-term plans to exploit coal resources in the future is of great importance. There are other greater resources deep in the underground that could be a supplement to the proved reserves, though they are not economical to be mined by means of the current technology. Underground coal gasification (UCG) is one of the modern energy production methods, employed for coal seam mining. UCG is a promising clean coal technology to exploit the huge coal resources which are unmineable by the conventional mining technologies.

UCG has several advantages over conventional coal gasification process and the traditional underground coal mining methods. Some of them include (i) the elimination of coal mining and ash handling operation, (ii) low capital investment, (iii) minimal greenhouse gas emission, (iv) low water consumption, and (v) the lack of necessity for the presence of coal miners underground, which is of significant value for man's occupational safety. Furthermore, UCG technology has generated possible sites (cavities) for CO_2 sequestration after gasification (Gregg and Edgar 1978; Burton et al. 2006; Couch 2009; Roddy and Younger 2010). Although UCG has many advantages, its process may also have a surface and subsurface environmental impact in terms of groundwater pollution and surface subsidence. McInnis et al. (2016) studied mitigation and adaptation strategies for global change via implementing underground coal gasification. They reviewed the process of UCG and evaluated the opportunities, challenges, risks, competitive analysis and synergies, and commercial initiatives. They also provided a road map to solutions via the modeling and simulation of UCG.

In a UCG process, at the first stage, the injection and production wells are drilled from the surface to the coal seam. Second, these wells are linked together in the underground. Afterwards, air or oxygen is sent to the coal seam through the injection well where the coal is ignited in a controlled manner. In the gasification panel, the temperature rises to 700–1200 °C due to coal gasification (Couch 2009; Burton et al. 2006). Finally, the syngas with a temperature of 550 K flows to the surface though the production well and is sent to the end user after cleaning.

In the controlled retraction injection point (CRIP), two or three in-seam parallel holes are drilled in the lower part of the seam and then turned near the end to meet at a point, possibly 500 to 700 m off the place where they have started (Couch 2009). A schematic view of the parallel CRIP configuration (two in-seam holes) (in commercial scale) is demonstrated in Fig. 1.

In order to support mitigation strategies for clean coal production and policy development, research needs to be conducted so as to understand the stability analysis of UCG well during gasification. In order to manage the gasification process under normal conditions, the injection and production wells must be stable during this process.

2 Environmental aspects of a UCG vertical well

Vertical well instability in UCG operation leads to environmental problems as mentioned below (McInnis et al. 2016; Couch 2009; Burton et al. 2006; Marg 2009; Brown 2012; Gregg 1977; Imran et al. 2014):

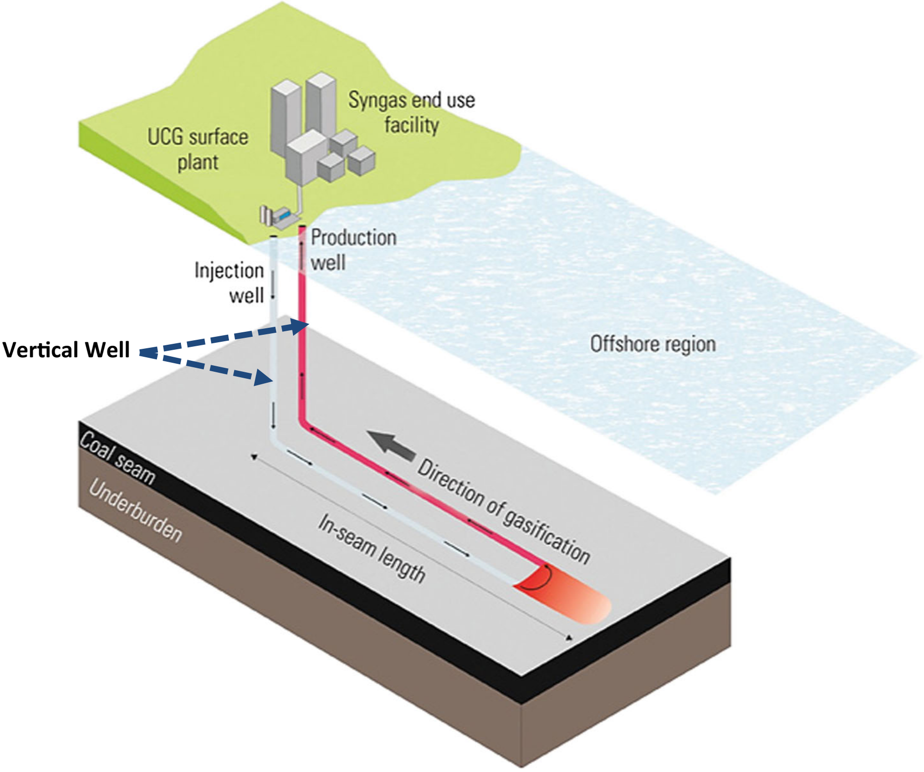


Fig. 1 The UCG process, using the controlled retracting injection point (CRIP) method

- The possibility of groundwater flowing from the upper layers through the well into the cavity increases. This problem might result in the UCG reactor shutdown and a rise in the groundwater pollution.
- The syngas leakage from the production well to the overburden layers will increase, propelling cracks in the overburden layers and the groundwater pollution.
- The growing possibility of syngas leakage to the ground surface will create surface water pollution and acidification.
- As a whole, the syngas released into the atmosphere may initiate global warming and air pollution with a rise in the temperature of the region.

Therefore, it is clear that UCG vertical well stability reduces the greenhouse gas emissions and water pollution. However, one of the most challenging problems in UCG design is the stability analysis of injection and production wells. During the UCG process, the vertical wells (especially production well) are subjected to high temperature from syngas and syngas pressure. Moreover, coal seams and their surrounding stratum are often far weaker than the surrounding strata in most oil reservoirs. The well lining in UCG should also reduce the influx of water from the surrounding strata. These wells need to withstand the utilized operating pressure and to retain their integrity when the surrounding ground moves (Couch 2009). Therefore, it is essential to develop an advanced model for the stability analysis of UCG vertical wells. Adaptation of thermal and mechanical simulation would aid the optimization of the UCG process while helping to control and mitigate the environmental risks, inducing well instability and syngas loss to the groundwater.

3 Literature review

In order to mitigate the risk during and after gasification and reach the optimal design of UCG, many laboratory studies (Stańczyk et al. 2012; Laciak et al. 2016; Wiatowski et al. 2016; Daggupati et al. 2010), field monitoring (Luo et al. 2008; Synfuels 2012), and analytical (Perkins and Sahajwalla 2006; Luo et al. 2009) and numerical methods have been performed.

The geomechanical modeling of UCG process and wellbore stability in the oil and gas industries has been proposed by many researchers in recent years. Vorobiev et al. (2008) concluded that the hybrid continuum and discrete approaches are among the best methods for predicting ground subsidence by UCG. In their modeling, the pressure and temperature in the cavity were set to zero and the material was assumed as elastic. Two-dimensional numerical modeling of UCG in the layered rock mass was performed by Tan et al. (2008) using ANSYS software. They studied the stress distribution and concluded that the roof and floor rocks of the coal seam at both sides suffer tensile and compressive stress. Tian (2013) developed a thermomechanical Hoek-Brown (TMHB) and Mohr-Coulomb (TMMC) rock failure criteria for UCG in CRIP configuration to study the ground surface subsidence. This two-dimensional numerical result suggested that ground subsidence increases with the growing size of UCG panel and a rise in temperature. Jamshidi and Amani (2014) studied the effect of mud cyclic loading, hole length, stress regimes, and fluid pressure wellbore stability analysis, while employing discrete element models. They deduced that the direction of minimum horizontal stress is the optimum drilling direction. Najafi et al. (2014) developed a new three-dimensional thermal-mechanical model for UCG based on CRIP configuration to predict stress distribution in the vicinity of UCG panel. In this model, the caving behavior of roof material was examined after each step of gasification. Yang et al. (2014) developed a three-dimensional numerical modeling to study temperature and stress distribution around the cavities of UCG by ABAQUS software. This model was able to simulate the heat propagation, surface subsidence, and the stress distribution around cavities during the UCG process. Also, Otto et al. (2016) developed a three-dimensional UCG thermomechanical model based on the real structural geological data and investigated the impact of temperature distribution (in the vicinity of an UCG panel) on the ground subsidence, hydraulic conductivity changes, and fault integrity at a commercial underground coal gasification site. Akbarzadeh and Chalaturnyk (2013, 2016) investigated the impacts of different operational conditions, temperature, and material properties on the geomechanical response of the strata to UCG activity using three-dimensional coupled fluid-thermal-mechanical simulations, monitoring the caving behavior of roof strata. Elahi (2016) developed a coupled three-dimensional reservoir-geomechanical simulation to study the effects of various geomechanical parameters, including different constitutive models of coal on the stress solutions in a typical UCG process. Laouafa et al. (2016) examined the mechanical and thermomechanical impact of underground coal gasification exploitation using nonlinear finite element modeling. This numerical result revealed that the size of cavity and the presence of a heat source are two indispensable factors, influencing the UCG process evolution. Mellors et al. (2016) studied the advanced geophysical techniques for monitoring the UCG process. They concluded that it is possible to predict cavity geometry from interferometric synthetic aperture radar (InSAR) data through geomechanical modeling. Das and Chatterjee (2017) presented three types of failure criteria, including Mohr-Coulomb, Mogi-Coulomb, and modified Lade for wellbore stability analysis and prediction of minimum mud weight for few wells in Krishna-Godavari Basin, India.

