The effect of rock permeability value on groundwater influx in underground coal gasification reactor

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Abstract. Rock permeability value is one of the most significant rock’s physical properties that affect groundwater influx processes in underground coal gasification (UCG). This value of rock permeability (K), namely the vertical permeability of flanking rocks (Kv) and horizontal permeability of coal (Kh). The purpose of this study was to determine the extent of the influence of the value of rock permeability on the potential of groundwater influx. The effect of rock permeability on groundwater influx into the UCG gasification reactor cavity in the presence of thermal loads and mineral composition content is large and significant to consider. Based on the resistance to heat loads, the type of sandstone lithology is relatively more resistant compared to siltstone and claystone lithology.

1. Introduction

Underground coal gasification (UCG) is a promising clean coal technology where in this technology converts transforming coal that cannot be mined into syngas in situ. Real-time monitoring of hydrological and geological conditions such as groundwater influx, cavity growth, and their interactions with the cover is a dominant factor in the UCG process [1]. The permeability of coal during the UCG process depends on the ability of the gas to pass through the coal seam. Coal permeability is influenced by many natural factors, such as coal maceral, fracture, coal porosity, and stress by surrounding rocks [2]. The absolute permeability of coal can be measured when the fluid in the pores is a single liquid phase. If more than one fluid phase flows through the coal pore structure, characterization is needed to determine the relative permeability of each phase [3]. The entry of excess groundwater into the gasifier reactor can completely disrupt the process or the intensity of the gasification in the process becomes low. The entry of groundwater can occur both from the coal layer itself and from the upper and lower aquifer layers that line the coal layer [4]. The hydraulic conductivity is progressively increasing with the increase of injection water pressure [5]. Several studies have been conducted to investigate the thermal effects on the hydraulic conductivity of saturated Boom Clay. These studies generally suggest that the hydraulic conductivity increases with increasing temperature [6].

Permeability value (K) is a value indicating a rock’s capacity to flow water (fluid). K value has an important role to play in controlling the groundwater influx to the UCG gasifier reactor. The K value can be obtained from field test results, including the pumping test, packer test, slug test and laboratory (falling head permeameter). In this study, the permeability value was obtained using the
falling head approach (constant head triaxial cell test) from the results of the laboratory test, which is generally considered more suitable for soils with high permeability [7].

The spread of permeability values can be used as a guide in choosing the right location for UCG applications and knowing the potential for groundwater influx entering the UCG gasifier cavity. Groundwater influx into the cavity of the subsurface coal gasification reactor comes from; upper flanking rock layers (Kv1), coal seams (Kb), lower flanking rock layers (Kv2). To support the optimization of the subsurface coal gasification process, it is necessary to research the characteristics of the permeability value of the flanking rock layers and the coal itself. The main factors affecting coal permeability are effective stress, swelling, shrinkage, deformation, and gas slip. After a long period of gas production, coal can experience a phenomenon where permeability increases with increasing effective pressure [8].

This research has a hypothesis about the thermal effect on rock deformation that causes fundamental changes, including; discoloration, mass density, cracks, microstructure changes, and mineral conditions, so it is also related to porosity and permeability value of rocks before and subsequently given thermal loads. Other hypotheses related to the entry of groundwater are also about the distribution of the face stock and face cleats. Permeability has a large sensitivity to the condition of the fracture aperture and the greater the aperture will cause an increase in permeability is greater. Coal has a strong heterogeneity after a long sedimentation process and has a wide permeability variation, especially in the vertical and parallel direction of the coal seam [9], as well as information on hydrostatics and operations that occur during the coal gasification process below the surface underway. The presence of groundwater can affect coal gasification emissions and heat values during the gasification process and prove the cause of ground air pollution.

1.1. Geological and hydrogeological setting

UCG can not separate the process considerations from the environment because they are closely related. Unlike conventional surface carbon gasification facilities in which the reactor environment is fully engineered and controlled, in situ gasification performance is significantly impacted by the geological, and hydrogeological setting in which it is operated [10]. The regional geological condition of the study area can be seen on the 1: 250,000 Scale Systemized Indonesia Map of the Geology Research and Development Center. The research area is included in the coverage of the Indonesian Systemized Geological Map No. 913 Sarolangun Sheets [11] and Systematic Geological Maps No.1013 Palembang Sheets [12]. Research sites in the Muara Enim Formation with depths of > 250 m (Figure 1).

