CO_2-geothermics in abandoned coal mines

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ABSTRACT

In light of raised environmental concern focussing on the mitigation of greenhouse gases, renewable energy sources attract new attention. In response to this, the concept of CO_2-geothermics was developed in combination with CO_2-sequestration in abandoned coal mines. These would create a reservoir with an unstable fluid distribution due to a reversed density profile, leading possibly to limited convection. CO_2-geothermics aims at enhancing this density profile by cooling and condensing CO_2 using a heat exchanger at the top of the reservoir. This would boost the convection currents that will transport heat to the top of the reservoir, where energy is extracted by the heat exchanger. CO_2-geothermics has the potential to economically exploit low-temperature geothermal energy because of its high efficiency, the very limited energy input and required facilities, on condition of correct geometry and seal of the closed mines.

INTRODUCTION

Geothermics produces renewable and emission-free power by extracting heat from the subsurface. The most common way is to extract warm formation water or steam and use this for heating or power generation. A second technique, Hot-Dry-Rock (HDR), is under development. It aims at exploiting heat by injecting cold water in a fractured reservoir and recovering it after it has been heated. A third method is CO_2-geothermics. This concept has been developed in combination with assessment studies for the sequestration of CO_2 in abandoned coal mines (fig. 1).

Suited conditions for CO_2-geothermics are only met in CO_2-filled reservoirs that are located at a correct depth and have a sufficient vertical extent. Currently the concept of CO_2-geothermics can not be tested, but in the near future such reservoirs may be created when coal or other mines would be used for CO_2-sequestration. CO_2-geothermics is potentially several times more efficient than hydrothermal geothermics, and therefore may allow the economic exploitation of low-temperature geothermal heat.

FLUID PROPERTIES OF CO_2

A fluid may occur as a gas or a liquid at sub-critical conditions or as a super-critical fluid above critical conditions. Basically, a sub-critical fluid behaves conform to common expectations. A gas will condense to a liquid when it is cooled sufficiently at constant pressure, while a liquid will vaporise when it is depressurised at constant temperature. These phase transitions do not occur in a supercritical fluid. It will gradually change from a low- to a high-density fluid or vice versa. Except for the phase transitions, there is no fundamental difference between the behaviour and the properties of sub- and super-critical fluids.

For CO_2-geothermics the most important parameters are pressure, temperature and density. In the most general situation, when only one fluid phase is present, the three parameters are interdependent, meaning that either two of them will determine the third parameter. The behaviour of a fluid can be predicted using an equation of state. Unified Helmholtz energy functions describe the fluid behaviour accurately, also close to the critical point, but are currently only available for pure systems. The one used for CO_2 is the Span & Wagner equation of state [1]. At saturated conditions both gas and liquid coexist. Pressure and temperature are then dependent, but density is not a function of pressure and temperature (fig. 3).

A change of the fluid properties corresponds generally to a change of the energy (enthalpy) of the system. Increasing the heat and pressure of a CO_2-system will increase its internal energy, and vice versa. Special phenomena are the phase transitions when the density of the fluid changes dramatically at a constant pressure and temperature. As a result, large amounts of energy are either released (condensation) or adsorbed (vaporisation) by the fluid system. At supercritical conditions the change from a high to a low-density fluid is continuous, but is accompanied by a comparable amount of energy exchange. Close to critical conditions such transitions require only limited changes of temperature and pressure.

CO_2-SEQUESTRATION IN A MINE RESERVOIR

In order to mitigate the emission of CO_2 into the atmosphere, CO_2 can be captured from flue gasses and sequestrated. Geological reservoirs and oceans are sufficiently large to allow the semi-permanent storage of large quantities of CO_2. Possible geological reservoirs are aquifers, depleted oil or gas fields, virgin coal seams and abandoned underground mines. In spite of the limited volumes that can be stored in mines, their high permeability and injectivity compared to virginal coal reservoirs, may make them good candidates for early opportunity projects, involving cheap supply of CO_2 from industries producing pure, process CO_2.

