Experimental study of water curtain performance for gas storage in an underground cavern

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Abstract: An artificial water curtain system is composed of a network of underground galleries and horizontal boreholes drilled from these galleries. Pre-grouting measures are introduced to keep the bedrock saturated all the time. This system is deployed over an artificial or natural underground cavern used for the storage of gas (or some other fluids) to prevent the gas from escaping through leakage paths in the rock mass. An experimental physical modeling system has been constructed to evaluate the performance of artificial water curtain systems under various conditions. These conditions include different spacings of caverns and cavern radii located below the natural groundwater level. The principles of the experiment, devices, design of the physical model, calculation of gas leakage, and evaluation of the critical gas pressure are presented in this paper. Experimental result shows that gas leakage is strongly affected by the spacing of water curtain boreholes, the critical gas pressure, and the number and proximity of storage caverns. The hydraulic connection between boreholes is observed to vary with depth or location, which suggests that the distribution of water-conducting joint sets along the boreholes is also variable. When designing the drainage system for a cavern, drainage holes should be orientated to maximize the frequency at which they encounter major joint sets and permeable intervals studying in order to maintain the seal on the cavern through water pressure. Our experimental results provide a significant contribution to the theoretical controls on water curtains, and they can be used to guide the design and construction of practical storage caverns.

Key words: artificial water curtain; model test; storage cavern; gas pressure

1 Introduction

Large underground caverns have been used for the safe and economical storage of hydrocarbon gases, gasoline, home heating oil, jet fuel and crude oil. The need to support the rapid industrialization of the 1970s and to avoid oil crises by creating significant storage capabilities stimulated the construction of underground storage caverns for such materials as crude oil and liquefied petroleum gas (LPG), and pumped storage power plants [1–3]. A number of underground caverns have been constructed for oil and gas storage in China. Korea has a short construction history of large-scale underground energy storage caverns.

Underground storage of pressurized gases in unlined rock caverns has advantages over above-ground storage in terms of safety, environmental protection and economy [4]. However, underground storage caverns require specific geological conditions that are not available everywhere. For example, intact rock is never completely impermeable. In unlined rock caverns, gas is kept from escaping by ensuring that the groundwater pressure in the rock around the caverns exceeds the gas pressure in the storage caverns [5]. High gas pressure can be achieved by locating a cavern at a sufficient depth or by installing a “water curtain” around the cavern.

Water curtains are an array of boreholes that are installed parallel to each other over the roof of a cavern and around the sidewalls if necessary. With a water curtain, the groundwater pressure around a cavern can be increased sufficiently to prevent gas leakage. The idea is to make water continuously flow toward the cavern from outside so that the stored gas can never escape out of the cavern. The cavern must be sited deep enough to ensure that the hydraulic pressure in rock fractures around the cavern is always higher than the gas pressure in the cavern. The water pressure is maintained by injecting water into the rock through
bores above the cavern to maintain a stable groundwater level. The effectiveness of an unlined oil storage cavern is strongly dependent on the water tightness of the rock mass around the storage cavern. Thus, it is essential that all the cracks are filled with water during the construction and operation of a storage cavern [6]. This method is termed as the water dynamics sealing method [7, 8].

Previous researches have developed the theory and application of water curtain installations. The extensive works of Zimmels et al. [9–11] have developed the principles of water curtains, and provided useful suggestions for practical installations. Lindblom et al. [12, 13] advanced this work with simple numerical simulations. Kim et al. [14, 15] experimentally modeled and monitored underground LPG storage caverns below the groundwater table. Liu et al. [16] used finite element analysis to model gas storage in rock cavern under high pressure. The installation of a water curtain at the Kvilldal hydroelectric power station in Norway has enabled the practical evaluation of such systems. After installation, the permeability coefficients of the rock mass around the storage caverns were studied and the rate of gas leakage was observed to rapidly reduce [6].

The schematic cross-section in Fig.1 shows the horizontal water curtain boreholes used in the hydraulic tests. According to the results, the permeability coefficients range from 9 to 11 cm/s. These values are slightly lower than those obtained from site investigations.