Evidently, in most of the previous studies, the stability analysis of UCG vertical well has not considered on a commercial or traditional scale.

4 Scope and objective

A coupled thermomechanical model through FLAC3D software was used to study the stability analysis of vertical well (production well) of UCG. Then, a series of sensitivity analyses are presented and discussed to ilustrate the influences of gasification time on well diameter, mean stress, and volumetric and shear strain around the well.

5 The methodology of thermomechanical modeling

Unlike other underground coal mining methods, the coal in the vicinity of a UCG panel are subjected to the high temperature of more than 1000 °C. Therefore, UCG operation imposes significant geomechanical changes to the strata. The UCG process involves complex chemical, thermal, hydrological, and mechanical processes (Daggupati et al. 2010; Nitao et al. 2010, 2011; Sarraf et al. 2011; Sarraf 2012; Najafi et al. 2014; Najafi 2014). The complex interactions among these processes complicate UCG process. Furthermore, since the UCG process takes place in underground, it is difficult to use instruments to monitor the entire coal reaction conditions, stress distribution, well stability, caving behavior, and its effect on the surrounding rocks. Consequently, the numerical modeling can provide comprehensive and qualitative understanding of UCG process. In this study, the thermomechanical simulation of UCG process has been conducted by three-dimensional finite difference approach (FLAC3D) software for the stability analysis of vertical wells in UCG process. Figure 2 reveals a flow sheet of the thermomechanical modeling of UCG vertical wells. The variables involved in the heat conduction in FLAC3D are temperature and the three components of the heat flux (Itasca 2012). The thermal option of FLAC3D allows simulation of transient heat conduction in materials as well as the development of thermally induced displacements and stresses. Solving thermal stress problems requires reformulating incremental stress strain relations, which is accomplished by subtraction from the total strain increment due to temperature change.

The basic law that defines the relation between the heat flux vector and the temperature gradient is Fourier's law. For a stationary, homogeneous, isotropic solid, this constitutive law is given in the following form (Itasca 2012):

$$q_{\mathrm{i}} = -K.T_{\mathrm{i}} \tag{1}$$

where q_i is heat flux vector, T is the temperature (°C), and K is the thermal conductivity (W/m °C).

In FLAC3D software, a convective boundary condition has the following form:

$$q_{\mathrm{n}} = h(T - T_{\mathrm{e}}) \tag{2}$$

where q_{n} is the component of the flux normal to the boundary in the direction of the exterior normal, h represents the convective heat transfer coefficient (W/m^2 °C), T denotes the temperature of the boundary surface, and T_{e} is the temperature of the surrounding fluid (°C). Note that in the numerical formulation used in FLAC3D, boundaries are adiabatic by default.

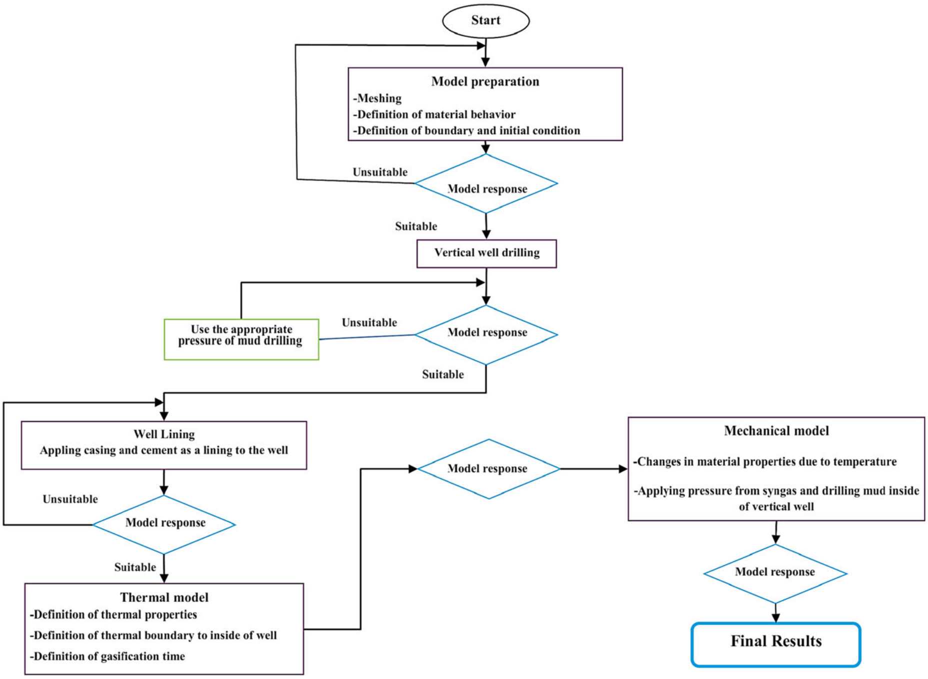


Fig. 2 The underground thermomechanical modeling of vertical wells in UCG process

As free thermal expansion results in no angular distortion in anisotropic materials, the shearing strain increments are unaffected. The thermal strain increments associated with the free expansion, corresponding to the temperature increment ΔT, have the following form (Itasca 2012):

$$\Delta\in_{\mathrm{ij}} = \alpha_{\mathrm{t}}.\Delta T.\delta_{\mathrm{ij}} \tag{3}$$

where $\Delta\in_{\mathrm{ij}}$ is the thermal strain increments, $\alpha_{\mathrm{t}}$is the coefficient of linear thermal expansion, and δ_{ij} is the Kronecker delta.

In the present simulation, the normalized yielded zone area (NYZA) criterion, i.e., the ratio of the surrounding yielded cross-sectional area to the initial area of the well, was used to assess the stability condition. It has been confirmed that the value of NYZA larger than one leads to well instability (Elyasi and Goshtasbi 2015; McLellan and Hawkes 2001).

In this research, the M2 coal seam in Mazino coal deposit (Iran) was selected in order to investigate the stability of vertical well in a UCG process. Figure 3 illustrates the view of vertical well, coal seam, and surrounding rocks in Mazino coal deposit at the depth of 600 m, alongside the casing and cementing part. Meanwhile, it should be noted that 550 m of overburden is not shown in this figure. The Mazino formation consists of sandstone, coal, and shale (Anon 2005), and the thickness of M2 coal seam is 3.5 m.

In UCG process, after vertical well drilling, the well is steel cased from the surface down to the coal seam. This casing is installed about 50 cm deep inside the coal seam, after which the casing operation will stop. Note that the other part of vertical well in coal seam is lined by cement for the maintenance of stability. They are normally cemented above the level of the

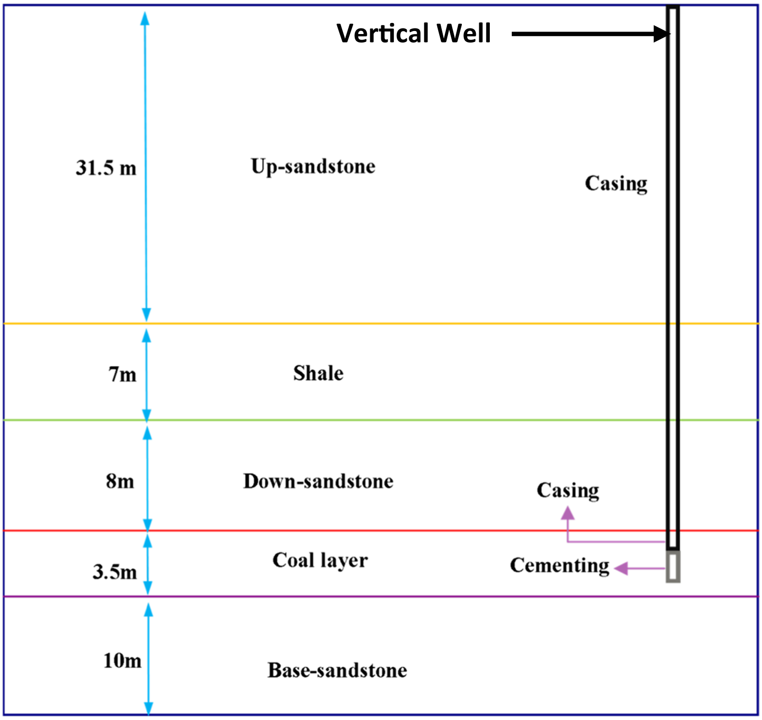


Fig. 3 The designed UCG vertical well

reaction zone to facilitate the controlled introduction of the oxidant (air or oxygen-enriched air, possibly with steam) and to prevent the loss of produced gasses into the overlying strata (Couch 2009).

Due to the number and thickness of layers as well as high complexity of computer calculations, modeling was conducted for each layer separately, while considering an element out of each layer for design purposes. Furthermore, the responses of the mentioned model are not different from those of a model that encompasses all layers as a result of appropriate stress and boundary conditions for each layer.