Aquifers and depleted oil or gas fields are largely horizontal structures. When used for CO_2-sequestration, reservoirs deeper than ~800 m are chosen because CO_2 will be supercritical and relatively dense at this depth. When CO_2 is injected, displacement of formation water to adjacent aquifers, or compression of the grains of the reservoir rock, creates the necessary storage space. The leak-off pressure (maximum reservoir pressure) is determined by the quality of the seal and the injection wells. As a rule of thumb, this will be around 30 % above hydrostatic pressure.

A mine reservoir has different properties. Contrary to the horizontal nature of most geological reservoirs, it usually has a vertical extent of several hundreds of meters. The top of the reservoir is defined by a cap rock and by the shaft seals. The cap rock may be the host rock itself (e.g. excavation in basement or salt rock) or impermeable younger strata overlying the mined-out zone. The bottom of these artificial seals is usually well above 800 m, which implies that part of a mine reservoir will be shallower than 800 m even for mines that exploit deeper levels. The maximum reservoir pressure is determined by the quality of the seal at the shallowest part of the reservoir, which usually is the artificial shaft seal. To allow CO_2-sequestration, leak-off pressure should be higher than hydrostatic pressure. The quality of shaft sealing may be insufficient in many cases, or open fractures may link the closed mine to the surface or to neighbouring underground workings. Therefore only a limited number of existing abandoned mines are suited for CO_2. However, the sealing of shafts is given more attention due to increasing safety and environmental awareness.

Two complications result from this peculiar architecture. First of all, because of the shallow position of the artificial seal, the reservoir pressure will be relatively low. This means that part of the CO_2 in the reservoir will be gaseous (low-density). Secondly, due to the large vertical extent of the reservoir also high-density CO_2 can occur. The distribution and behaviour of CO_2 with different densities throughout a mine reservoir may be of practical use and will be discussed further.

Mines that would be used for CO_2-sequestration are necessarily well-sealed structures. This implies that they are not much subjected to flooding. At the moment of injection they will therefore be largely dry and have a very low initial pressure, close to atmospheric. Injected CO_2 will primarily occupy the non-flooded space, first as a gas and during later stages partly in a liquid-like state. CO_2-pressure will then prevent later flooding of the mine. Only a smaller fraction will go into solution in mine water, as this is a less efficient way of storing CO_2. Moreover, in coal mines important amounts of CO_2, of similar order to the amount stored in free-space, will be adsorbed onto the remaining coal.

DENSITY DISTRIBUTION AND SPONTANEOUS CONVECTION

Usually the density of a fluid increases with depth. In specific settings however, the hydrothermal gradient may be high enough to heat deep-seated water sufficiently to become lighter than water at shallow levels. This results in convection or even violent eruptions. It is therefore not just depth, but the competing effect of pressure and temperature gradients that determine the density evolution of a fluid with depth.

This concept can also be applied to CO_2 in a geological reservoir. The temperature of CO_2, filling the reservoir, can be assumed to be in equilibrium with the prevailing geothermal gradient. However, the reservoir pressure is not necessarily in equilibrium with the hydrostatic pressure. In a CO_2-saturated porous medium, a CO_2-static gradient will prevail, just as a hydrostatic gradient prevails in a water-saturated medium. When the medium, in this case the reservoir, has a sufficient vertical dimension, then the pressure gradient will deviate significantly from the hydrostatic gradient in the surrounding formations. This effect should therefore be taken into account for mine reservoirs that can be up to hundreds of meters high, but can usually be neglected for flat reservoirs, such as depleted oil and gas fields. Reservoir pressure is ultimately determined by the weakest points in the reservoir seal, such as injection wells or shafts. A suited coal mine reservoir would be able to withstand a pressure between 20 and 30 % above hydrostatic pressure at the top of the reservoir. Currently only few abandoned coal mines, including all collieries in the Belgian Campine basin, have shaft seals that could withstand these pressures. If case studies prove the viability of mine sequestration, then more attention should be given to the sealing of newly abandoned deep coal mines.