![Fig.1 Relative location of horizontal boreholes, water curtain tunnels, construction and storage caverns.](image)

Underground storage caverns can have multiphase gas-liquid-solid coupling problems. There are two established methods for studying gas-liquid and fluid-solid coupling problems. One multiphase gas-liquid-solid coupling physical modeling test of water curtain performance was conducted by Wong in 1994 [17]. Another physical model of the air pressure in a tunnel was established by Baghbanan et al. in 1994 [18–20]. These kinds of tests are limited by the difficulty in controlling the coupling of the gas, liquid and solids in the system.

Figure 2 shows different methods to limit or eliminate leakage from an underground gas storage cavern. These methods are based on two main principles of permeability and groundwater control. Permeability control means that the gas leakage is eliminated or kept at an acceptable level by ensuring that the rock mass around the storage has a sufficiently low permeability. The permeability coefficients of the rock mass play an important role in the process of controlling groundwater seepage and stress within the rock. The permeability coefficient of a rock mass will increase with the expansion of cracks. In faulted rock, the permeability coefficients are different in different directions, i.e. anisotropic. Generally, in the direction normal to fault, the permeability coefficient is large, whereas in the direction normal to fault, the permeability coefficient is relatively small.

![Methods to limit gas leakage from a pressurized underground storage](image)

Permeability coefficient tests are routinely conducted in the field. Field tests include both affusing and pumping tests. The permeability coefficient of a rock mass can be obtained by pumping water at a constant flow rate from a borehole and measuring the decrease in groundwater level at an observation well. The permeability coefficient can be calculated by a simple equation.

The principle of groundwater control is based on the fact that the presence of groundwater reduces gas leakage. The leakage reduction, or degree of groundwater control, depends on the magnitude of the groundwater pressure as compared with the storage pressure. Leakage prevention by groundwater control, as mentioned earlier, can be based on either the natural groundwater pressure or water pressure artificially enhanced through the use of a water curtain. In this way, an inward hydraulic gradient is established, which is high enough to prevent outward gas migration.

The water curtain should cover at least the crown of the storage cavern. Under extreme conditions, a water
A water curtain that completely surrounds the storage cavern may be necessary. To completely avoid leakage by groundwater control, the water pressure in all potential leakage paths, directed upward from the storage, must exceed the storage pressure over at least a small distance.

Gas storage based on natural groundwater pressures, in general, does not have the economical attraction that high-pressure storage has, because the pressure of the gas must be lower as it is related to the thickness of the overburden. A water curtain can be used to increase the groundwater pressure artificially. This will allow a higher ratio between storage pressure and depth, and will increase operational flexibility. Experience shows that water curtains can successfully avoid gas leakage at pressures up to twice the hydrostatic groundwater head.

Despite the success of earlier implementations of water curtains, some practical problems remain to be solved. For example, the influence of the spacing of water curtain boreholes and the influence of water curtain invalidation on gas tightness is poorly understood. Therefore, we have designed a set of tests to evaluate the performance of a water curtain system in an underground gas storage cavern. The key point of our experiment is to add a water curtain across an identified fluid migration path to improve the sealability of the cavern. We will present construction details for the water leakage control system, hydraulic test results, and a revised instrumentation program.

The seal on the unlined rock cavern can be defined by its hydrogeological design. The water pressure at the water curtain should be increased to the level where the boundary conditions of a cavern remain unchanged. The pressure around the cavern should be larger than that inside the cavern, to have the flow directed inward to the cavern as shown in Fig.3. The condition for the tightness (or sealability) can be expressed using the following equation [21, 22]:

\[ H > P + F + S \]  

where \( H \) is the hydraulic head at the crown, \( P \) is the maximum pressure head inside the cavern, \( F \) is the shape factor of safety, and \( S \) is the factor of safety.