![Figure 1. Regional Geological Map (Modification from [11,12]).](image-url)
Regionally, the condition of coal in the Rear Arc Basin shows the alternation between bright lithotype and dull lithotype, which is caused by the influence of fluctuating surface water changes. Dry conditions cause dull black lithotypes while wet conditions cause bright black lithotypes. In addition, brightly colored coal is associated with a large amount of vitrinite mineral content, whereas coal with a more dull color is associated with high inertinite content and mineral content [13,14] (Figure 2).

![Figure 2. Map of Geology and Stratigraphy, South Sumatera (Modification from [12]).](image)

2. Materials and Methods

2.1. Field Sampling
The rock permeability testing was carried out at 20 UCG drill points (UCG-01 – UCG-24) (Figure 3). This test is carried out with treatment without thermal load and with thermal load at temperature variations of 100 – 600 °C. The type of lithology around the target coal is sandstone, claystone, and siltstone. UCG-15 has a fairly thick coal seam of 5 to 9 meters. Coal with a thickness of 9 meters is targeted in the UCG implementation plan at a depth of 323,5 – 331,5 meters with a slope of 20 - 70° and spreads in a northwest-southeast direction. The target coal is flanked by claystone with a thickness of 19 meters above the coal and claystone with a thickness of 7 meters below the coal.

Drilling results show that there are 2 main aquifers around the study area. Aquifer 1 is a coal-inserted sandstone facies with a thickness of 127 meters located at a depth of 14 - 144 meters and aquifer 2 are claystone facies of sandstones and coal with a thickness of 32 meters at a depth of 268 – 300 meters.

The methodology in this study uses a comprehensive approach involving field research, laboratory, and modeling. Based on field observations and data collection related to subsurface conditions by observing topography, drilling, logging, core sampling, groundwater level measurements, pumping tests, water sampling.
2.2. Groundwater Influx

Groundwater influx into the cavity of the subsurface coal gasification reactor (UCG) mainly comes from; upper coal seam (Kv1), coal seam (Kh), lower coal seam (Kv2). The amount of groundwater flow that enters the cavity of the subsurface gasification reactor (UCG) is mainly influenced by the value of the rock permeability. The research is more focused on aquifer 1 in the coal-inserted sandstone facies. Aquifer 1 is dominated by sandstone lithology but there are also inserts of siltstone, claystone, and coal.
Based on the modeling of the aquifer layers around the location, it can be determined the number of aquifer layers, the direction, and type of distribution, the thickness of the aquifer, and the determination of primary and secondary aquifer layers (Figure 4).

The limitations used are:

a. Geological Settings; coal characteristics, characteristics of flanking rocks (Kv1 & Kv2, parameters of physical, mechanical, and chemical properties, system aquifers, coal permeability (Kh), the geometry of coal seams and flanking rocks, characteristic characteristics of cleats (face cleats & butt cleats) and porosity.

b. Fluid; Viscosity of fluids and types of fluids.

c. Hydrostatic pressure (Ph) and operational pressure (Po) and thermal load during the coal gasification process.

2.3. The Effect of Thermal Load on Permeability Value. The amount of groundwater entering the gasifier is determined not only by the natural conditions of the coal deposit but also by other specific factors that arise during coal gasification: high temperatures in the gasifier, excess air pressure and injected gas, and deformation of roof rocks above the cavity gasification. High temperatures can change the physical and mechanical properties of rocks on the coal seam floor and roof. While clays are naturally impermeable at ambient temperatures, during gasification high temperatures can cause clays to dry and crack, and thus become permeable to water [17].

2.3.1. Cleat Properties. In coals, including lignites, cleats (fractures, joints) are discontinuities. They are important in mining and UCG activities because of their gas and water permeability in hard coal and, above all, because of their water permeability in lignites. Cleats are natural opening-mode fractures, which are almost perpendicular to the coal seam bottom and roof. They typically occur in two sets which are called “face” and “butt” cleats in present-day terminology. These two cleat sets are nearly perpendicular to one another and the beds. Cleats are characterized by geometrical properties that include orientation, spacing, aperture, height, length, and connectedness. The spacing and aperture of the cleat do not depend on the thickness of the lignite, but the spacing of the cleat increases with an increase in mineral-matter and xylite content, whereas the aperture increases with the decrease in content [18]. The butt cleats and face cleats interlace with each other and form a complex fracture network in cross sections of coal block. It was assumed that all the fractures in the processed image were approximate rectangles [19].

