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INTEGRATION OF CO_2 SEQUESTRATION AND CO_2 GEOTHERMICS IN ENERGY SYSTEMS FOR ABANDONED COAL MINES

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(3 figures and 1 table)

ABSTRACT. A reservoir located within the 500-1000 m depth range under the thermal conditions reigning in Western Europe, and filled with pure CO_2 until a sufficient internal pressure is reached to prevent water flooding, will show a reversed density profile. This reversed profile may result in condensation at the shallowest levels of the reservoir, causing convection that will transport heat to shallower parts of the reservoir. On the long term, the deep levels of the mine will cool, the top will warm, and convection will become insignificant.

However, these reservoir properties can be used to produce geothermal energy by extracting heat from the top of the reservoir. Cooling the top of the reservoir will increase the density differences and stimulate convection. Because of the heat exchange during the phase transformations, and because of the large density differences between liquid and gas, the efficiency and capacity of this system are potentially very high.

CO_2 geothermics enables the sequestration of CO_2 in coal mines. Enhanced Coal Mine Methane and Coal Bed Methane are other sources of environmentally friendly energy that may be developed in conjunction with the injection of CO_2. It is also expected that CO_2 in a coal mine will reduce the risk of contamination of overlying aquifers. A case study for the Campine collieries shows that CO_2 sequestration can be a key element in an energy system that combines both economic and environmental aspects.

Keywords: CO_2 geothermics, CO_2 sequestration, abandoned coal mines, Belgium, Campine basin.

1. Introduction

CO_2 sequestration in abandoned coal mines may be technically feasible and may possibly assist Belgium or the Flanders region to reduce greenhouse gas releases into the atmosphere. The choice to actually develop this option is a policy matter, whereby public awareness is of increasing importance in political decision making. CO_2 sequestration as a complementary option to green alternatives such as wind or solar energy may be contested (CO_2-dumping would allow the continued use of fossil fuels), but it may become unavoidable to reach a sufficient reduction in CO_2 emissions.

Sequestration in coal mines becomes more acceptable when integrated into a complete, overall energy development plan. Such a plan would have multiple environmental benefits, such as reducing the risk of mine-related contamination and the production of green energy (AMM = abandoned mine methane, ECBM = CO_2-enhanced coalbed methane recovery, geothermal energy). Many of these benefits, such as seal improvement, ECBM, or CO_2 geothermics, are not possible without the sequestration of CO_2. This implies upgrading CO_2 from waste to recycled material.

Geothermics enable to extract heat from the subsurface. They are a potentially interesting source of energy as they are renewable and produce emission-free. The most common form of geothermal energy is to extract warm formation water or steam and use this for heating or power generation (Dreesen & Lagrou, 1999), or to extract heat from the formation water in-situ using a borehole heat exchanger. A second technique, Hot-Dry-Rock (HDR) aims at exploiting heat by injecting cold water in a fractured deep reservoir and recovering it after it has been heated. A new method is CO_2 geothermics. This concept has been developed in combination with the assessment of sequestration of CO_2 in abandoned coal mines (Dusar & Piessens, 2003a; this volume).

Suitable conditions for CO_2 geothermics are only met in CO_2-filled reservoirs that are located within the correct depth window with sufficient vertical extent. A typical coal mine may extent from 500 m to 1000 m in depth. When such a mine is used for CO_2 sequestration, the reservoir pressure should equal hydrostatic pressure near to the bottom of the reservoir - if sealing properties allow. In this way, the whole reservoir will become overpressured and the influx of formation water would largely be prevented.

The reservoir temperature is determined by the geothermal gradient of the host rock. The pressure gradient, however, depends on the density profile of CO_2, and not on the hydrostatic gradient, which prevails outside the reservoir. Since the density of CO_2 is lower than the density of water, even in its liquid state, the pressure gradient (increase of pressure with depth) in the reservoir will be lower than the hydrostatic gradient.

This low pressure gradient, combined with the normal thermal gradient and the physical properties of CO_2, results in a reversed density profile with the densest fluid occurring at the top of the reservoir. This is not a stable situation. The dense, cold CO_2 fluid will move down, whereas the lighter and warmer fluid from the deeper parts of the reservoir will rise. This convection will transport heat to more shallow parts of the reservoir and will continue as long as the temperature difference between the bottom and top of the reservoir is sufficiently large to sustain a reversed density profile.