2 Design and manufacture of the model

We have developed a physical modeling system that can be used to simulate many aspects of a water curtain-controlled underground cavern including multiple cavities, different spacings of water curtain boreholes, different cavern diameters, and the position of the water curtain installation above the cavern. This test device system consists primarily of a test frame, the physical model (described in more detail below), a gas supply device and a measuring device (Fig.4). The length, width, and height of the model are 200, 30, and 90 cm, respectively. Three rows of drain holes are arranged above three caverns. An air compressor is used to supply the gas to the test caverns through a pressure-stabilizer tank. Barometers are used to monitor the fluid pressures. They are installed inside holes arranged around the three caverns to monitor changes in the water pressure field under different working conditions.

![Fig.4 Physical model test device for a water curtain system.](image)

a–Pressure regulator and gas supply device; b–Barometer; c–Gas supply pipe; d–Artificial water curtain holes; e–Unlined test cavern; f–Measuring points for pressure field; g–Reaction setting; h–Reaction frame; i–Drain hole; j–Pressurizing system for water curtain; k–Micrometer gauge.

Through a series of material modeling tests (e.g. density and void ratio tests), it was found that the material strength increased and deformation reduced sharply when the relative density of materials changed from 0.7 to 0.8. Therefore, a relative density of 0.8 was used to manufacture the model. The model was made of layered and compacted sand. Each layer is 5 cm thick and was tamped 10 times to pack the layer down. During assembly, the recording instruments were installed in the model at the designed positions. For instance, the so-called high-accuracy mini-type multi-point extensometers are installed inside the model. Subsequently the model was saturated with water. The model was then left to stabilize for about 24 hours. Finally, pressure sensors, a measuring pipe and the water curtain pipes were installed. Copper pipes with a diameter of 3 mm were installed inside the model; others, with a diameter of 6 mm, were installed outside the model.
3 Testing the water curtain system

Joints, discontinuities and fractures are common in most rocks. The simulation of these irregularities in a rock mass model is important. However, their irregular nature makes this a difficult procedure [23, 24]. The key point is that all of the fractures must be filled with pressurized water. For the practical engineering development of a water curtain system, it is necessary to ensure that the water curtain covers and encircles the storage caverns, assumed in this case to be tunnel-shaped. This is accomplished by building a network of water curtain boreholes above the caverns, with borehole axes parallel to the caverns’ axes. If needed, other boreholes can be positioned beside the galleries, extending several meters downward (Fig.5). Such a water curtain system is generally linked by galleries that can access the diagonal and horizontal water curtain borehole system.

![Fig.5 Relative position of storage caverns and sidelong boreholes from water gallery.](image)

In our physical model, the water curtain boreholes were spaced at intervals of 0.5 or 0.8 m, as shown diagrammatically in Fig.6. During excavation, these boreholes were pressurized to 0.2 MPa. They act as the main water curtain system to prevent gas from leaking into fissures due to a fall in the groundwater level. However, when the facilities begin operation (i.e. the injection of gas), the water curtain boreholes will be opened to the curtain gallery, which will be filled with water with a pressure less than 0.2 MPa.

![Fig.6 Sketch of water curtain test for a typical cavern arrangement.](image)

In this paper, the water curtain tests include single, double or triple storage caverns. During the experiment, the water curtain boreholes are open to be filled with pressurized water at a range of pressures: 0.3, 0.4, 0.5, 0.6 and 0.7 m of hydraulic heads. The spacing of water curtain holes is varied.

We will show that gas leakage rises as the water curtain pressure is reduced or the interval spacing is increased. In general, water curtain invalidation will be shown to occur in unlined caverns and at high gas pressures.

4 Leakage calculation

4.1 Gas leakage calculation

In this test, the general equation of state for an ideal gas is used to calculate the leakage of gas mass or bulk volume:

\[
p^s V = nRT
\]

where \( p^s \) is the gas pressure (MPa), \( V \) is the bulk volume (m\(^3\)), \( R \) is the universal gas constant of 8.13 J/(mol·K), \( T \) is absolute temperature (293.15 ± 20) K, and \( n \) the molar amount of gas (mol). In turn, \( n = m / M \), where \( m \) is the air mass (kg) and \( M \) is the gas molar mass (kg/mol). For air, its molar mass \( M_{\text{air}} = 0.0289 \) kg/mol. Submitting \( n \) into (2), we obtain

\[
m = \frac{p^s V}{RT} M
\]

Gas mass can be calculated by Eq.(3), and from that gas leakage can be obtained.