2.3.2. Permeability (K). Permeability is the property of rocks that is an indication of the ability of fluids (gas or liquid) to flow through rocks. High permeability will allow fluids to move rapidly through rocks [19]. Permeability testing is performed using a fall head permeameter by taking soil samples carried out following ASTM D5084 (American Standards For Testing Material) [20]. This test can be determined by first looking at the face water and height after changing the face water [3].

Permeability and hydraulic permeability, both of which indicate the value for passing fluids on an object. The difference between the two coefficients is that the hydraulic conductivity depends on the media and the fluid (the viscosity and density of the fluid which depends on pressure and temperature), while the permeability only depends on the physical properties of the rock. This permeability can be stated by Darcy's Law in the following equation [14,17]:

\[ V = \frac{k \Delta H}{\mu \Delta L} \]  

Notation, \( V \), Darcian velocity (L/T); \( k \), intrinsic permeability (L²); \( \rho \), density (M/L³); \( g \), Acceleration of gravity (L/T²); \( \mu \), Dynamic viscosity (M/LT); \( \Delta H \), Pressure height difference (L); \( \Delta L \), Flow distance (L); Rock permeability is influenced by several factors; rock texture, shape and size, geological structure, porosity, viscosity, gravity, sedimentation and thermal.
3. Results

The permeability coefficient value is obtained from the falling head permeameter test results. In principle, this test is done by calculating how long it takes for a rock to be able to escape the water. The results of the falling head permeameter test (ASTM D5084) will get the permeability value. Permeability values can be calculated by the following equation [14,17]:

\[
k = \frac{2.30 a L}{At} \times \log \frac{h_1}{h_2}
\]  

(2)

Notation \( k \), permeability (cm/sec); \( L \), Sample height (cm) = 6.112 cm; \( a \), The surface area of the sample (cm\(^2\)) = \( \frac{1}{4} \pi D^2 = \frac{1}{4} \pi \times (6.061)^2 = 28.83 \) cm\(^2\); \( t \), Time of water level decline (s or seconds) = 46 seconds; \( h_1 \), Initial water level (cm) = 117 cm; \( H_2 \), final water level (cm) = 90 cm; \( a \), \( (Q_{out}/h_1-h_2) \), \( a \) = Burette area = 0.2595 cm\(^2\). Average permeability coefficient (falling head permeameter), \( \Delta k = \frac{(3.134E-04+3.067E-04+2.772E-04)}{3} = 3.991E-04 \) cm/sec. The permeability value can be divided into five classes, as in Table 1.

| \( k \) (cm/s) | Permeability class |
|----------------|--------------------|
| > 10\(^{-1}\)  | High Permeability  |
| 10\(^{-1}\) – 10\(^{-3}\) | Medium Permeability |
| 10\(^{-3}\) – 10\(^{-5}\) | Low Permeability |
| 10\(^{-5}\) – 10\(^{-7}\) | Very Low Permeability |
| < 10\(^{-7}\) | Impervious |

UCG-15, permeability values range from 1.24E-02 cm/s - 4.06E-08 cm/s, where the highest permeability coefficient value is in the sandstones and the lowest permeability coefficient is in the form of claystone. Permeability testing is carried out on sandstone, siltstone, and claystone. In general, aquifers are divided into two parts, namely at a depth of 0 ± 50 m that can escape water but is very low with low permeability aquifer characteristics while at 50 ± 150 m aquifers are very difficult to pass water with very low permeability aquifer characteristics. The types of aquifers are aquifers, aquitards, and aquiclude, with aquifers and aquitards dominating.

3.1. Permeability Value

Thermal is one of the key factors in determining sustainable production and stability in the process of underground coal gasification [22]. Example heating is done by the method of try and error, wherein the heating process the maximum strength of each rock that survives in heating a certain temperature is sought. This is done to determine the extent of the ability of rocks to survive in a state of heat. Tables 2, 3 and 4 [15].

The lithology of sandstone when heated at a temperature of 100 - 500°C, the permeability value has decreased, most of all the sandstone is more compact and has strengthened. However, at a temperature of 600°C, sandstones have experienced cracks and the permeability value has increased so that the strength limit of sandstones is at a temperature of 500°C (Table 2).