CO_2 geothermics uses the heat transporting capacity of a CO_2-filled reservoir. Conceptually, a heat exchanger is placed at the top of the reservoir to extract warmth from the reservoir. This will cool the top of the reservoir, causing the CO_2 to become denser and thus enlarging the reversed density gradient. The most effective system can be developed in a low-density reservoir, this is a reservoir that is either filled with gas or supercritical low-density CO_2. When the top of such a reservoir is cooled sufficiently, part of the CO_2 will condense. The liquid CO_2 will rain or run down the reservoir until it warms and vaporises. The cooling and downward mass transport will result in a pressure drop. In response to the pressure and density gradients, warm CO_2 will rise to the top of the reservoir. This can in turn be condensed by the heat exchanger to extract thermal energy.

This convection has the potential of transporting heat in a very efficient way because of the large amounts of energy that are released and absorbed during the condensation (top of reservoir) and vaporisation (lower parts of reservoir). The heat itself is extracted mainly from the fissured and broken rocks, which are present as gob in the formerly mined panels. The required energy input and surface facilities for this way of geothermal energy production may be minimal, as there is no need to pump large amounts of fluid and, given a suited mine design, heat from a large portion of the subsurface is transported to a limited number of heat exchangers.

2. The conditions for CO_2 geothermics

2.1. Pressure and density distribution in a CO_2-filled reservoir

Pressure and density differences in a CO_2-filled reservoir are generally neglected since most underground reservoirs have limited vertical dimensions. This is different for most coal mines, which typically have a vertical extent of several hundred meters. Since the permeability of the residual space of coal mines is relatively very high in respect to their host rock, they can be modelled as continuous and open reservoirs. The calculation of a CO_2 pressure gradient in such a reservoir is basically the same as determining a hydrostatic or lithostatic gradient. Some complications arise from the fact that gas is much more compressible than liquid or rock. This means that the density cannot be assumed to be constant over a significant depth interval. Also, the density of gas is strongly dependent on temperature, and temperature variations with depth need to be taken into account. Last but not least, the reservoir pressures are close to the critical point of CO_2. This means that density will not always be a continuous function of pressure and temperature.

Accurate calculations can be performed using the spreadsheet CO_2-VR (Dusar & Piessens, 2003b), but the basic principles can be demonstrated using PTd-plots (pressure-temperature-density diagrams). Temperature and pressure, both increasing with depth, have opposite effects on the density of CO_2. Also, abrupt changes in density related to phase transitions from gas to liquid and vice versa may occur at certain pressures and temperatures.

Typical coal mines that are suited for CO_2 sequestration, such as the Campine coal mines, have a depth range from 500 to 1000 m. In a realistic scenario, it is possible to fill the mine with CO_2 until hydrostatic pressure is reached at a depth of about 800 m. In the long term, this will guarantee that the mine will not be completely flooded by formation water (Dusar & Piessens, this volume). The mean surface temperature is 10 °C, and temperature increases with depth at a rate of 0.03 °C/m.

From the preset pressure and temperature conditions, the density of pure CO_2 in the reservoir can be calculated. Below 703 m, CO_2 will be supercritical. Because the geothermal gradient is sufficiently high, the density will decrease from 600 kg/m³ at 670 m to 500 kg/m³ near the bottom of the reservoir. This reversed density profile is not stable. Between 500 and 670 m, CO_2 is not a homogeneous phase. This means that both gas and liquid are present, the latter possibly as a mist (Fig. 1a). The density of the gas is 250 kg/m³, and the density of the liquid CO_2-drops to only 700 kg/m³ (Fig. 2A). This liquid is the densest fluid in the reservoir. Therefore it will rain or run down the reservoir, until it reaches a depth where it can take up sufficient geothermal heat to vaporise again.

The condensation at shallow levels will decrease pressure, whereas vaporisation at deeper levels will increase pressure. This will induce a pressure gradient, which will cause relatively warm CO_2-vapour to flow upward (Fig. 1a). The reversed density profile will then result in circulation of CO_2 in the reservoir, which is enhanced by condensation and evaporation.