4.2 Air leakage calculation

With the exception of gas that leaks through the joints and fractures of the bedrock around the caverns, there is also some gas that will dissolve in the pressurized water. The loss of gas through dissolution in water is given by Henry’s law:

\[
X^s = \frac{p^s}{H}
\]

where \( X^s \) is the amount of the gas dissolved (the balanced molar component), \( p^s \) is the component of actual gas pressure, \( H \) is Henry’s constant of actual gas that varies with gas pressure and temperature [25]. Henry’s law only gives the gas loss that dissolves in water at a steady state. We assume that the measurements we make for this research are done in a steady state, and therefore the dissolved bulk gas in water is calculated by Eq.(4).

5 Testing process and results

5.1 Natural (stable) water level test
In practical engineering, a rock mass is characterized by faults, joints and bedding planes. Groundwater flow in rock masses is complicated by these discontinuities, and therefore it is difficult to accurately consider all such factors in groundwater models. Fortunately, host rocks for gas storage are generally selected to be hard and massive with few fractures. A simplified groundwater model can then be used to numerically analyze the groundwater flow. Gas tightness design and hydraulic modeling in such settings can be performed by continuum approaches [26–29]. Although the influence of a single fissure on groundwater flow in fractured rock masses might not be negligible, the analysis results presented in this study are based on following assumptions for bulk media.

1. The groundwater flow obeys Darcy’s law.
2. The medium is continuous, heterogeneous and anisotropic.
3. The groundwater flow is steady, i.e. groundwater conditions are constant.
4. Groundwater is incompressible.
5. Rock around the storage caverns is saturated with water.

Figure 7 shows the relationship curves between different working gas pressures and gas leakage for single, double and triple cavern models. The results show that the process curves can be divided into three segments. For the first segment, gas leakage has no significant change. For the second segment, gas leakage increases slightly as the gas pressure increases. For the third segment, gas leakage increases quickly. The inflexion points on the curves indicative of gas leakage rate increases are distinct. For single, double and triple cavern models, the inflexion points occur at 0.6, 0.5 and 0.4 m, respectively (Fig.7).

\[ Q_{\text{ru}} = \begin{cases} \frac{a + bp^g}{c + dp^g} & (p^g \leq p^c) \\ \frac{a + bp^g}{c + dp^g} & (p^g \geq p^c) \end{cases} \] (5)

where \(a, b, c,\) and \(d\) are the constants related to number and shape of caverns; and \(p^c\) is the critical gas pressure, i.e. the working gas pressure corresponding to the inflexion in Fig.7 or 8. When the pressure is greater than \(p^c\), gas leakage will increase rapidly.

5.2 Influence of the pressure difference

The difference between the water curtain pressure and the gas pressure is called the water curtain pressure difference, \(p_d\). This important factor influences gas tightness [30–32]. For example, in the case of the triple cavern model, when \(p_d\) is larger than 0.2 m, gas leakage from the caverns is modeled to be nearly zero (Fig.9). When \(p_d\) falls below -0.2 m, obvious leakage can be found. When \(p_d\) falls below
0.0 m, the gas leakage increases quickly and air bubbles escape rapidly from the top of the model. Centralized seepage paths develop in the range from 10 to 20 cm below the top of the model.

In comparing the curves of the single, double and triple cavern models (Fig.9), note that the curves of the single and double cavern models are fairly similar to each other, in that their departure from the line of no leakage is at about the same point (i.e. where \( p_d \) falls below 0.0 m). To ensure that the gas is completely contained in the underground caverns, the water curtain pressure difference must be larger than the fluctuant value (like those identified for the three cases above) of the water seepage pressure.

5.3 Influence of the spacing of water curtain boreholes

In practical engineering applications, one of the concerns in the construction and operation of a new cavern is the stability of neighboring caverns [33–35]. For this reason, the caverns should be adequately separated. In addition, the dewatering of the rock mass around an existing cavern should be prevented by constructing the vertical water curtain system around the access galleries and shaft. Our preliminary design proposed a separation distance between caverns of (400 ± 25) m [36]. However, in our model test, these geometrical dimensions were found to be too large, regardless of the dimensions of the caverns or the water curtain boreholes.