In this research, the stability analysis of the vertical well was performed for two parts of the well including the coal seam part as well as the down-sandstone, shale, and up-sandstone parts.

In the following section, the numerical modeling of vertical well in the coal seam has been explained, considering the fact that its modeling in down-sandstone, shale, and up-sandstone parts has been conducted similarly.

5.1 Modeling a vertical well in coal seam

In order to burn the coal properly in a UCG process, the vertical well is usually drilled to the bottom of coal seam. Accordingly, in this research, a vertical well with a diameter of 20 cm was drilled to the bottom of coal seam. Then, the model dimensions were taken as 3.5 m on the $+X$, $+Y$, and Z coordinate axes, respectively. Additionally, the mesh size varied from 0.017 to 0.35 m in this modeling. However, to improve the accuracy of the result on the stresses and the displacement around the vertical well, finer meshing systems were assigned in the domain where these wells were located (NYZA value used). Radcylinder elements were used for model development around the vertical well while the model had 28,000 zones and 30,015 grid points, as illustrated in Fig. 4.

The average overburden thickness was 600 m; therefore, at the top of the model, a vertical load of 14.56 MPa was applied to simulate the overburden weight. The ratio of horizontal stress to vertical stress was taken as 1.12. As a result, the value of 16.31 MPa stresses was

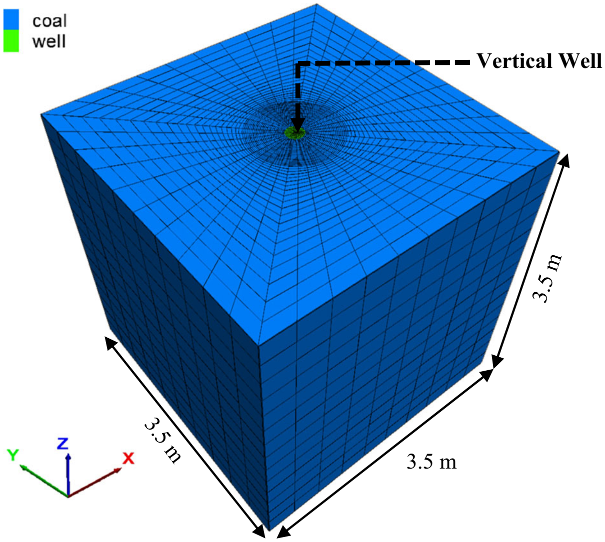


Fig. 4 A typical numerical model geometry for UCG vertical well in the coal seam

applied in the *X* and *Y* directions of the model. In addition, the bottom of the model was fixed, and the vertical walls of the model in *X* and *Y* directions were selected as rollers, with the top of the model assigned as a free boundary (Fig. 5). All the materials related to the study were assumed to be isotropic and homogeneous.

In this research, the conduction model of heat transfers was used. Furthermore, the isotropic thermal model was considered for all layers, and when the vertical well was drilled, the thermal null model was assigned to it. The Mohr-Coulomb failure criterion was selected for all layers. Table 1 presents the mechanical, thermal, and physical properties for all layers. Since the temperature makes some changes in the mechanical, thermal, and physical properties of sedimentary rocks, the variation of mechanical properties of coal and sandstone was considered to be temperature dependent in this numerical molding (Najafi et al. 2014; Najafi 2014).

The numerical modeling of the vertical well was performed according to the configuration displayed in Fig. 2. Hence, after the model ran into equilibrium, the vertical well was drilled, and to minimize the plastic zone around the well, drilling mud was also applied. Then, the steel casing was modeled for 50 cm length of the well in the coal seam and the remaining length was cemented to increase the vertical well stability. Subsequently, the vertical well was subjected to 550 K at a specific time, and the syngas pressure of 3 MPa was applied to the inside wall of the vertical well.

Wells are usually cased with carbon or high-strength stainless steel. Similar to the oil well, the Portland cement-type casing can be used in UCG wells. The thermal and mechanical properties of vertical well lining are presented in Table 2 (Mohanto et al. 2014).

The syngas temperature rose up to 550 K in the vertical well (production well), and the temperature level of this gas on the ground surface was kept at about 530 K (Khan et al. 2015). However, it should be noted that the initial temperature for the formation was already fixed at 300 K.

The geometry of the casing and cement elements is indicated in Figs. 6 and 7. Note that the mechanical elastic modulus was used for casing.

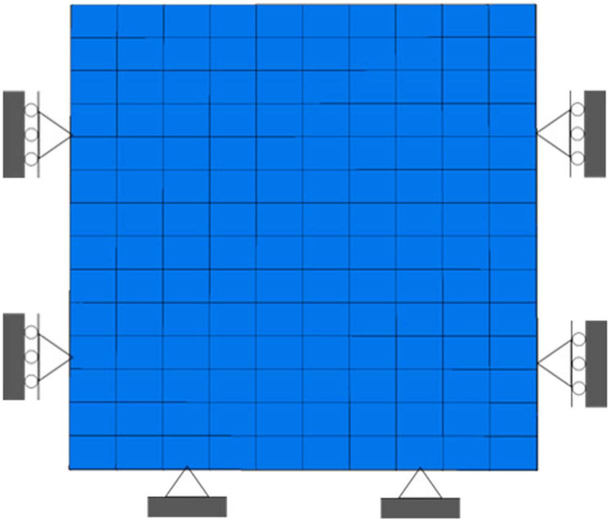


Fig. 5 The boundary conditions of the assigned model

Table 1 Physical, thermal, and mechanical parameters of the selected rock mass (Najafi et al. 2014; Najafi 2014)

Rock property	Unit	Coal	Sandstone (up and down)	Shale
Density (γ)	kg/m^3	1580	2600	2300
Internal friction angle (ϕ)	Degree	23	32	29
Cohesion (C)	MPa	0.5	4.7	1.5
Poisson's ratio (ν)	–	0.29	0.3	0.27
Young's modulus (E)	GPa	0.7	3.5	1.5
Tensile strength (σ_t)	MPa	0.66	2.8	0.3
Bulk modulus (K)	GPa	2.38	2.916	1.086
Shear modulus (G)	GPa	1.162	1.346	0.59
Dilation angle ($\bar{\nu}$)	Degree	5	10	5
Specific heat (C_P)	(Jkg^{-1} K^{-1})	1000	820	800
Thermal conductivity (λ)	(Wm^{-1} K^{-1})	0.3	1.34	1.32
Linear expansion coefficient (α)	(1 × 10^{-6}/°C)	3	10	5

5.2 Modeling results

5.2.1 Coal seam

After the model reached equilibrium, the vertical well was drilled from the surface to the coal seam. Figure 8 reveals the plastic zone around the vertical well in the coal seam after equilibrium. The NYZA was calculated as 44.72, indicating instability of the vertical well. As a consequence, the drilling mud had to be applied to the vertical well for the maintenance of stability.

The tensile failure occurs when the tangential stress is equal to the induced tensile stress and more than the strength of rock mass (Fjar et al. 2008). This kind of failure (Eq. 4) is called hydraulic fracturing.

$$P_{\mathrm{W,max}}^{\mathrm{frac}} = 2\sigma_{\mathrm{h}} - P_0 + \sigma_{\mathrm{t}} \tag{4}$$

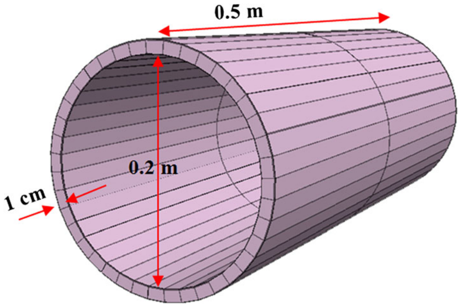
where σ_{t} is the tensile strength of rock, P_0 represents the pore pressure, σ_{h} denotes the minimum horizontal stress, and $P_{\mathrm{W,max}}^{\mathrm{frac}}$ shows the maximum well pressure at initiation of fracture.

This phenomenon occurs probably due to high well pressure or in cases where the differences between stresses are perpendicular to the well axis. In general, the tensile failure of well is defined by the minimum principle stresses and is consequently considered as the

Table 2 The thermal and mechanical properties of a typical UCG vertical well lining

Rock definition	Unit	Cement	Casing
Density (γ)	kg/m^3	2400	8000
Poisson's ratio (ν)	–	0.25	–
Young's modulus (E)	GPa	20	–
Bulk modulus (K)	GPa	–	160.8
Shear modulus (G)	GPa	–	74.23
Thickness	cm	2	1
Specific heat (C_P)	(Jkg^{-1} K^{-1})	–	500
Thermal conductivity (λ)	(Wm^{-1} K^{-1})	–	16.3
Linear expansion coefficient (α)	(1 × 10^{-6}/°C)	100	16.2

Fig. 6 The geometry of casing element



maximum level of drilling mud pressure. In other words, failure occurs where the minimum principal stress is more than the tensile strength of reservoir rock mass. Hence, such a failure can be expressed as (Fjar et al. 2008; Zoback 2007):

$$\sigma_3 - P_0 \leq -\sigma_t \tag{5}$$

In addition to the shear failure criterion, the aforementioned principle is used for determining the optimum drilling mud window. The NYZA values for different drilling mud pressures are shown in Fig. 9. The results indicate that the drilling mud window is between 5.7 and 28 MPa, according to which, when the pressure is less than 5.7 MPa and greater than 28 MPa, the shear and tensile failures occur in the well, respectively.