Siltstone lithology when heated at a temperature of 100 - 400°C, the permeability value has decreased, most of all the siltstone is more compact and strengthened. However, at a temperature of 600°C, the siltstone has experienced cracking and the permeability value has increased thus the strength limit of the siltstone is at a temperature of 500°C (Table 3).

The lithology of claystone when heated at a temperature of 100°C, the sample has experienced cracks and does not meet the requirements for falling head permeameter testing. However, samples from UCG-07 claystone can be tested at 200°C and the permeability value has decreased so that the claystone is more compact and strengthened (Table 4).
Table 2. Thermal Load Permeability Value of Sandstone Sample

| No | Drill ID | Code | Thermal (°C) | Time (Hour) | K (Natural) | K (Thermal) | Note |
|----|----------|------|--------------|-------------|-------------|-------------|------|
| 1  | UCG-15   | W-18 | 100          | 4           | 1.24E-02    | 2.37E-06    | K value decreases. General mineral composition Quartz, Siderite, Anortite, Montmorillonite, Kaolinite, Orthoclase, Ilite, Pyrite |
| 2  | UCG-15   | W-18 | 200          | 4           | 1.24E-02    | 2.79E-03    | K value decreases. General mineral composition Quartz, Siderite, Anortite, Montmorillonite, Kaolinite, Orthoclase, Ilite, Pyrite |
| 3  | UCG-11   | W-11 | 300          | 3           | 1.15E-07    | 1.79E-04    | General mineral composition Quartz, Siderite, Anortite, Montmorillonite, Kaolinite, Orthoclase, Ilite, Pyrite |
| 4  | UCG-15   | W-7  | 300          | 4           | 1.98E-03    | 1.70E-05    | K value decreases. General mineral composition Quartz, Siderite, Anortite, Montmorillonite, Kaolinite, Orthoclase, Ilite, Pyrite |
| 5  | UCG-11   | W-3  | 300          | 3           | 3.93E-04    | 4.06E-04    | K value, almost the same. General mineral composition Quartz, Siderite, Anortite, Montmorillonite, Kaolinite, Orthoclase, Ilite, Pyrite |
| 6  | UCG-15   | W-3  | 400          | 4           | 2.38E-03    | 7.50E-04    | K value decreases. General mineral composition Quartz, Siderite, Anortite, Montmorillonite, Kaolinite, Orthoclase, Ilite |
| 7  | UCG-15   | W-5  | 500          | 4           | 1.71E-03    | 8.94E-04    | K value decreases. General mineral composition Quartz, Siderite, Anortite, Montmorillonite, Kaolinite, Orthoclase, Ilite, Pyrite |
| 8  | UCG-15   | W-4  | 600          | 4           | 7.57E-05    | 3.31E-04    | K value, increases. General mineral composition Quartz, Siderite, Anortite, Montmorillonite, Kaolinite, Orthoclase, Ilite, Pyrite |

Table 3. Thermal Load Permeability Value of Siltstone Sample

| No | Drill ID | Code | Thermal (°C) | Time (Hour) | K (Natural) | K (Thermal) | Note |
|----|----------|------|--------------|-------------|-------------|-------------|------|
| 1  | UCG-15   | W-24 | 100          | 4           | 6.18E-08    | 4.02E-08    | K value decreases. General mineral composition Quartz, Kaolinite, Ilit |
| 2  | UCG-15   | W-9  | 200          | 4           | 1.11E-03    | 3.95E-04    | K value decreases. General mineral composition Quartz, Kaolinite, Ilit |
| 3  | UCG-15   | W-11 | 300          | 4           | 4.01E-06    | 2.01E-06    | K value decreases. General mineral composition Quartz, Kaolinite, Ilit |
| 4  | UCG-15   | W-9  | 400          | 4           | 1.11E-03    | 8.41E-06    | K value decreases. General mineral composition Quartz, Kaolinite, Ilit |
| 5  | UCG-15   | W-21 | 500          | 4           | 1.30E-06    | -           | General mineral composition Quartz, Kaolinite, Ilit |
| 6  | UCG-15   | W-21 | 600          | 4           | 1.30E-06    | 1.85E-05    | K value, increases. General mineral composition Quartz, Kaolinite, Ilit |
Table 4. Thermal Load Permeability Value of Claystone Sample