The density of sequestrated CO_2 can be calculated from the pressure and temperature conditions in a coal mine reservoir. This is done using CO_2-VR [2]. Assume a coal mine that is sealed to a depth of about 500 m, which is also the depth of the natural seal, and for which the deepest mine levels that are currently not flooded are 1000 m deep. The local geothermal gradient is around 0.03 °C/m and the roof of the mine can withstand a pressure of 130 % of the hydrostatic pressure. The calculated density profile shows that CO_2 is gaseous (< 0.44 kg/m³) and that its density decreases with depth (fig. 2). This means that for CO_2, the normal geothermal gradient has a greater effect on the density than the pressure induced by its own CO_2-static gradient. Since a reversed density profile is not stable and a mine reservoir has a very high permeability, CO_2 will start to convect. This circulation will redistribute the heat, as warm CO_2 moves up and cool CO_2 moves down. The shallow parts of the mine will eventually become warmer and the deeper parts cooler. This diminishing geothermal gradient will lead to slowing-down or cessation of the convection currents.

STIMULATED CONVECTION: CO_2-GEOTHERMICS

The spontaneously convecting CO_2 discussed in the previous paragraph is gas-like. When the reservoir conditions are plotted on a pressure-temperature-density diagram (PTd-diagram), it becomes clear that only a small decrease in temperature (< 10 °C, fig. 3) at the top of the diagram is necessary to trigger the phase transition of gaseous to liquid CO_2. This would be a very effective stimulus for maintaining the convection of CO_2, as will be shown next.

Figure 4a pictures a mine reservoir as a continuous and very permeable reservoir. In such a setting, spontaneous convection of low-density CO_2 will occur if it is located at the correct depth. In figure 4b a heat exchanger is installed at the top of the reservoir. This will extract heat from the top of the reservoir, and cool it to e.g. 10 °C. This will cause CO_2 at the top of the reservoir to condense into the liquid state, resulting in a mist or cloud of CO_2. The density differences in the already reversed density profile are thereby augmented by a factor 10. In response, liquid CO_2 will run or rain down the reservoir until it is heated and vaporised at deeper levels. This cooling and downward mass transport will result in a pressure drop at the top of the reservoir. In response to the pressure and density gradients, warm CO_2 will rise to the top of the reservoir, thus completing the convection cycle. Two-phase convection does not only boost the circulation, but also the energy transport. Vaporisation requires about 100 times more energy than the heating of CO_2 by one degree. This means that a given amount of CO_2 in figure 4b will transport about 4 times more energy than in the spontaneous system in figure 4a.

However, the jar pot model evidently represents an oversimplification of the real situation. Consider therefore a simplified mine design, with one central shaft, one exploitation level, a parallel gallery for ventilation and a limited number of vertical connections (fig. 5). The exploitation level is connected to panel workings that are not represented in the drawing. CO_2 that is condensed at the heat exchanger will run down the shafts and galleries. Since these have a limited surface, they also have a small thermal buffering capacity, meaning that they will be cooled quickly. Their importance for CO_2-geothermics is that they provide alleys for the convection currents. As main shafts and galleries were generally designed to last decades, they will function in the CO_2-geothermics scheme for the lifetime of such projects. Once the vertical shaft has cooled, the denser CO_2 will enter the lower horizontal gallery, and from there the collapsed panel workings. These have a high permeability, but also a large contact surface with the rubble and host rocks. It are these gob rich zones that provide the heat reservoir.

DISCUSSION: CONCEPT OR OPPORTUNITY?

No doubt CO_2-geothermics has currently the status of a concept, rather than of a technological opportunity. For one thing, general considerations have not yet been verified by dynamic modelling. Also it is linked to CO_2-sequestration in coal mines, and although this is an option for mitigation [3], it is currently not included in greenhouse reduction programs.