The optimum mud pressure for drilling is 9 MPa, as it reduces the extent of plastic zones to zero. Figure 10 displays the magnitude of displacement of the well's wall and the well's convergence at the bottom of the vertical well, while simultaneously revealing that the well convergence is about zero, yet the well is unstable at the mud pressure of 5.7 MPa.

After well lining installation, the syngas pressure and temperature were exerted inside the well. Following that, the numerical modeling was carried out for 10, 100, and 200 days of coal gasification. In order to maximize the well stability, the drilling mud pressure of 9 MPa was applied to the well wall. Then, the syngas pressure of 3 MPa was applied to the well after well lining. Hence, considering the mud pressure and the syngas pressure, a total pressure of 12 MPa was applied to the wall of the vertical well.

Figure 11 demonstrates the changes in NYZA value, being a result of pressure on the vertical well, after the lining installation for 10, 100, and 200 days of coal gasification. Note

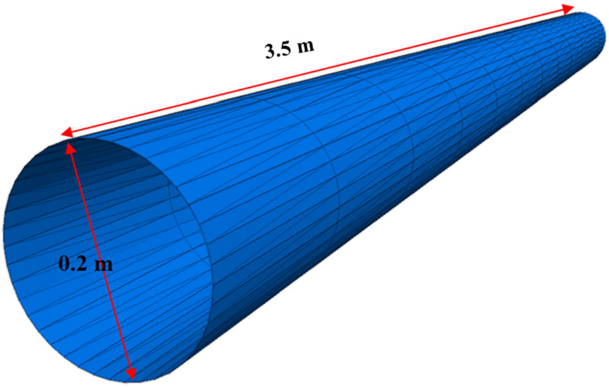


Fig. 7 The geometry of cement element

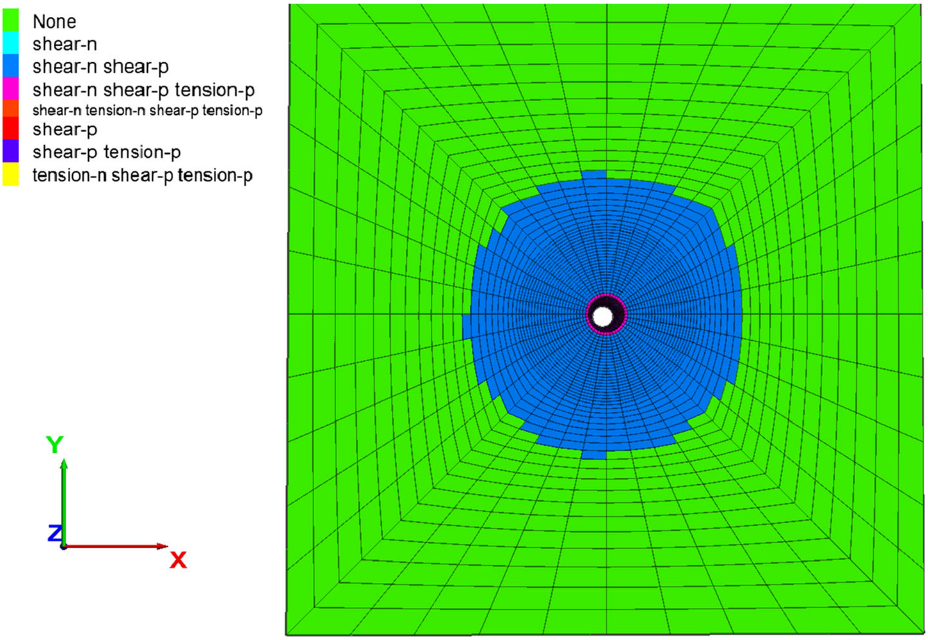


Fig. 8 Plastic zone around the vertical well

that the NYZA values have been calculated for the critical part of the vertical well. Based on this figure, the values of NYZA for 100 and 200 days of gasification are equal, which are less than that of the 10 days of gasification at each different applied pressure. These results suggest that the well cement is resistant to the pressure of 74 MPa. Nevertheless, after 100 days of gasification, the applied pressure can reach 84 MPa.

Figure 12 shows the temperature field around the well after 200 days of coal gasification. The main effect of temperature changes has been the pore pressure variations, which in turns altered the effective stress redistribution around the borehole. Such

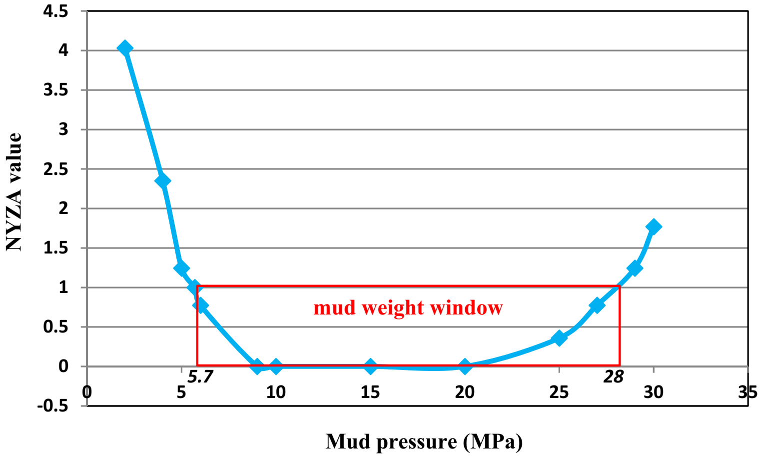


Fig. 9 Changes in NYZA value relative to the mud pressure for drilling a vertical well in the coal seam

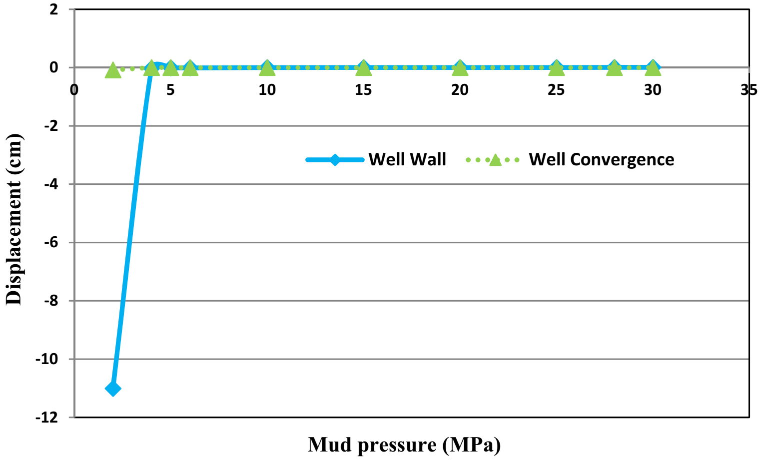


Fig. 10 Well convergence and displacement at different mud pressures

an induced thermal stress and the original stress at the borehole wall may exceed the rock strength, resulting in the collapse or fracture of the borehole, with the consequent impact on its stability (Fjar et al. 2008).

According to the numerical modeling results, it is clear that the optimum mud pressure 9 MPa for drilling results in the well stability. In addition, the well lining is suitable and the well can withstand the pressure of 84 MPa. This result suggests that the potential of gas leakage from the coal seam part to overburden layers is zero.

5.2.2 Up-sandstone, down-sandstone, and shale

Figure 13 reveals the plastic zone around the vertical well in each layer after equilibrium. The NYZA value has been calculated as 0.36, 3.09, and 0.359 for down-sandstone, shale, and up-