| No | Drill ID | Code | Thermal (°C) | Time (Hour) | K (Natural) | K (Thermal) | Note |
|----|----------|------|--------------|-------------|-------------|-------------|------|
| 1  | UCG-7    | W-6  | 200          | 4           | 1.20E-05    | 1.09E-06    | K value, decreases. General mineral composition, Quartz, Siderite, Kaolinite, Elite. |
| 2  | UCG-12   | W-11 | 1100         | 8           | 4.85E-05    | -           | K value, sample rupture. Mineral composition; Quartz, Elite, Siderite, Kaolinite. Mineragraph of minerals, pyrite, isotropic, very fine single grain. |

3.2. Permeability Value After heat

The permeability value changes after the rocks undergo a heating process. The data can be seen in Table 5 [15].

Table 5. Permeability Value After heat

| No  | Drill ID | Lithology | From | To  | Thermal (°C) | Time (Hour) | K (Natural) | K (Thermal) | Note   |
|-----|----------|-----------|------|-----|--------------|-------------|-------------|-------------|--------|
| 1   | UCG-15/ W18 | Sandstone | 77.52 | 78.06 | 100          | 4           | 1.24E-02    | 2.377E-06  | Decreased |
| 2   | UCG-15/ W18 | Sandstone | 77.52 | 78.06 | 200          | 4           | 1.24E-02    | 2.790E-03  | Decreased |
| 3   | UCG-15/ W7  | Sandstone | 51.3  | 51.5 | 300          | 4           | 1.975E-03   | 1.709E-05  | Decreased |
| 4   | UCG-15/ W3  | Sandstone | 42.75 | 42.9 | 400          | 4           | 2.383E-03   | 7.502E-04  | Decreased |
| 5   | UCG-15/ W5  | Sandstone | 48.62 | 48.8 | 500          | 4           | 1.706E-03   | 8.942E-04  | Decreased |
| 6   | UCG-15/ W4  | Sandstone | 48.1  | 48.23| 600          | 4           | 7.574E-05   | 3.305E-04  | Increased |
| 7   | UCG-15/ W24 | Siltstone | 149.3 | 149.92| 100          | 4           | 6.179E-08   | 4.024E-08  | Decreased |
| 8   | UCG-15/ W9  | Siltstone | 53.65 | 53.8 | 200          | 4           | 1.108E-03   | 3.950E-04  | Decreased |
| 9   | UCG-15/ W11 | Siltstone | 56.1  | 56.25| 300          | 4           | 4.013E-06   | 2.015E-06  | Decreased |
| 10  | UCG-15/ W9  | Siltstone | 53.65 | 53.8 | 400          | 4           | 1.108E-03   | 8.409E-06  | Decreased |
| 11  | UCG-15/ W21 | Siltstone | 128.9 | 129.1| 600          | 4           | 1.302E-06   | 1.853E-05  | Increased |
| 12  | UCG-07/ W6  | Claystone | 51    | 51.58| 200          | 4           | 1.203E-05   | 1.097E-06  | Decreased |

3.3. Groundwater Flow Discharge Calculation (Q)

Calculation of groundwater flow discharge into the UCG gasification cavity is done before and after being given a thermal load with temperatures between 100 °C - 600 °C, both in the overburden rock layer (Kv1), coal layer (Kh), and underburden rock layer (Kv2) around the combustion cavity UCG. Calculation of groundwater flows discharge by considering changes in physical properties, minerals, and microstructure of rocks to increase or decrease on permeability value.

3.4. Calculation of Flow Discharge (Q) - Natural Temperature

Based on the UCG-15 flanking rocks including stressed aquifers, the following equations are used for calculations [14, 21]:

\[ Q = Kxb \left( \frac{h_a - h_b}{L} \right) \times w \]

(3)

Notation, Q, Flowrate (m³/sec); K, hydraulic conductivity, cm/s is changed to m/s; b, Thickness; hA - hB, the difference in pressure height = 261.5 m - 189.03 m = 72.47 m; L, Flow distance = 283.6 m; w, Aquifer width = 1060 m (Figure 5).