This system is only possible when the right pressure and temperature gradients are combined. When convection is active, the changes in the pressure gradient will enhance circulation, but also the temperature gradient will be influenced. Condensation is an exothermal process, implying that temperature will increase at shallow levels where condensation takes place. Moreover, warm gas is brought up from deeper levels. Vaporisation is endothermal, and therefore the temperature at deeper levels

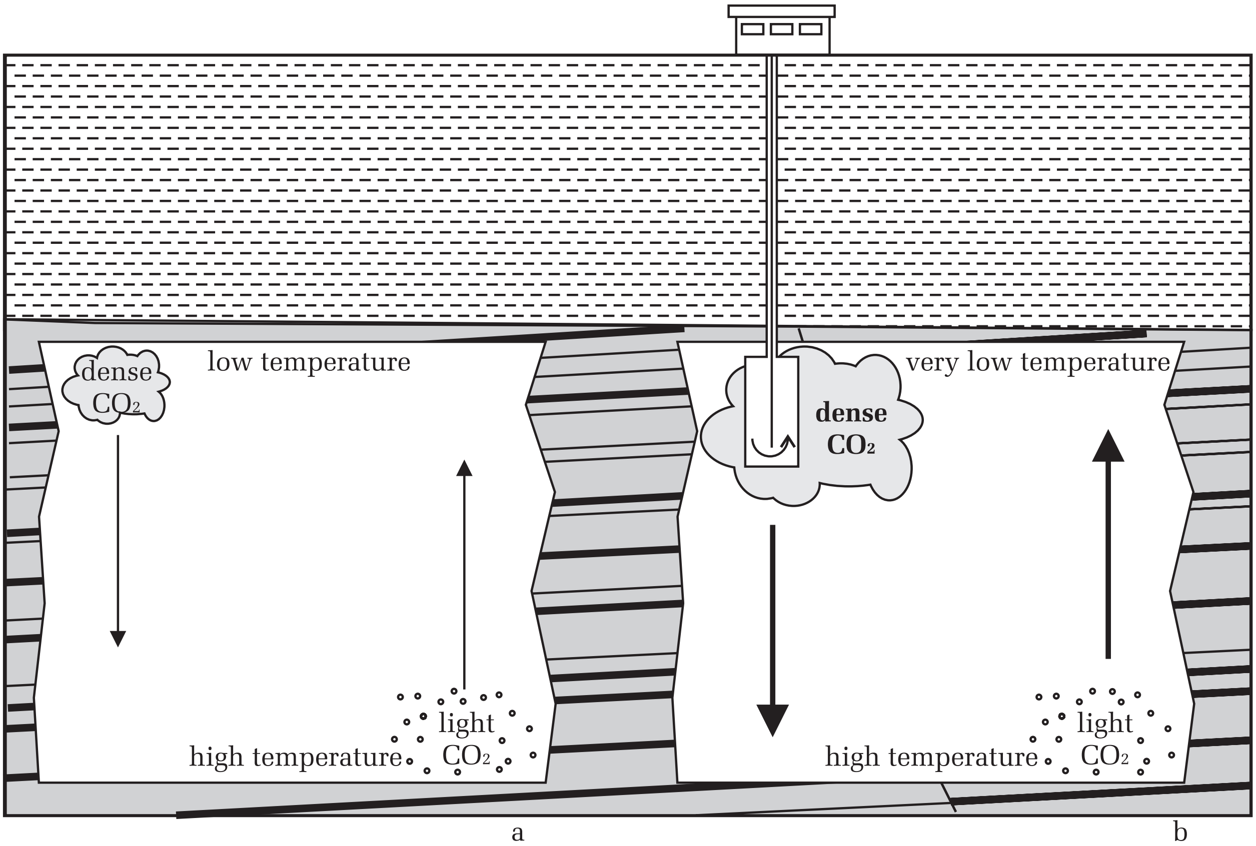

Figure 1. A mine may be regarded as a human-built cavity or as a reservoir with high to very high permeability, and therefore may be regarded as a large underground cavity. (a) Given the correct pressure and temperature conditions, which are governed by depth, reservoir pressure and geothermal gradient, CO_2 will be denser at the top of the reservoir than at the bottom. It is possible that CO_2 at the top of the reservoir will partly condense. Dense CO_2 will move down and light CO_2 will move upward until temperature equilibrium is reached and the density profile is stabilised (see also Fig. 2). (b) Heat extraction at the top of the reservoir, by pumping a coolant through a heat exchanger in close circuit, will cool the top of the reservoir. Much more CO_2 will condense, which will boost the convection in the reservoir. The two phase convection cycle will transport heat, extracted from the reservoir, to the heat exchanger.

will be decreased. The result will be a less pronounced thermal gradient in the reservoir. In response to this change, convection will slow down and will ultimately halt. The thermal gradient inside the reservoir is buffered to some extent by the external geothermal gradient in the surrounding rocks. Duration and amount of convection will therefore depend on the amount of heat that can be transferred to the host rock at the top of the reservoir or that could be extracted.