Apart from these practical considerations and limitations, a theoretical evaluation indicates some important benefits of CO_2-geothermics over other types of geothermal energy (tab. 1). The efficiency of the system is potentially very high, because the heat transport capacity per kg fluid in a dual-phase CO_2-system is almost 4 times higher than for a comparable hydrothermal project. The large convection cells in the galleries and shafts allow extracting heat from a large part of a coal mine using a minimum of heat-extraction points. The energy that drives this circulation comes from the density differences of the system itself. External energy input would only be necessary for circulation of the coolant in closed circuits, for the heat pumps in surface facilities that upgrade the thermal energy, and for distribution of the thermal energy to the end-users. It is expected that the temperature of the coolant can control the amount of energy that is extracted, and that it would therefore be possible to follow seasonal consumption patterns. Note also that, contrary to hydrothermal projects, there is virtually no limitation on the temperature of the coolant since the freezing point of CO_2 is as low as –56.6 °C.

The applicability of CO_2-geothermics is limited by the availability of mines filled with CO_2, by the correct depth window to allow two-phase convection, and by sufficient pressure to avoid flooding. The latter implies that any CO_2-geothermal project will be located at relatively shallow depths. Therefore only low-temperature thermal energy can be exploited. At low temperatures hydrothermal or hot-dry-rock techniques are not economic, but due to its higher energy efficiency CO_2-geothermics may well be feasible. The capacity is controlled by the size of a mine. A case study for the Belgian Beringen colliery indicates a thermal potential of 800 000 MJ or 200 000 MWh, or a continuous production of about 1 MWatt thermal energy production during 25 years. After this period, the heat-reservoir will be depleted. It is a renewable energy source, but it may take decades or centuries before the original geothermal gradient is restored. The impact on the environment is extremely low due to the limited surface infrastructure and the low energy input. On top of this, it can be considered as an optimal usage, possibly even recycling, of CO_2, and of abandoned mine infrastructure, which is in line with the current trend towards a resource efficient society, and preserving sound and economic viability of former mining regions.

CONCLUSION

CO_2-geothermics is a novel concept, and therefore several matters remain to be solved, such as the amount and extent of convection that can be induced, in relation to the geometry of the residual space, and the amount of heat that can be extracted. Reasons to further explore the opportunities of CO_2-geothermics are its potential to extract low-temperature heat from the sub-surface at a relative low cost where classic geothermal techniques fail, the current need for green energy production, and the reuse of the greenhouse gas CO_2.

REFERENCES

1. Span R. and W. Wagner, 1996: “A new equation of state for carbon dioxide covering the fluid region from the triple point temperature to 1100 K at pressures up to 800 MPa”; Journal of physical and chemical reference data, V. 25, p. 1509-1596.
2. Piessens K. and M. Dusar, 2003: “Modelling vertical reservoir properties using CO_2-VR”; this volume.
3. Piessens K. and M. Dusar, 2003: “CO_2-sequestration in abandoned coal mines”; this volume.