\[ Q_{v1} = 2.678E-6 \text{ m/s} \times 18.42 \text{ m} \times \left( \frac{72.47 \text{ m}}{283.6 \text{ m}} \right) \times 1060 \text{ m} = 1.335E-2 \text{ m}^3/\text{s} \]
For normal temperature, the groundwater flow rate in the overburden sandstones ($Q_{v1.1}$) is $1.335 \times 10^{-2}$ m$^3$/s and the claystone layer ($Q_{v1.2}$) is $4.688 \times 10^{-5}$ m$^3$/s. In the coal seam, the target flowrate ($Q_h$) is $1.828 \times 10^{-2}$ m$^3$/s. For groundwater flow in the underburden claystone ($Q_{v2.1}$) which enters the UCG gasification cavity is $1.485 \times 10^{-5}$ m$^3$/s and in the siltstone ($Q_{v2.2}$) layer is $7.147 \times 10^{-7}$ m$^3$/s and in the sandstone layer ($Q_{v2.3}$) is $1.327 \times 10^{-3}$ m$^3$/s. The overall flow rate of groundwater influx to the combustion cavity is $3.306 \times 10^{-2}$ m$^3$/s (Table 6).

For a temperature of 100°C, the overburden sandstone layer contained groundwater influx is $2.669 \times 10^{-6}$ m$^3$/s. For underburden siltstone is $4.654 \times 10^{-7}$ m$^3$/s and sandstones is $8.936 \times 10^{-4}$ m$^3$/s. The total flow of groundwater that enters the gasification cavity is $8.968 \times 10^{-4}$ m$^3$/s (Table 6 and 7).

**Figure 5.** Cross Section UCG-07 – UCG-15 (Modification from [12,20]).

3.5. Calculation of Flow Discharge at 100°C and Time 4 hours
Permeability coefficient values are based on the results of testing at each temperature in the same lithology. Based on the UCG-15 flanking mountains, including depressed aquifers, the calculation uses the following equation [8,15]:

$$Q = K \times b \left( \frac{h_A - h_B}{L} \right) \times w$$  \hspace{1cm} (4)

Notation Q, Debit (m$^3$/sec); K, Hydraulic conductivity (Table 7), m / s; b, Thickness; hA - hB, the difference in pressure height = 261.5 m - 189.03 m = 72.47 m; L, Flow distance = 283.6 m; w, Aquifer width = 1060 m:

- $Q_{v1} = 5.349 \times 10^{-10} \ \text{m}^3/\text{s} \times 18.42 \ \text{m} \times \left( \frac{72.47 \ \text{m}}{283.6 \ \text{m}} \right) \times 1060 \ \text{m} = 2.669 \times 10^{-6} \ \text{m}^3/\text{s}$
- $Q_{v2a} = 6.519 \times 10^{-10} \ \text{m}^3/\text{s} \times 2.64 \ \text{m} \times \left( \frac{72.47 \ \text{m}}{283.6 \ \text{m}} \right) \times 1060 \ \text{m} = 4.645 \times 10^{-7} \ \text{m}^3/\text{s}$
- $Q_{v2b} = 1.040 \times 10^{-6} \ \text{m}^3/\text{s} \times 3.17 \ \text{m} \times \left( \frac{72.47 \ \text{m}}{283.6 \ \text{m}} \right) \times 1060 \ \text{m} = 8.968 \times 10^{-4} \ \text{m}^3/\text{s}$

For a temperature of 100°C, the overburden sandstone layer contained groundwater influx is $2.669 \times 10^{-6}$ m$^3$/s. For underburden siltstone is $4.654 \times 10^{-7}$ m$^3$/s and sandstones is $8.936 \times 10^{-4}$ m$^3$/s. The total flow of groundwater that enters the gasification cavity is $8.968 \times 10^{-4}$ m$^3$/s (Table 6 and 7).
### Tabel 6. Flow rate (Q) – Normal Temperature