2.2. Heat transport in CO_2-versus H_2O-reservoirs

Heat transport in a CO_2 reservoir is more efficient than classical convection in H_2O-dominated systems, provided the convection scheme includes both liquid and gaseous phases. The efficiency of two-phase convection (liquid and vapour) arises in part from the large density differences. For the conditions in Figure 2A, the density difference between low- and high-density CO_2 fluids are on the order of 100 times higher than for water under the same conditions. This results in much faster convection of a dual-phase CO_2 system than for a one-phase H_2O-system. High flow velocities in a CO_2 reservoir are further encouraged by the dominance of gas, which has a much lower viscosity than liquid. In general, the capacity of dual-phase systems to transport heat is higher than that of single phase systems. This is due to phase transitions (condensation, vaporisation), which involve the release or absorption of relatively large amounts of heat. This means that the heat transported per kg CO_2 in a reservoir such as a Campine coal mine at the envisaged conditions (near hydrostatic pressure with dual-phase convection) is larger than the heat transported by convecting H_2O for temperature differences smaller than 60 °C (cf. Lemmon et al., 2001), although the heat capacity of liquid CO_2 is only about 75% of the heat capacity of H_2O. A final benefit is that the heat liberated through condensation is released at a very specific level (the level that is actively cooled). Therefore, heat loss during thermal transport in the reservoir is minimised.