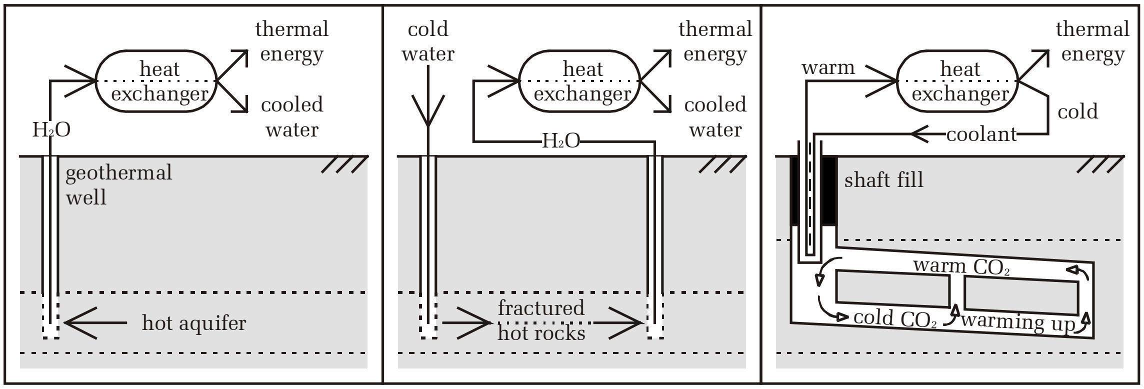
TABLES

Applicability:	Local, in combination with CO_2-sequestration in (coal) mines.
Type:	Low-temperature, thermal energy.
Economics:	Potential to economically exploit low-temperature geothermal energy. Investment and operational costs low or moderate, if seen as part of a CO_2-sequestration project.
Efficiency:	Potentially very high: - Heat transport capacity: between 3 and 4 times higher than of a comparable hydrothermal project. - A limited number of heat extraction points for one mine due to large convection cells. - No extraction and re-injection of fluid.
Capacity:	Low to medium.
Flexibility:	Good, may be possible to follow e.g. seasonal demands.
Energy input:	Very limited, only for circulation of coolant, upgrading of energy (heat pump) and distribution of energy to end-users.
Environmental impact:	Very low: - Very limited infrastructure (apart from existing coal mine). - Limited energy input, therefore limited emissions. - Exploitation of renewable energy, although energy extraction (~10 years) will occur faster than energy recharge (>100 years).

Table 1:

Overview of the properties of CO_2-geothermics.

FIGURES



a b c

Figure1:

Three methods to extract geothermal energy: (a) by pumping water from a hot reservoir, with possible re-injection of the cooled brine, (b) by circulating cold water through a fractured medium, and (c) by condensation of CO_2 sequestrated in a coal mine.

Figure 2:

Density profile of CO_2 in a reservoir as calculated by CO_2-VR. CO_2 is gaseous and the density slightly increases from the bottom to the top of the reservoir. The sharper increase at the top of the reservoir indicates that conditions are close to the saturation line (close to the condensation point). Reservoir from 500 to 1000 m, geothermal gradient = 0.03 °C/m, pressure at 500 m = 120 % of hydrostatic pressure.