| Rock Condition | Lithology | K (cm/s) | K (m/s) | K (m/s) | Thick (m) | (h1-h2) | Length (m) | Wide (m) | Flow rate (m³/s) |
|----------------|-----------|----------|---------|---------|-----------|---------|------------|----------|-----------------|
| Overburden (Kv1) | Sandstone | 7.183E-04 | 7.183E-06 | 1.027E-04 | 1.027E-06 | 2.577E-04 | 2.577E-06 | 2.481E-04 | 2.481E-06 | 1.038E-05 | 1.038E-07 |
|                | Claystone | 5.260E-07 | 5.260E-09 | 1.420E-06 | 1.420E-08 | 9.730E-09 | 9.730E-11 | 1.597E-06 | 1.597E-08 |            |            |
| Seam Coal (Kh)  | Coal      | 7.300E-04 | 7.300E-06 | 1.420E-06 | 1.420E-08 | 7.183E-09 | 7.183E-11 | 1.597E-06 | 1.597E-08 |            |            |
| Underburden (Kv2) | Claystone | 6.661E-07 | 6.661E-09 | 1.001E-07 | 1.001E-09 | 2.577E-04 | 2.577E-06 | 2.577E-04 | 2.577E-06 | 1.038E-05 | 1.038E-07 |
|                | Siltstone | 2.429E-07 | 2.429E-09 | 1.420E-06 | 1.420E-08 | 5.349E-09 | 5.349E-11 | 1.597E-06 | 1.597E-08 |            |            |
|                | Sandstone | 3.191E-04 | 3.191E-06 | 1.027E-04 | 1.027E-06 | 1.597E-09 | 1.597E-11 | 3.17E-06  | 3.17E-08  |            |            |
| Total          |           | 1.159E-05 | 3.306E-02 |            |            |          |            |          |                |            |

### Tabel 7. Flow rate (Q) – Temperature 100°C (4 hours)

| Rock Condition | Lithology | K (cm/s) | K (m/s) | K (m/s) | Thick (m) | (h1-h2) | Length (m) | Wide (m) | Flow rate (m³/s) |
|----------------|-----------|----------|---------|---------|-----------|---------|------------|----------|-----------------|
| Overburden (Kv1) | Sandstone | 7.183E-04 | 7.183E-06 | 1.027E-04 | 1.027E-06 | 2.577E-04 | 2.577E-06 | 2.481E-04 | 2.481E-06 | 1.038E-05 | 1.038E-07 |
|                | Claystone | 5.260E-07 | 5.260E-09 | 1.420E-06 | 1.420E-08 | 9.730E-09 | 9.730E-11 | 1.597E-06 | 1.597E-08 |            |            |
| Seam Coal (Kh)  | Coal      | 7.300E-04 | 7.300E-06 | 1.420E-06 | 1.420E-08 | 7.183E-09 | 7.183E-11 | 1.597E-06 | 1.597E-08 |            |            |
| Underburden (Kv2) | Claystone | 6.661E-07 | 6.661E-09 | 1.001E-07 | 1.001E-09 | 2.577E-04 | 2.577E-06 | 2.577E-04 | 2.577E-06 | 1.038E-05 | 1.038E-07 |
|                | Siltstone | 2.429E-07 | 2.429E-09 | 1.420E-06 | 1.420E-08 | 5.349E-09 | 5.349E-11 | 1.597E-06 | 1.597E-08 |            |            |
|                | Sandstone | 3.191E-04 | 3.191E-06 | 1.027E-04 | 1.027E-06 | 1.597E-09 | 1.597E-11 | 3.17E-06  | 3.17E-08  |            |            |
| Total          |           | 1.159E-05 | 3.306E-02 |            |            |          |            |          |                |            |

3.6. Calculation of Flow Discharge at 200°C - 600°C and Time 4 hours

With the same equation, it can be seen the discharge of groundwater flow into the UCG gasification cavity for each lithology in overburden and underburden (Table 8).
In recent decades the permeability of coal and its influencing factors have been studied extensively. Researchers generally believed that, in addition to cleat gap and connectivity, permeability is linked to the effect of effective stress, adsorption, and gas slippage. The permeability of coal generally decreases exponentially with increasing effective stress. The sensitivity of permeability to stress is related to the sample [13]. In underground coal gasification, the immediate roof strata not only undergo displacement and deformation involving continuity of loss but also change their mechanical properties, composite chemical and mineralogical, and aggregate state. This results in a loss of UCG gasifier cavity integrity, increased oxygen supply, and gas losses, and heat loss to surrounding strata [24].