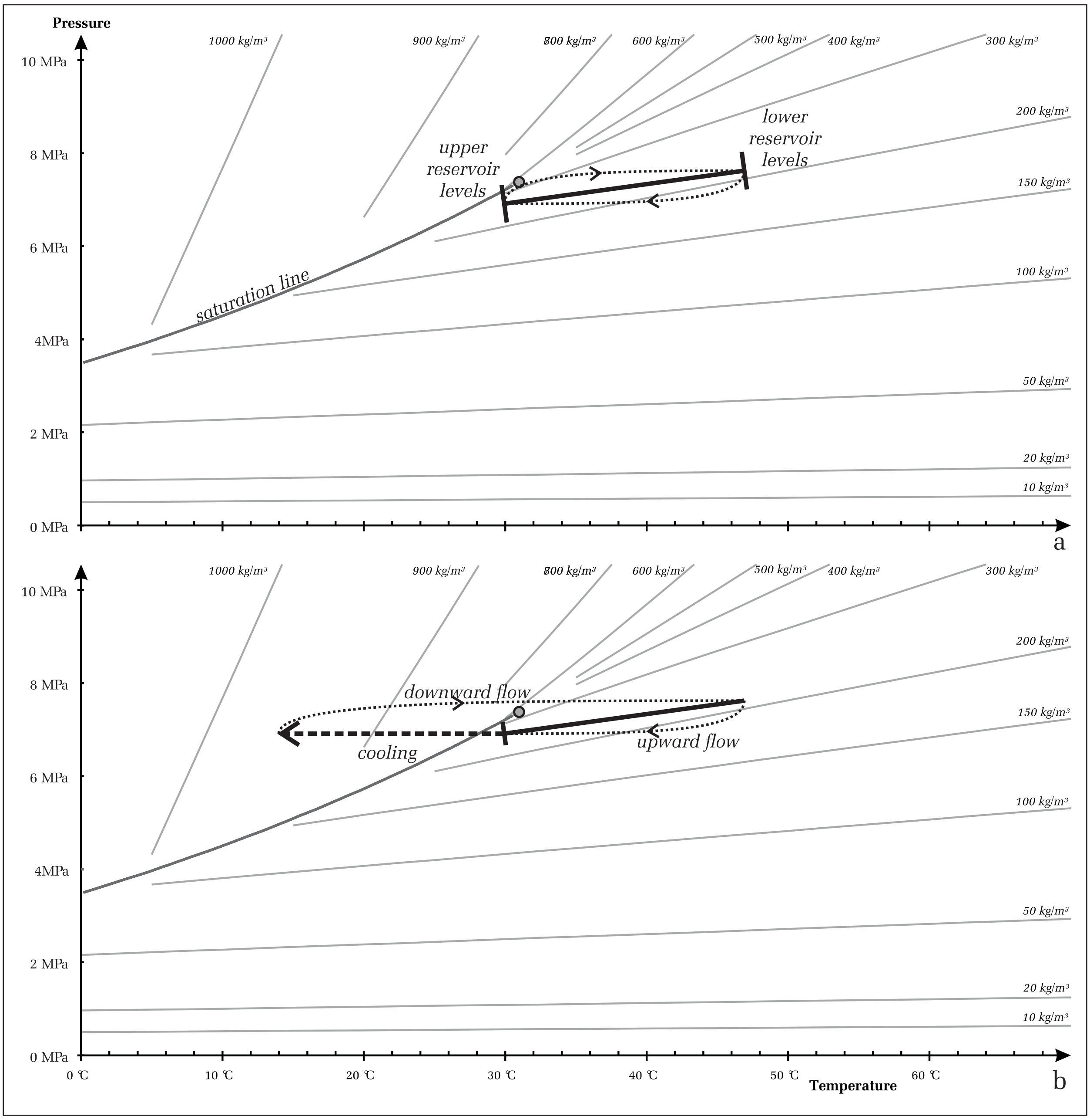

Figure 2. Density of CO_2 as a function of pressure and temperature. (a) Reservoir conditions are shown as a solid black line. This line has a slightly more gentle slope than the isochores, implying more dense CO_2 at the top than at the bottom of the reservoir. The conditions in the upper part of the reservoir are very close to the saturation line, and therefore part of the CO_2 may condense, resulting in an even stronger reversed density gradient. (b) Cooling the top of the reservoir (moving the conditions across the saturation line), will cause a large part of the CO_2 to condense. This will create a large density difference. Liquid CO_2 will move down the reservoir and boost convection.

2.3. Gas composition

The final gas composition after sequestration will not be pure CO_2, but a mixture containing possibly some CH_4, N_2, NO_2, H_2S, SO_2, and H_2O. This effects the phase transition and the position of the critical point. A mixture of CO_2 and CH_4, for example, will have a critical point that is always lower than 31.1 °C (the critical point of CO_2) at pressures that are always higher than 7.4 MPa (74 bar, critical pressure of CO_2). A critical point at a higher temperature is also possible, as is the case for the CO_2-H_2O-system. Since the CO_2 convection scheme relies heavily on the favourable position of the critical P-T-conditions relative to the natural P-T-conditions, these changes may make convection and heat transport less effective or impossible. Another complication is the replacement of the saturation line in the diagram of a unary (one-component) system by a domain caught between a bubble point curve and a dewpoint curve in the diagram of a binary system.

Also, the different components will often be immiscible when condensing to the liquid state. As a result, the distribution of the components throughout the reservoir will be inhomogeneous. Equations for complex compositions are possibly not sufficiently accurate. Therefore, more experimental work focussed on CO_2-dominated mixtures at the envisaged conditions is necessary.

In a reservoir that contains water, formation of clathrate and/or ice is possible when the temperature is lowered sufficiently. The formation of clathrate (a gas hydrate) will be more likely when CH_4 is present, and is possible up to temperatures of ~30 °C. The geothermal cycle will then not only consist of liquid and vapour, but will also include solids. This may be a benefit (faster heat transport…) or a detriment (inability of solids to flow, reduction of permeability/effective porosity, ice and/or clathrate formation of heat exchange, etc.).

3. The concept of CO_2 geothermics

A geothermal system that extracts heat in the shallow parts of the mine would boost the convection, because heat would no longer have to be passed on to the host rock. The geothermal system depicted in Figure 1B is a closed system using a coolant fluid for efficient heat transport to the heat exchanger at the surface. This has some technical and environmental benefits over an open system.

Any decrease in temperature in the higher parts of the reservoir will cause additional condensation at these levels (Fig. 2B). In practice, CO_2 will condense until a new liquid-gas equilibrium is reached, because of the resulting decrease in pressure and increase in temperature. The liquid CO_2 will move downward, and convection will start or accelerate. The convection scheme is based on connected parallel galleries and internal shafts, corresponding to the original ventilation scheme of the mine (Fig. 3).

When in operation, the amount of convection, and therefore the amount of vertical heat transport, will be controlled by the temperature and the amount of coolant in the geothermal system. This means that the faster the heat is extracted, the faster the system will produce heat. The only major limitation is the heat buffering capacity at deeper levels and the geometry of the mine. From an operational point of view, this implies that CO_2 geothermics can follow a seasonal energy consumption pattern.

Another benefit is the possibility of working with very low temperatures down to several tens of degrees below zero. This is possible because the freezing point of CO_2 is -56.6 °C, whereas geothermal systems exploiting aquifers face a freezing point of about 0 °C.