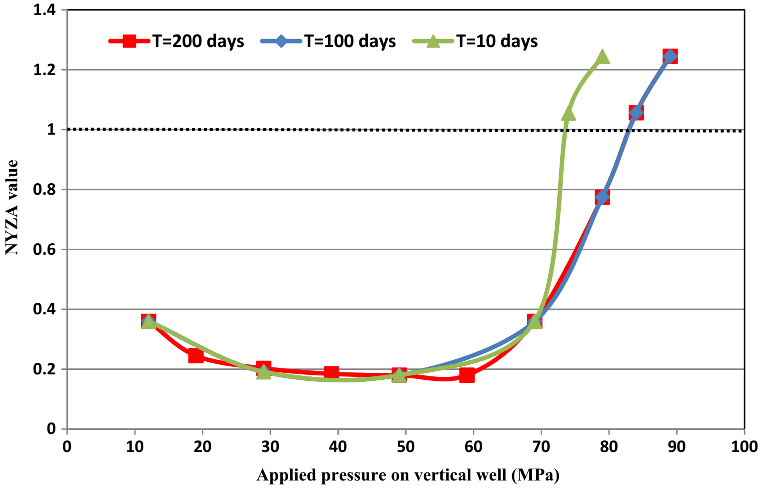


Fig. 11 Changes in NYZA value as a result of pressure on the vertical well

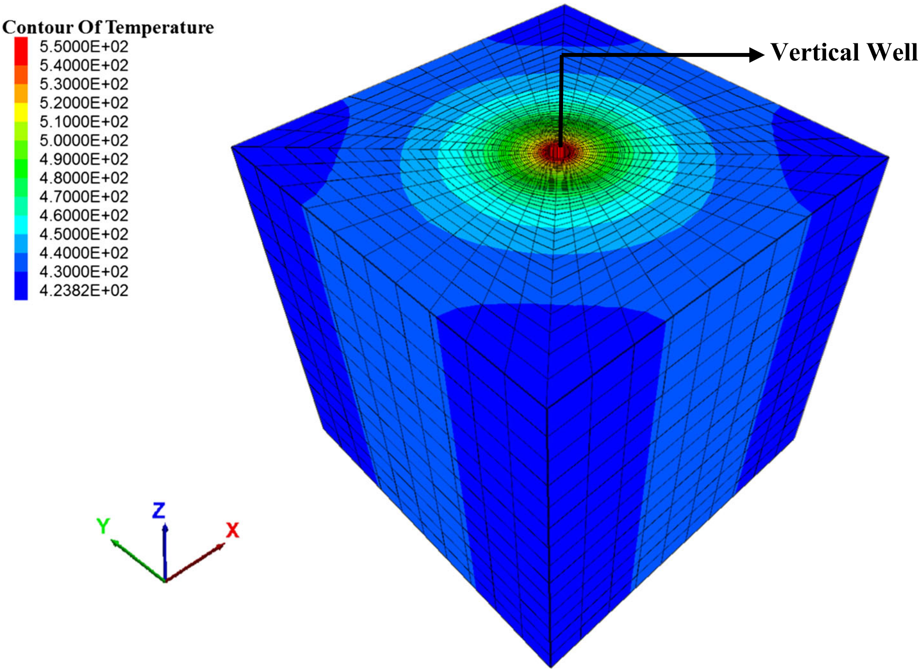


Fig. 12 Temperature field around the well after 200 days of heat transfer (coal seam)

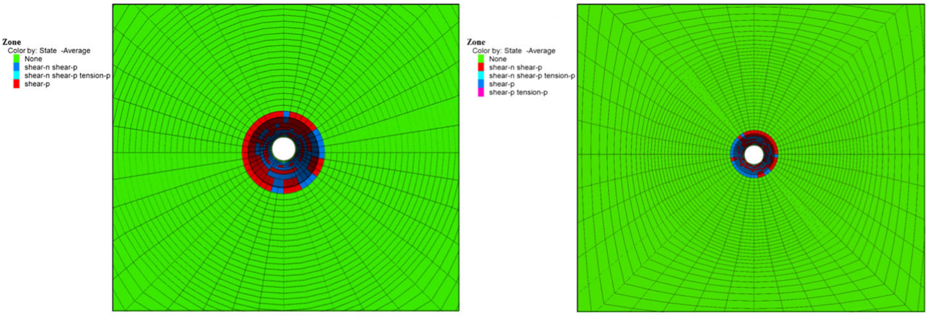
sandstone, respectively, suggesting the instability of the vertical well in the shale layer. Thus, drilling mud must be applied to the well in this layer.

In order to achieve the maximum stability, the plastic zones around the well must be minimized or reduced to zero. The NYZA values for different drilling mud pressures are shown in Fig. 14. The numerical modeling results suggest that the drilling mud windows vary between 0–39, 2.4–32, and 0–37 MPa for down-sandstone, shale, and up-sandstone, respectively. According to Fig. 14, drilling mud pressures of 3, 6, and 3 MPa are appropriate for drilling the vertical well in down-sandstone, shale, and up-sandstone, respectively. The notable point is that the drilling mud pressure must be constant at each stage of drilling. The coal seam has been in the lowest part of the model, and the mud pressure of 9 MPa has been calculated for this layer. Therefore, drilling mud pressure of 9 MPa is appropriate for drilling the vertical well before coal gasification operation.

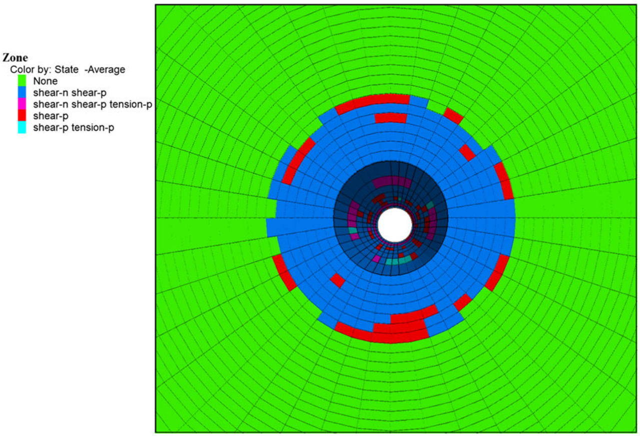
After well lining, the temperature and syngas pressure (3 MPa) were applied inside the well at each layer. Then, a total pressure of 12 MPa (mud pressure plus syngas pressure) was exerted on the wall of the vertical well. Afterwards, numerical modeling was performed for 10, 100, and 200 days of coal gasification operation. Note that the elastic model was used for well lining during the stability analysis of the vertical well.

To measure the strength of the well lining, a significant pressure was applied to the well wall. During the UCG operation, this pressure can result from roof caving of the stope. The changes in NYZA value as a result of pressure on the vertical well for 10, 100, and 200 days of coal gasification are shown in Fig. 15 for each layer.

According to this figure, the lining can be stable up to the pressure of 380 MPa. Nevertheless, this high pressure does not exist in UCG operation which simply indicates



A: Up-sandstone **B: Down-sandstone**



C: Shale

Fig. 13 Plastic zone around the vertical well at different layers

the accuracy of design of the vertical well lining. Moreover, due to high mechanical properties of casing and cement, the time of gasification does not have a significant effect on the stability of vertical well.

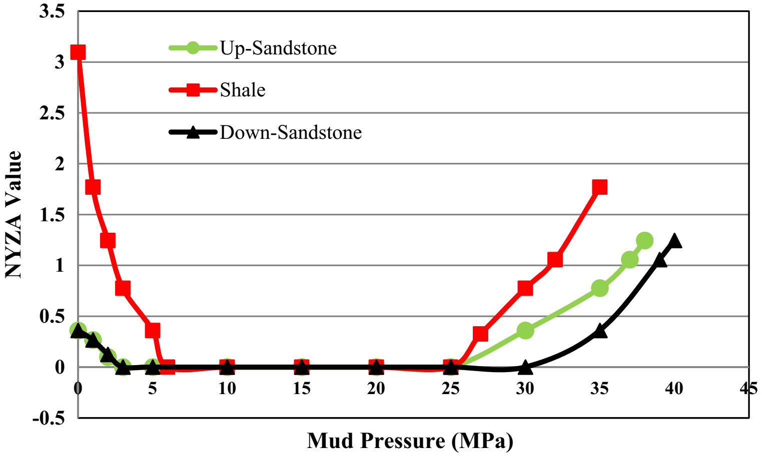


Fig. 14 Change in NYZA value

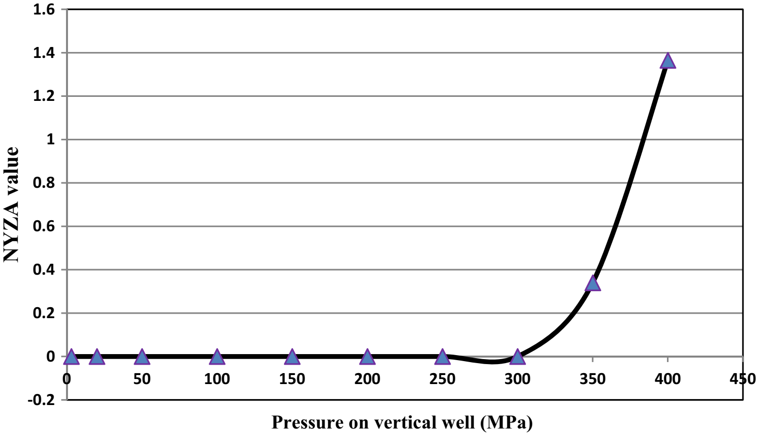


Fig. 15 Changes in NYZA value as a result of pressure on the vertical well in each layer of shale, up-sandstone, and down-sandstone

6 Sensitivity analysis

In the UCG process, a syngas, at a temperature of about 550°C, flows in the production well. Thus, the gas temperature can make alterations to the mechanical and geometrical properties of the well which eventually results in its instability. In this regard, in this section, the changes in the vertical well diameter, the mean stress, the volumetric and shear strains around the well, mesh size effect, and the impact of rock heterogeneity are investigated numerically.