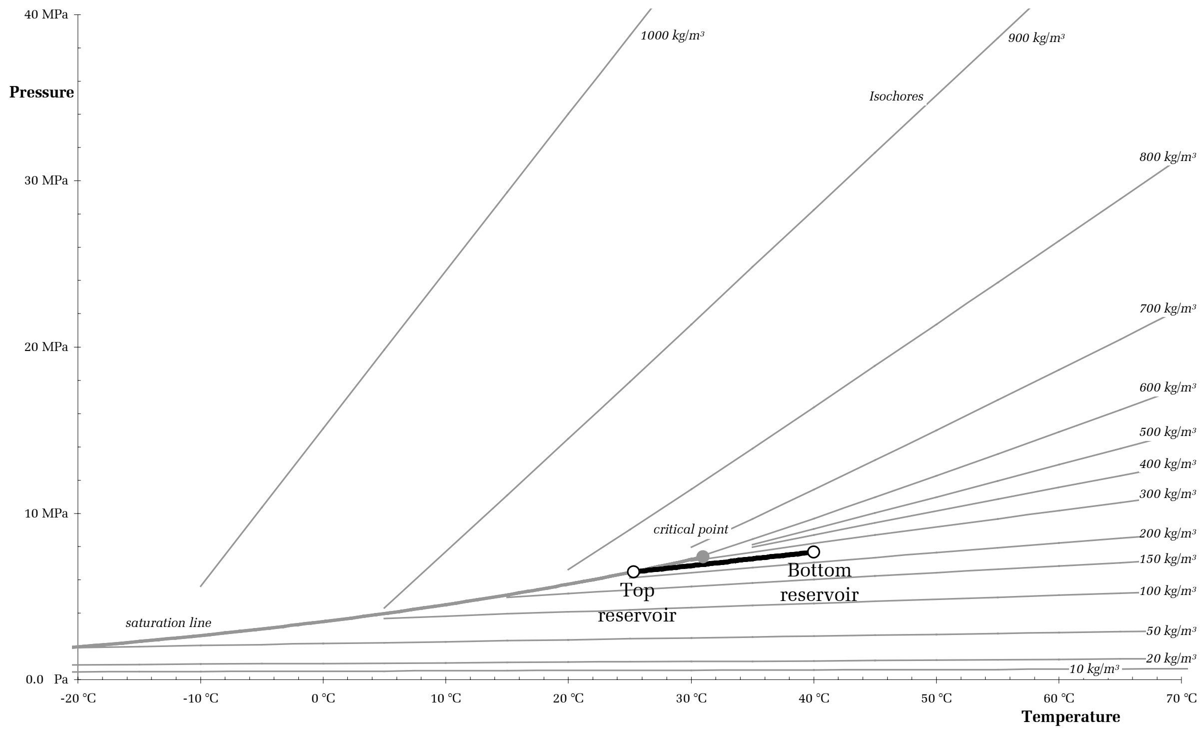


Figure 3:

Density of CO_2 plotted as a function of pressure and temperature. The reservoir conditions are indicated by the thick black line. Note that the conditions at the top of the reservoir are very close to the saturation line. Any temperature decrease will move the conditions to the left of the saturation line, corresponding to the condensation of CO_2.

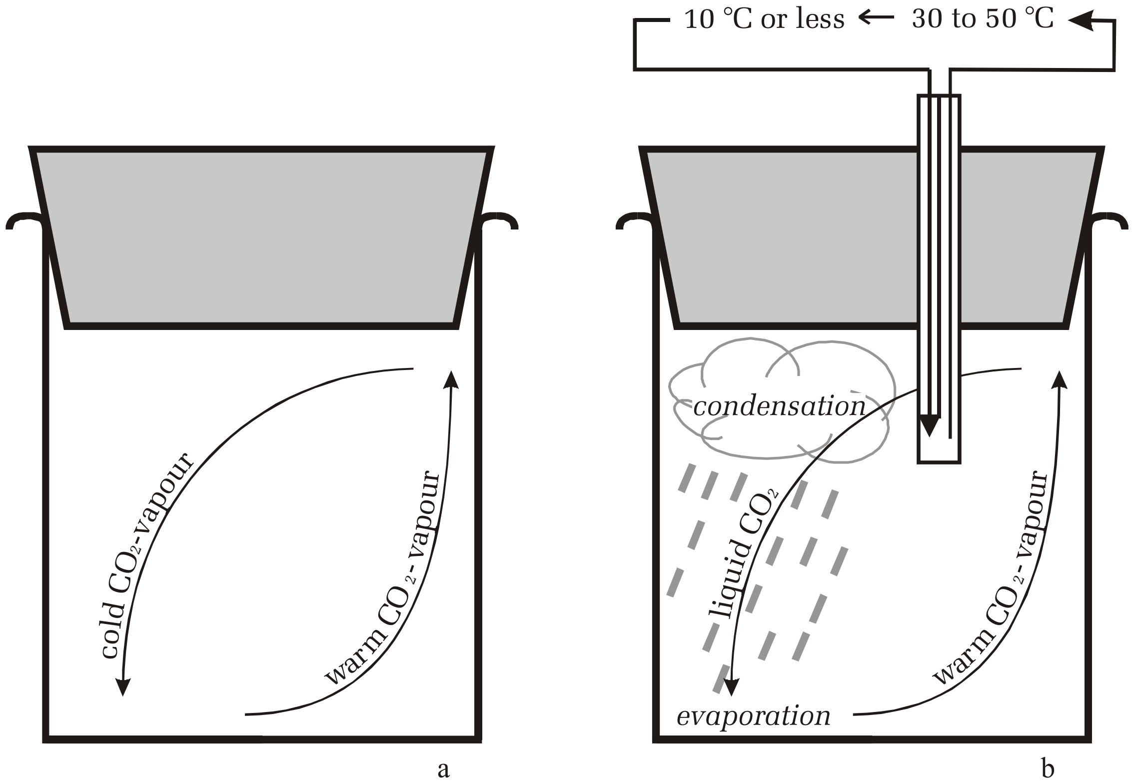


Figure 4:

(a) Schematic presentation of a mine and the spontaneous convection that may occur after CO_2-injection. (b) Stimulated convection by implementing a low-temperature geothermal system that essentially consists of a heat exchanger, placed near the top of the reservoir.