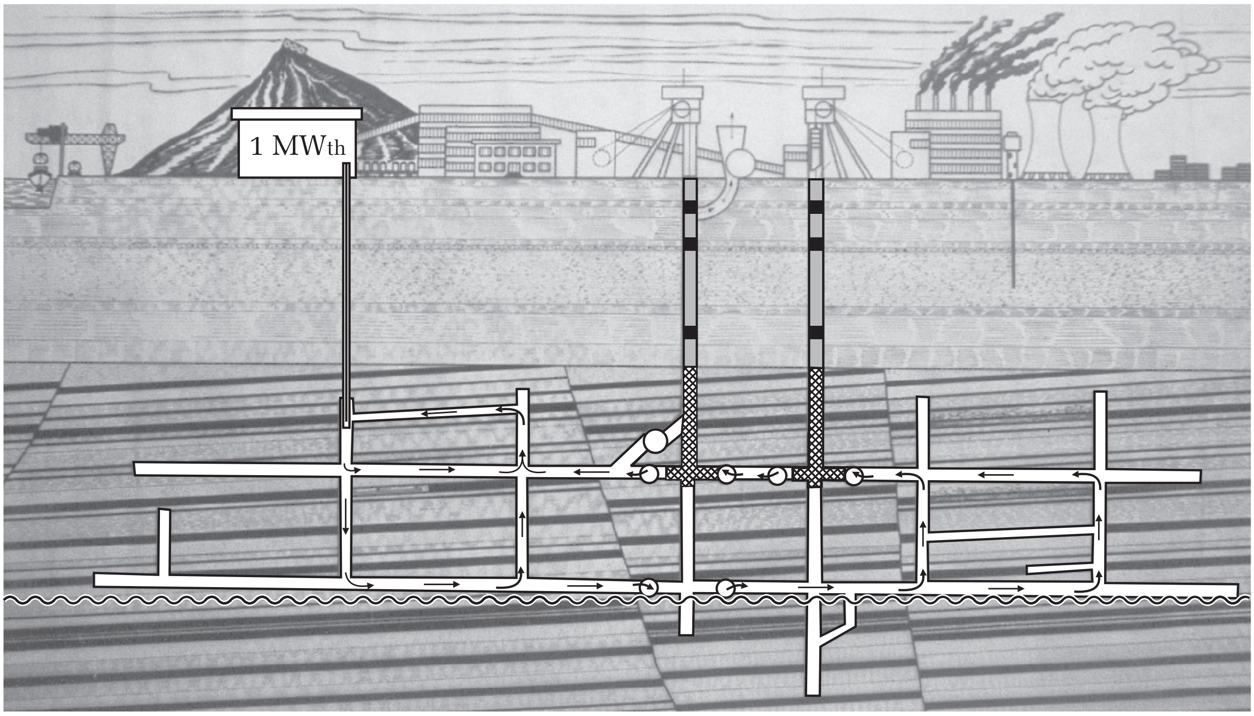

Figure 3. Simplified, but realistic cross section of the ventilation scheme of the Eisden colliery, one of the Campine coal mines (pen drawing, unknown author). In-seam driveways omitted. An overlay shows the shaft fill, consisting of large concrete plugs, stabilised sand and clay. In case CO_2 would be sequestered in the mine, the level of mine water would not rise above the lower main working level. This would allow the convection throughout the whole mine. A tentative convection scheme for CO_2 geothermics, based on the original ventilation diagram, is indicated.

The efficiency of the vertical heat transport, the extent of the reservoir and its corresponding heat-buffering potential, the possibility of controlling the rate of heat production and the option of using coolants far below the freezing point of water are advantages of CO_2 geothermics over classical low-temperature geothermics. Possibly, these benefits are such that CO_2 geothermics can provide renewable and affordable energy for the heating of housing or industrial facilities, where normal low-enthalpy geothermics are less effective.

4. CO_2 recycling in the abandoned coal mines of the Campine basin (Belgium)

The Campine collieries were closed in 1992 after 86 years of production. The subsurface infrastructure created by mining is well known because of mine plans that document the whole history of the mines, which have been digitised by the Flemish Institute for Technological Research (Dreesen et al., 1998). Until now, no leakage from the mines, either diffuse or along the former shafts, has been observed by direct measurement of the CH_4 and CO_2 content in the air at the filling point of the shafts and in the immediate surroundings at the surface (nv Mijnen, pers. comm.). However, the absence of monitoring contributes to uncertainty concerning the current condition and flooding level of the mines.