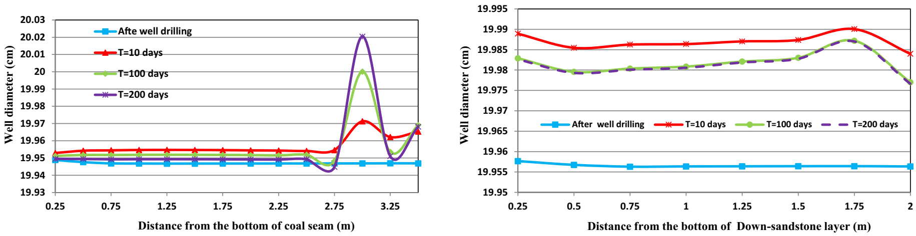
6.1 Vertical well diameter

Generally, the rise in the heat and the syngas, flowing through the vertical well, can increase the well diameter. Figure 16 displays the growth in the well diameter across all layers (alongside the model) at different times of gasification. The results of numerical modeling imply that the largest increase in the well diameter occurs in the coal seam between the boundary of the cemented section and the casing of the well, where the well diameter increases due to discontinuities in the lining system. The notable result, observed across all layers, is that the well diameter reaches its maximum value after 10 days of coal gasification. This is because only the area around the well is affected by the heat during this period, and no temperature alteration occurs in other parts of the other layers. During coal gasification, these areas are affected by a rise in the temperature, and thus may expand. In this case, they exert pressure on the well and cause a negligible decrease in the well diameter.

6.2 Mean stress

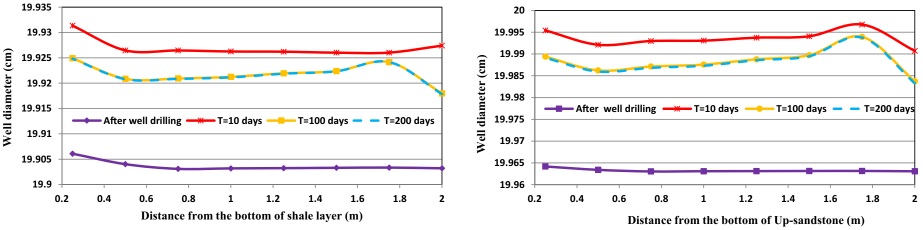
Figure 17 reveals the average stress change across all layers during different coal gasification periods; according to which, the following conclusions can be drawn:

- After 10 days of coal gasification, the average stress in the coal seam drops and then increases to a level higher than that of the well drilling status (Fig. 17a). After 100 and 200 days of coal gasification, the average stress around the well reaches its highest value



a: Coal seam

c: Down-sandstone



b: Shale

d:Up-sandstone

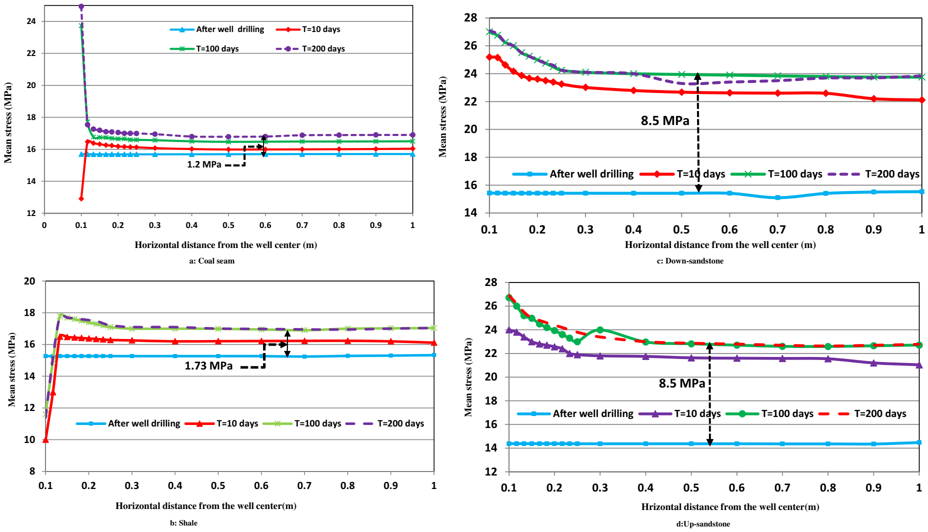
Fig. 16 The effect of gasification time on the vertical well diameter

and then declines gradually, yet it is always higher than its initial values. The average increase in the stress is approximately 1.2 MPa after 200 days of coal gasification, as compared to the post drilling status, which is mainly caused by the thermal stress.

- The average stress around the well in the shale layer (after coal gasification and at all periods) is less than that of the well drilling status. Then, it suddenly soars, while exhibiting a negligible downtrend towards the boundary of the model. The average stress levels are equal in the course of 100 and 200 days of coal gasification, which seem to remain constant at longer durations. Hence, the thermal stress in this layer is 1.73 MPa (Fig. 17b).
- At the upper and lower sandstone layers, the average stress level (after coal gasification) is higher as compared with its level after well drilling (it has the highest level) and then declines while moving to the border of the model (Fig. 17c, d). Its level rises with an increase in the gasification time and then becomes constant at longer gasification times. For this reason, after 100 and 200 days of coal gasification, the curves are similar and no change is observed. An important point is that the greatest change in the average stress belongs to the lower and upper sandstone layers, since the thermal conductivity of these layers is the highest when compared with the layers of coal and shale. However, all parts of this coal seam are under the influence of thermal stress, produced by the coal gasification. As the thermal conductivity of the shale layer is also higher than that of the coal seam, the thermal stress in this layer is greater than that of the coal seam. The level of thermal stress in the upper and lower sandstone layers is approximately 8.5 MPa after 200 days of coal gasification.

6.3 Volumetric and shear strains

Almost all rocks undergo volumetric strain with an increase in the temperature. The numerical modeling results suggest that a rise in the time of gasification causes an increase in the volumetric strain, so after 200 days of coal gasification, the level of shear strain reaches its



a: Coal seam

c: Down-sandstone

b: Shale

d:Up-sandstone

Fig. 17 The effect of gasification time on the mean stress around the well

maximum value in the coal seam (Fig. 18). In general, when the time of gasification extends, the minimum volumetric strain belongs to that part of the well where the steel casings are located. The increase in the volumetric strain after coal gasification is caused by the heat which is 0.00113 at the coal seam. The extent of shear strain around the well at the coal seam increases with a rise in the time of gasification, which is the lowest around the steel casing.

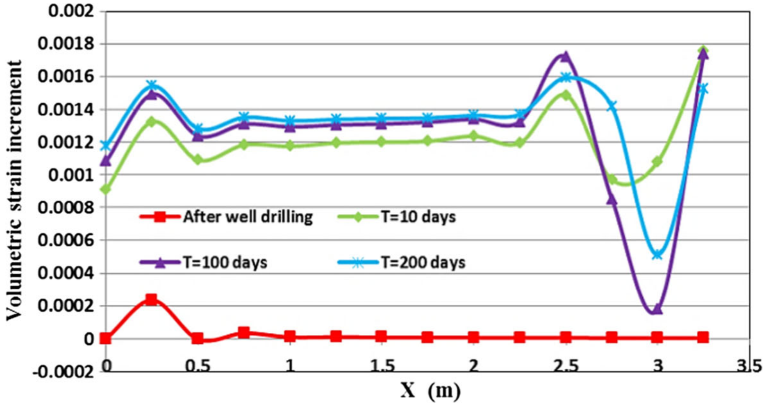
In the shale layer, much of the volumetric strain occurs after 10 days of coal gasification, when the other parts of this layer do not expand and thus do not push the wall. However, over time, the heat is transferred to these areas, leading to the expansion of layers, and exercises pressure around the well. This, in turn, prevents an increase in its volumetric strain. However, these volumetric strains are so low which are negligible (Fig. 19).

Overall, an increase in the time of gasification brings about a rise in the volumetric strains at the three layers of upper sandstone, lower sandstone, and shale, when compared with the case after vertical well drilling state. After 100 and 200 days of coal gasification, the volumetric strains in the three layers are equal. The volumetric strains around the vertical well in the lower and upper sandstone layers and in the shale layer after 200 days coal gasification are 0.0045, 0.0045, and 0.0021, respectively. Since both sandstone layers have a thermal conductivity, being greater than that of the other layers (shale and coal seam), they experienced the highest increase in the volumetric strain (Figs. 20 and 21).

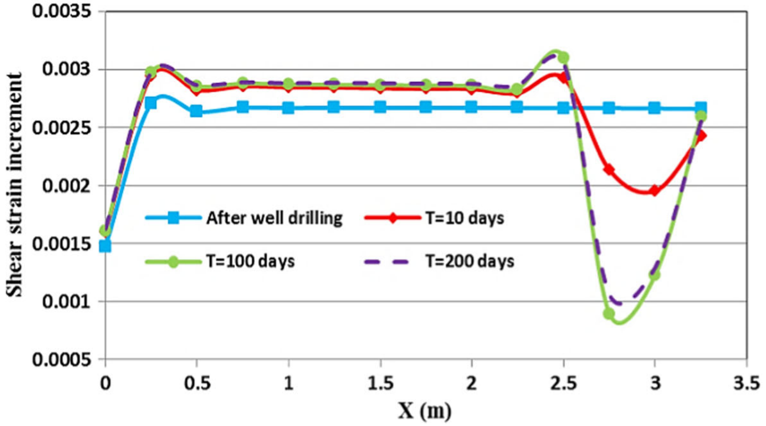
Generally, the shear strains, in the upper and lower sandstone layers, increase with a rise in the time of gasification. Then, after 100 and 200 days of coal gasification, they reach their highest level and become equal.