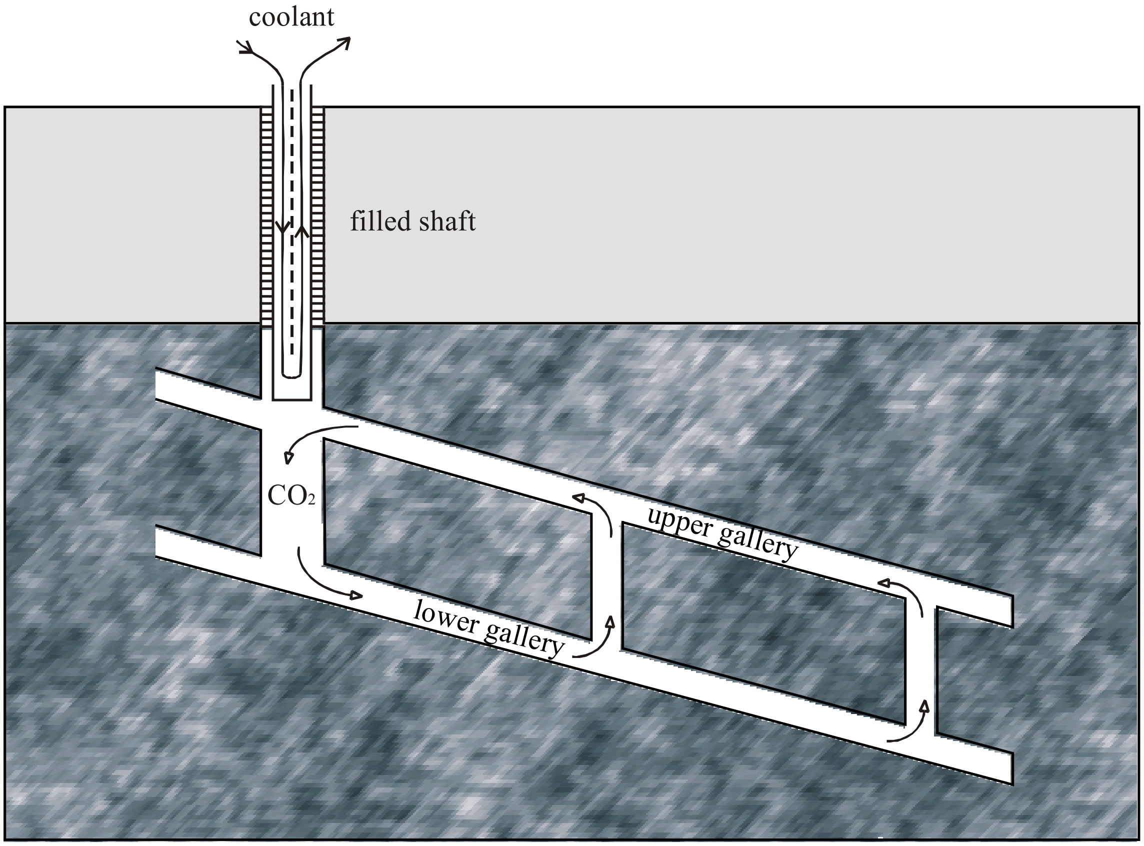


Figure 5:

Simplified mine design, consisting of one vertical shaft, a lower gallery connected to panel workings, an upper gallery for ventilation and some vertical connections between them. The former galleries and shafts still have a very high permeability and allow large convection cells, whereas the thermal energy will mainly be extracted from the gob in the panel workings.