4.1. Feasibility of CO_2 sequestration at the Beringen colliery

Among the 7 former Campine coal mines, all possessing similar depth range, coal seams, overburden composition and production history, the Beringen colliery had the most rational design of underground workings and has been used as a model. The thickness of the overburden varies from 570 m to 665 m. The main stone drifts are located between 660 and 842 m in depth. The medium to high volatile A bituminous coal contains between 23 and 35% volatile matter daf. The total concession is 52.9 km² in area, of which 44.5 km² has actually been mined (Van Tongeren & Dreesen, 2000; Van Tongeren & Laenen, 2001). During exploitation, two connecting galleries were driven to the neighbouring Zolder-Houthalen collieries, and limited communication probably exists between these three inactive mines. Direct communication with the surface was limited to six central shafts (two for each mine) that are now completely sealed.

Faults connecting the overburden with the mine reservoir are known to occur at Beringen. These faults are generally related to the actual extensional tectonic setting of the Campine basin. As for all faults in the Campine mine area, they have proved to be watertight after initial draining of the sandy basal Cretaceous strata which form part of the coal measures hydrological system. This indicates that the Carboniferous and basal Cretaceous are sealed from more shallow aquifers. Therefore, it is assumed that no gas migration along these faults is actually occurring. It also means that flooding of the mine will have considerably slowed down after abandonment, since there is no longer any mining-induced subsidence.

The ascertained sequestration capacity for the Beringen colliery is estimated at $3{\cdot}10^6$ tons CO_2, with a potential to sequester about $5.5{\cdot}10^6$ tons, assuming the mine is still mostly dry. The ascertained capacity is relatively low, but quite adequate for a pilot project. When combined with the neighbouring and possibly interconnected Zolder and Houthalen collieries, their combined ascertained capacity is about $7{\cdot}10^6$ tons CO_2, extendable to possibly $13{\cdot}10^6$ tons. This is sufficient to sequester between 300 000 and 500 000 tons/y for 25 years (see Piessens & Dusar, this volume).

At maximum capacity, the pressure in the Beringen mine at 570 m (top of reservoir) would be 128% of the hydrostatic pressure. When compared with oil and gas reservoirs, this is a reasonable amount of overpressure. It nevertheless should be tested if both the natural seals and the shaft sealing can withstand these pressures.

4.2. Development program with CO_2 sequestration

The future problems of rising saline ground water contaminated by industrial and anthropogenic wastes left underground are currently neglected, and no plans exist for using the subsurface infrastructure of the abandoned Campine coal mines. Opposed to the current situation are several possibilities to reduce or prevent the risk of contamination, to produce environmentally friendly energy from the colliery, and to use it for CO_2 sequestration. These options are proposed as development scenarios and are arranged in increasing order of intervention.

4.2.1. No-action scenario

Currently, the pressure in the Beringen mine reservoir is lower than the hydrostatic pressure that prevails in the surrounding formations. Therefore, release of pollutants from the reservoir is unlikely. When the mine becomes flooded, the pressure will become hydrostatic, and where sufficient mine gas is present to form gas pockets, overpressure will be reached. The release of CH_4 and possibly other contaminants toward the overlying drinking water reserves is then possible.

4.2.2. Monitoring and remediation scenario

The rising mine water in the Campine coal mines is not monitored. If the rising mine water will result in a release of contaminants, then the first indication for this will be a change of groundwater quality. At that point, contamination will already be widespread, and remediation will be extremely expensive. It is therefore advisable to install monitoring wells. Recording the rise of mine water will provide a good estimate of the time at which the mine becomes completely flooded, and this is when the risk of breakthrough is highest. Sampling will indicate at which rates physical and biological degradation of the contaminants occurs and which products are formed. If these reactions progress slowly, or when they produce new contaminants, then in-situ remediation may be considered.

The most effective remediation can be carried out before the contamination spreads. In an abandoned mine such as Beringen, the temperature is relatively high, which generally favours reaction speed. It is possible that anoxic biodegradation of certain pollutants has already started, and these processes may be enhanced by adding nutrients. If this is not the case, then oxidation of organic components (mineral oils, PCB's...) may be an option, for example by mixing H_2O_2 in the mine water.

4.2.3. Abandoned Mine Methane (AMM)

Extracting the mine gas can reduce the risks resulting from the no-action scenario, because it eliminates the possibility of the formation of gas pockets. This technique is known as the extraction of Abandoned Mine Methane (AMM). The energy produced from this gas has been granted an environmentally friendly label in Germany and the UK, because of the very likelihood in these countries that the very potent greenhouse gas CH_4 with time will be released to the atmosphere. This technique is well known and economic. Extraction of mine gas leaves all other options for development of the mine site open.