6.4 Mesh size effect

In numerical simulations, the mesh size has a great impact on the accuracy of the result. In order to obtain the most accurate plastic zone area, different mesh sizes have been used in the modeling of each layer. Therefore, the down-sandstone layer was selected to study the effect of mesh size on the



A: volumetric strain



B: Shear strain

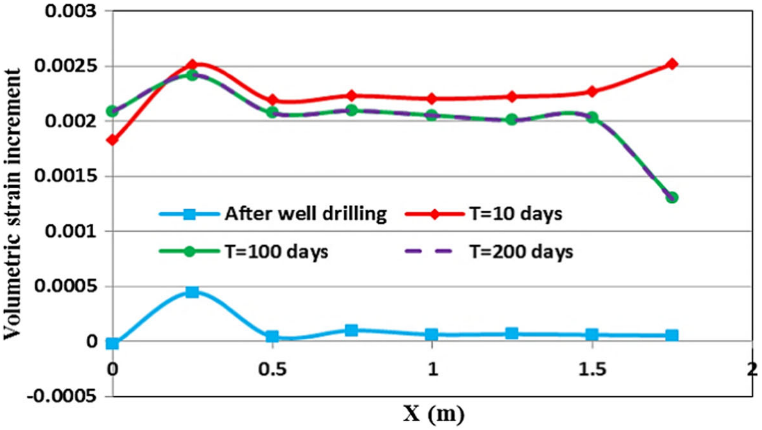
Fig. 18 The effect of gasification time on volumetric and shear strain in coal seam

numerical results. The radcylinder elements were used for the model development around the vertical well with a size of 0.017 m. Accordingly, in this research, the size of mesh should have been reduced to a range from 0.1 to 0.0125 m. In order to calculate the changes in the plastic zone areas around the well, a drilling mud pressure of 40 MPa was considered. One important point to consider is that if the extent of plastic area calculated for a zone is more than half of it, the whole zone is considered to behave plastically, and if this value is less than half of it, the zone remains elastic (Itasca 2012). The results of mesh dependency are presented in Table 3.

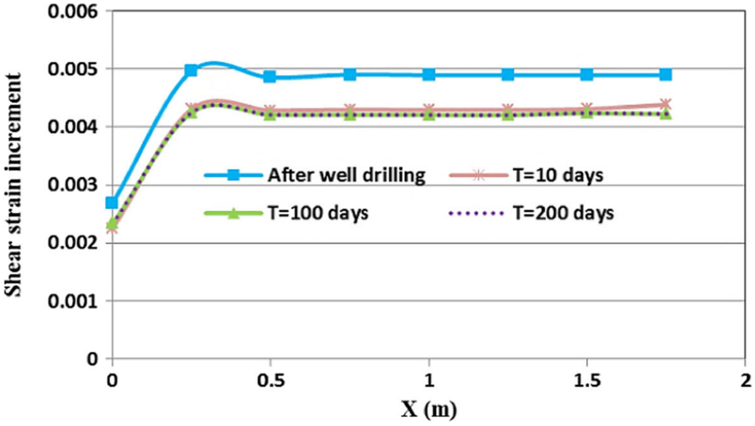
According to Table 3, the value of NYZA parameter with high mesh sizes around the vertical well is unrealistic, and when the mesh size reaches 0.017 m, the NYZA value is not different from that of the smaller mesh size (0.0125 and 0.01 m). In other words, it is at the mesh size of 0.017 m when the NYZA values converge to 1.244866.

6.5 The effect of rock heterogeneity

In order to consider the rock as heterogeneous, the effect of permeability and porosity of down-sandstone layer on the vertical well stability was studied for after 10, 100, and 200 days of coal



A: volumetric strain



B: Shear strain

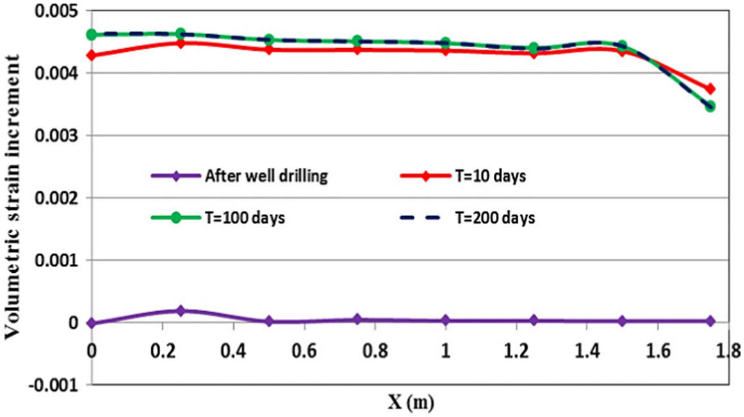
Fig. 19 The effect of gasification time on the volumetric and shear strains in shale layer

gasification. The geomechanical properties of the sandstone and syngas are presented in Table 4. It should be noted that the steel lining in vertical production well has been affected by the syngas temperature and pressure.

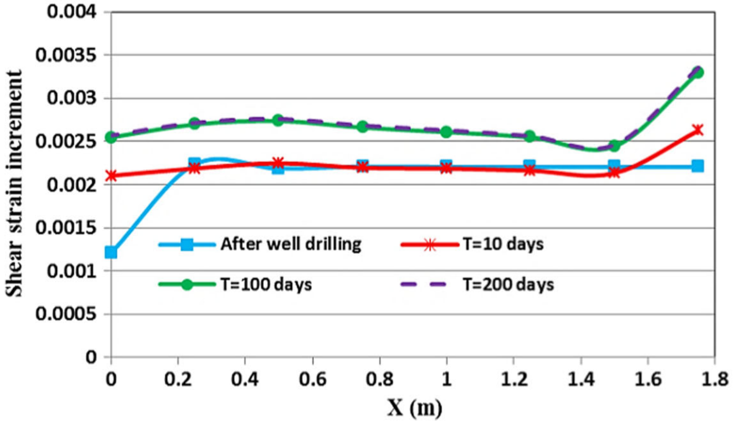
The results of the numerical modeling for the NYZA and well displacement are shown in Table 5 and Fig. 22, respectively. Based on these results, the rock heterogeneity does not significantly affect the NYZA value and displacement around the production well. Therefore, in order to reduce the computational running time, all the materials here have been assumed as isotropic and homogeneous.

7 Discussion

Analytical method can cover only some of the hypotheses of a numerical method. The numerical results have been compared with the analytical results proposed by Bray. In this method, he developed an analytical method for calculating the radius of plastic zone around



A: Volumetric strain



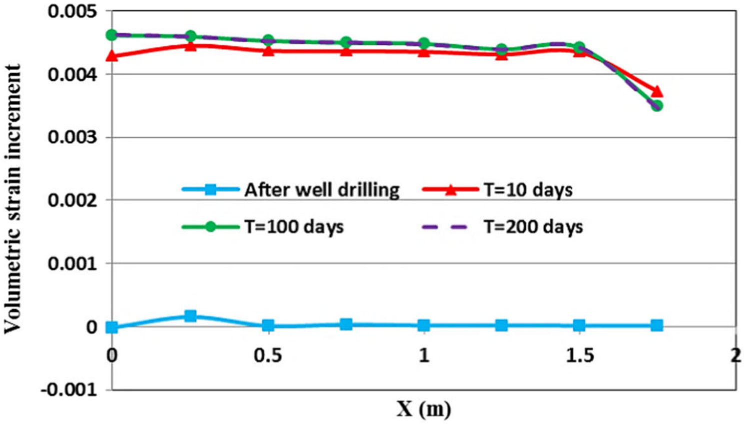
B: Shear strain

Fig. 20 The effect of gasification time on the volumetric and shear strains in down-sandstone layer

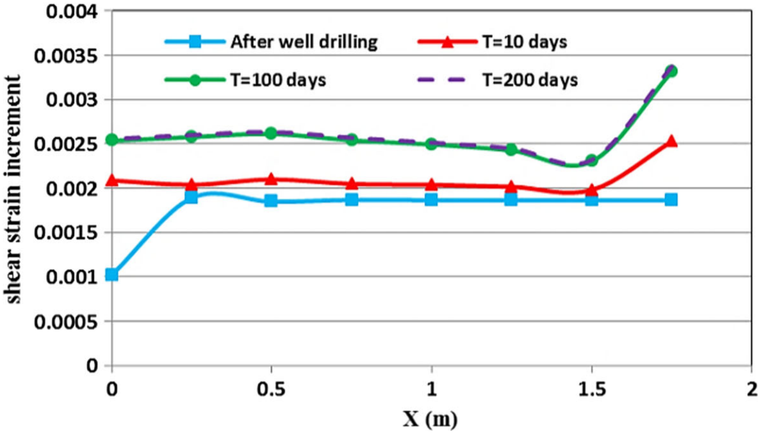
the well. In his method, it was assumed that an area is created around the well that cannot support the stresses as a result of drilling and thus fails according to Mohr-Coulomb criterion (Goodman 1989). To simplify the problem, it is assumed that the distribution of stress occurs in the form of axial symmetry. This model assumes that the angle δ is generated in the radial direction between the fractures in the plastic zone. Bray presented the following equations for plastic zone radius (R) around the well (Goodman 1989):

$$R = a\left[\frac{2P - q_{\mathrm{u}} + \left[1 + \tan^{2}\left(\frac{\pi}{4} + \frac{\varphi}{2}\right).S_{\mathrm{j}}.\cot\varphi_{\mathrm{j}}\right]}{\left[1 + \tan^{2}\left(\frac{\pi}{4} + \frac{\varphi}{2}\right).\left(P_{\mathrm{i}} + S_{\mathrm{j}}.\cot\varphi_{\mathrm{j}}\right)\right]}\right]^{\frac{1}{Q}} \tag{6}$$

$$Q = \frac{\tan\delta}{\tan\left(\delta - \varphi_{\mathrm{j}}\right)} - 1 \tag{7}$$