Physical changes in rock condition after thermal load are very visible from the change in color to darker burning until it becomes brighter and rock structures that become cracks [16,25]. Based on its resistance to heat, sandstone is a rock that is more resistant to heat compared to siltstone and claystone, this is not only caused by the condition of mass density, the porosity of the rock, the size of the grains is also caused by the presence of chemical composition content which is generally in the form of quartz minerals, siderite, anorthite, montmorillonite, kaolinite, illite. Changes in the value of sandstone permeability at warming temperatures 100 - 500°C permeability value is smaller than the
original state. Proving that the ability of rocks to escape water becomes more difficult and becomes more compact. Changes in the highest permeability value occur when heating at a temperature of 100°C and the permeability value becomes smaller can be seen in Figure 6. This shows that an increase in temperature causes changes in the permeability value to become smaller. Unlike the heating temperature of 600°C where the permeability value increases.

For normal temperature, the groundwater flow rate in the overburden sandstones (Qv1.1) is 1.335E-02 m³/s and the claystone layer (Qv1.2) is 4.688E-05 m³/s. In the coal seam, the target flowrate (Qh) is 1.828E-02 m³/s. For groundwater flow in the underburden claystone (Qv2.1) which enters the UCG gasification cavity is 1.485E-05 m³/s and in the siltstone (Qv2.2) layer is 7.147E-07 m³/s and in the sandstone layer (Qv2.3) is 1,327E-03 m³/s. The overall flow rate of groundwater influx to the combustion cavity is 3,306-02 m³/s.

Claystone looks crushed after being heated, UCG-15 has very low heat resistance. However, in UCG-07 some claystone can still be tested despite experiencing small cracks in the rock. At 200°C the permeability value is smaller (Figure 6).

![Changes of Sandstone Permeability Value](image1)

![Changes of Siltstone Permeability Value](image2)

![Changes of Claystone Permeability Value](image3)

**Figure 6. Changes of Permeability Value (sandstone, siltstone & claystone).**

The main sources of groundwater intrusion in the reactor cavity include; The entry of water is caused by the permeable coal seam due to the combustion process (Kh), the entry of water through the cover layer, upper coal seam/overburden (Kv1), and lower coal seam / underburden (Kv2).

Based on the spread of permeability values in the study area shows that the western part of the study site generally has a smaller value than the value of permeability in the east of the study site. For the selection of application locations for subsurface coal gasification technology is required in locations that have a small permeability value (aquifer no active), so for the selection of gasification test sites for subsurface coal, it is recommended to be chosen in a Western location (Figure 7).
5. Conclusions
The effect of rock permeability on groundwater influx into underground coal gasification reactor is large and significant to consider, this is due to the thermal load and mineral composition contained in the rock. Based on heat resistance, sandstones are more resistant to heat compared to siltstone and claystone. From the test results, the physical properties of sandstone, siltstone, and claystone show the differences in rock characteristics before and after being given thermal loads. Changes in rock characteristics due to thermal loads are evidenced by changes in physical shape, the color becomes darker, mass density, porosity, cracks, and microstructure, thus causing changes in the value of rock permeability around the UCG gasifier cavity.

The lithology of sandstone by heating 100 - 500°C, the permeability (K) value is smaller and more compact, generally composed of the mineral quartz, siderite, anorthite, montmorillonite, kaolinite, illite. The discharge of groundwater entering the UCG cavity is relatively decreased. Heating 600°C the rock structure has cracks and the permeability value is greater so that the discharge of groundwater flowing into the UCG cavity also increases relatively. Siltstone lithology by heating 100 - 400°C, the permeability value becomes smaller and more compact, in general, the mineral composition is quartz, kaolinite, and illite. The discharge of groundwater entering the UCG cavity is relatively decreased. At the temperature of 500°C, the sample was destroyed, but at 600°C the value of the silt permeability coefficient was greater, so the discharge of groundwater flowing into the UCG cavity was relatively also increased. The lithology of claystone by heating 200°C, the permeability value is smaller, generally, the mineral composition is quartz, siderite, kaolinite, and illite. The discharge of groundwater entering the UCG cavity is relatively decreased.

The study results provide additional information about permeability values of sandstone, siltstone, and claystone with changes in temperature and mineral composition, which is an important parameter in calculating the potential of groundwater intrusion into the UCG reactor. The rock’s properties of the sandstone, siltstone, and claystone have been validated thereby increasing the confidence in the hypothesis of these rock’s permeability value. However, further investigations to clarify other impacts on rock permeability are still needed.

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