Figure 10 shows the relationship curves between \( p_d \) and gas leakage for two arrangements of the water curtain boreholes (represented by 1 and 2 in Fig.10). In arrangement 1, all of the water curtain boreholes are in a functioning state. In arrangement 2, some of the water curtain boreholes are closed. The test shows that the separation of the water curtain boreholes can greatly affect the relationship curve. At the same water curtain pressure, a greater spacing of boreholes can make the relationship curves increase more rapidly than that when the spacing is closer. Although the water curtain pressure difference is the same, the degree of capillary saturation is smaller for more widely spaced boreholes than for narrowly-spaced ones. This means that, for the overall rock mass, the permeability is larger. That is why the amount of gas leakage is higher in systems with greater borehole spacings. The determination of suitable borehole spacings is therefore critical for the efficient enclosure of an underground cavern with a water curtain.

5.4 Water curtain invalidation

Water curtain invalidation is of an extreme state, but its possibility cannot be ruled out for practical underground storage caverns. When water curtain invalidation occurs, the gas will leak freely, and the water curtain must be improved to return the system to a normal working state. The most likely remediation measures that could be undertaken involve the enhancement of the water curtain pressure (by increasing the head) or the number of boreholes used in the water curtain. Figure 11 shows a relationship curve that schematically describes the evolution of such a process from the point of gas leakage due to water curtain invalidation to the restoration of the water curtain pressure at some later time.

5.5 Critical gas pressure

The critical gas pressure \( p_c^{GC} \) separates leaky pressure regimes from tight pressure regions. Once the working gas pressure increases above the critical gas pressure, gas leakage will increase rapidly. Figure 12 shows the relationship curves between the square of the cavern working gas pressure and gas leakage. When the square of the cavern pressure reaches 0.5 m², the corresponding cavern pressure is about 0.7 m. According to Muskat theory, if the seepage area and permeability coefficient are assumed to be constant, the radial gas discharge is prorata with the square of gas pressure. This is confirmed by the straight-line fits to the experimental data (Fig.12).
When the working gas pressure exceeds the critical gas pressure, the water curtain begins to fail and gas leakage increases rapidly. In our model, this happens not only for the case of the single storage cavern model, but also for the double and triple cavern models. Note that the critical gas pressure will change with a change of the water curtain pressure (Fig.13), borehole spacing and storage caverns dimensions.

Fig.12 Relationship curves between gas leakage and the square of cavern working gas pressure.

Fig.13 Relationship curves between the water curtain pressure difference and gas leakage with available gas pressure.

6 Conclusions

In this paper, the mechanics of water curtain systems have been evaluated through physical modeling. The hermetic characteristics of underground storage caverns have been modified by varying the water curtain pressure difference, the numbers of the caverns, the number and spacing of boreholes in the water curtain, and so on. Several problems have been discussed in detail, and some important conclusions have been obtained.

(1) The positive pressure difference of a water curtain can ensure gas storage in underground caverns. For the designer, the primary problem is to ensure that the water curtain pressure difference is larger than the fluctuant value of the water seepage pressure.

(2) After an artificial water curtain is set, test results show that the critical gas pressure can change. For example, at the same working gas pressure, the critical gas pressure will change as the numbers of the caverns are increased.

(3) Inside the caverns, the gas working pressure or the critical gas pressure increases as the water curtain pressure increases. As the water curtain pressure cannot be increased without limit, it is essential to ensure optimization of cost and benefit in the performance and design of a system.

(4) Under the same gas pressure or water curtain pressure difference, gas leakage will increase as the number of caverns increases. Increasing the number of caverns causes an increase in the number of leakage paths but the degree of capillary saturation in the rock mass decreases.

(5) In practical engineering applications, the water curtain pressure or gas pressure of the cavern can change unsteadily. During the design or construction of an underground storage cavern, these possible dynamic changes must be considered.

These modeling results provide some important reference values for theoretical evaluations of water curtain systems. They are also of significance for the design and construction of practical projects.

References