A: volumetric strain



B: Shear strain

Fig. 21 The effect of gasification time on the volumetric and shear strains in up-sandstone layer

where P_i indicates the hydrostatic pressure inside the well (hydrostatic pressure caused by the mud weight in Pascal), q_u denotes the uniaxial compressive strength (in Pa), and P represents the in situ stress ($P = \sigma_\mathrm{v}$) (in Pa). The parameter a is the well radius (in m), φ is the internal

Table 3 The effect of mesh size on NYZA value for 1 m of down-sandstone layers (at a mud pressure of 40 MPa)

Mesh size (m)	Plastic zone volume (m^3)	NYZA value
0.1	0.062305	1.983254
0.0625	0.061107	1.945103
0.05	0.054495	1.734644
0.025	0.040404	1.286125
0.017	*0.039109*	*1.244866*
0.0125	0.039108	1.244845
0.01	0.039109	1.244866

Table 4 The geomechanical properties of the sandstone and syngas

Properties	Down-sandstone	Syngas
Porosity (%)	1	–
Permeability (10^{-13} m^2/Pa s)	10	–
Syngas bulk modulus (kPa)	–	100
Syngas density (kg/m^3)	–	0.656

friction angle (in degrees), δ is equal to $(\pi/4)+(\varphi/2)$, and φ_j and S_j are the internal friction angle (in degrees) and cohesion (in Pa) in the rock fractures, respectively.

In this case, the analytical method cannot capture the effect of steel lining and gasification of coal (the effect of temperature) on the stability of a vertical well. However, this method can be used to calculate the mud pressure during the drilling operation of a vertical well. Using the criterion stated in Eq. 6 and applying the research parameters, this study examines the stability of the vertical well at coal and shale layers during the drilling stage (the mud pressures are estimated to be 5.4 and 2.6 MPa, respectively). In other words, at this mud pressure, the NYZA parameter value is less than one, which is close to the values obtained by the numerical method (before applying temperature). At the mud pressure of 9 MPa, the NYZA values for all layers are equal to zero. This result is shown in Fig. 23 which suggests that the results of the numerical model have satisfactory and reasonable accuracy. The disadvantage of this approach is that the stress and strain, caused by the temperature rise, are not taken into account. In addition, it cannot be used for sandstone layer which has a high uniaxial compressive strength, as the term under the radical in Eq. 6 becomes negative. Therefore, a numerical method is needed for the thermomechanical analysis of UCG wells.

8 Conclusions

Several environmental and economic benefits can be realized by UGC process, as compared with the conventional mining methods, surface gasification process, and even coal-bed methane drainage method. This process eliminated the operations of coal mining and ash with a minimum greenhouse gas emission, lowered the water consumption, and did not need the presence of coal miners underground (which is of importance, concerning human safety). UCG also had surface and subsurface environmental impacts in terms of groundwater pollution and surface subsidence. In the UCG method, there was no direct access to the underground and the coal seam, which required a high degree of knowledge (including geology, rock mechanics, mining engineering, chemistry, and fluid mechanics) for optimal control of this process. In spite of all the recent attempts made by the researchers in this field, there has not been any complete and successful application of UCG method in the world so far. These scientific gaps indicated that some more research should be devoted to this important

Table 5 The effect of rock heterogeneity on NYZA at a mud pressure of 9 MPa

Gasification time (day)	NYZA value (rock homogeneity)	NYZA value (rock heterogeneity)
10	0	0.08
100	0	0.0923
200	0.04	0.095

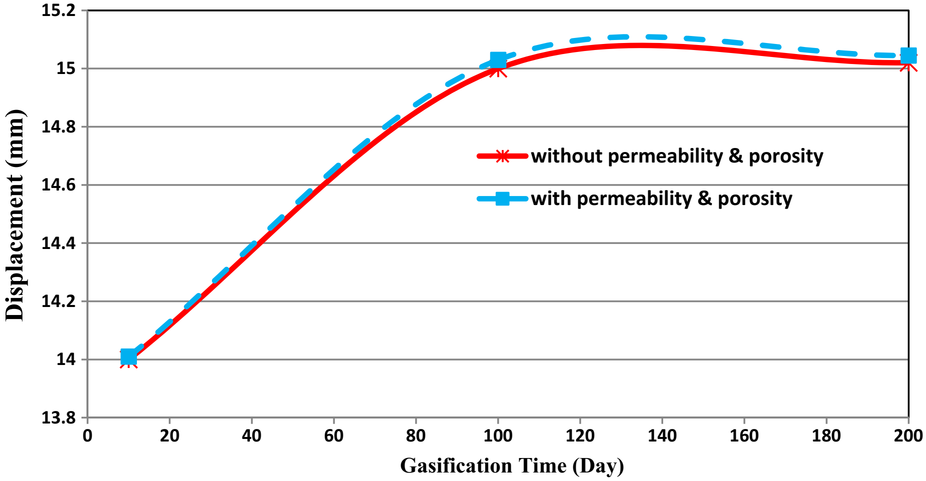


Fig. 22 The effect of rock heterogeneity on the vertical well displacement

issue. One of the most important concerns that had to be considered in a UCG operation was the vertical well stability. Gas leakage, resulting from the well instability, could result in surface water pollution and acidification, global warming, air pollution, and an increase in the average temperature of the region.

In this study, the mitigation strategies for the environmental aspect of a UCG vertical well were numerically investigated, considering breakout and fractures while drilling. For this purpose, the stability of a vertical well (production well) was analyzed in the UCG method. The UCG wells were under the influence of high thermal stresses from coal gasification which may influence their stability and environmental safety. To provide a stable and safe working and global environment, the numerical modeling analysis was performed, suggesting that the vertical well (at all layers) in the studied area should be drilled at a constant mud pressure of 9 MPa. The cemented part of the well and its casing can withstand pressures of 84 and 380 MPa after 200 days of coal gasification, respectively, suggesting relatively proper design of the lining system. The vertical well's diameter, the mean stress, as well as the volumetric and shear strains

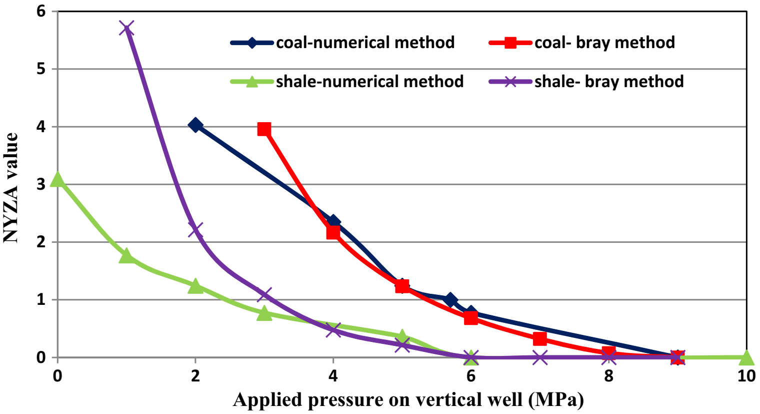


Fig. 23 The NYZA value for coal and shale layers by analytical and numerical methods

around the vertical well all increase (in all layers) by prolonging the duration of coal gasification. However, the extent of increase in these parameters depends on the level of thermal conductivity of the surrounding rock and other supporting materials. According to the thermomechanical numerical modeling and the sensitivity analysis, carried out in this work, it was found that the vertical well was stable during this typical UCG operation. Therefore, the potential of gas leakage, ground surface subsidence, ground water pollution, and acidification is zero. This result suggests the accuracy of the vertical well lining design in the UCG process. The NYZA value, volumetric and shear strain, mean stresses, and displacement must be considered in the stability analysis of UCG wells to reduce the potential of greenhouse gas emission. By using the methodology (thermomechanical modeling) presented in this study, the potential of greenhouse gas emissions and water pollutions (resulting from the instability of the vertical well) decreases. Therefore, this modeling strategy may be used as a basis for the stability analysis of the UCG wells during and prior to commencing any UCG operation. Eventually, a properly designed vertical well can eliminate the gas leakage into the environment.

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