4.2.4. CO_2-Enhanced Abandoned Mine Methane (EAMM)

After or during AMM it may be decided to switch to CO_2-Enhanced AMM (EAMM). A motivation may be to optimise the extraction of CH_4 or to advance CO_2 sequestration. EAMM builds on the theory that flooding the deeper parts of the mine with CO_2 will release additional amounts of adsorbed CH_4 and concentrate the remaining CH_4 in the shallow, updip parts of the reservoir. This may or may not be successful, but it requires no additional infrastructure than the AMM-extraction and CO_2-injection wells. In the unfavourable situation where the Cretaceous seal would prove to be unsuited to withstand superhydrostatic pressure, a minimum of 300 000 tons of CO_2 could still be injected safely (solution capacity of flooded mine). When the mine becomes flooded, this will result in very CO_2-rich mine water that is expected to enhance the sealing properties of the overlying reactive chalk by mineral trapping and therefore reduces the risk of spreading of contamination.

4.2.5. CO_2 sequestration

If the Cretaceous chalk and marl seal is suited for superhydrostatic pressures, then CO_2 sequestration in the abandoned Beringen mine is possible. Rock mechanical investigation of the chalk and marl may be necessary, as has already been done for the aquifer storage at Loenhout in the Western Campine basin (see Tab. 1). Other requirements, such as the availability of reliable and nearby CO_2 producers and determination of the storage capacity, were already evaluated positively. Apart from these technical issues, it is a matter of policy if priority is given to maximal extraction of CH_4 or if the need for CO_2 sequestration is more pressing.

4.2.6. Enhanced coalbed methane extraction (CO_2-ECBM)

Enhanced coalbed methane extraction with use of CO_2 (CO_2-ECBM) is currently at an early stage of development, and technical uncertainties still exist around this storage option (CO2NET, 2002), especially for its application in Europe where geologic conditions are not favourable for classic coalbed methane extraction (CBM). One of the main reasons for this is the low permeability of coal in European coal fields. It has been suggested that the zones influenced by mining activity provide more favourable conditions because of the mining-induced fracturing (Van Tongeren et al., 2002). This hypothesis can be tested once the mine has been filled with CO_2

Borehole	Depth (m)	Porosity (%)	Density (g/m³)	k (mdarcy)
7E 225	1048.68	12.8	2.71	0.026 at 68 bar,
				displacement P >150 bar
7E 281	1031.30	36.2		2.58
16E 229	856.15	36.6	2.71	1.49
16E 231	1030.53	14.6	2.71	0.27
16E 232	1035.0	11.7	2.70	0.009

Table 1. Petrophysical data of sandy basal Cretaceous chalk in the Antwerp Campine area (source Distrigaz)-(borehole numbers refer to the GeoDoc filing system of the Geological Survey of Belgium). Because the purpose of the study of Distrigaz was identifying possible reservoir leaks, samples with the seemingly highest permeability and/or porosity were selected. Therefore, the overall permeability will be much lower, although this needs to be verified by new tests.

by placing methane extraction wells in or close to the mine-influenced zone. If successful, new injection and production wells may be placed away from the mines. This hypothesis opens the possibility to sequester CO_2 and produce CH_4 in unmined coal after, and thanks to, CO_2 sequestration in abandoned mines. The potential benefits of ECBM are such that, in spite of the current technical uncertainties, pilot projects are operational or being started in the USA (Allison unit, operated by Burlington Resources in the San Juan basin), Canada (Alberta Research Councils projects), and Poland (RECOPOL = Reduction of CO_2 emission by means of CO_2 storage in coal seams in the Silesian Coal Basin of Poland) – (Gale, this volume).

4.2.7. CO_2 geothermics

Once the reservoir has been filled to a suitable pressure, it may be used to produce cheap, low-temperature geothermal energy using the CO_2 geothermics principle. This concept is new, but technical uncertainties seem to be limited. For the Beringen colliery, 800 000 MJ or 200 000 MWh may be produced when the top of the reservoir is cooled to 20 °C at maximum reservoir pressure. This comes down to a continuous production of 1 MW for a period of 25 years. The production can be optimised by further lowering the temperature and selecting the most suitable reservoir pressure (commencing CO_2 geothermics before the end of sequestration). CO_2 geothermics is a renewable energy source, but as with hot-dry rock techniques, heat is extracted faster than it is replenished, and it may take a long time before the geothermal gradient is restored.

5. Conclusion

CO_2 storage in the abandoned coal mines of the Campine basin can be realised with low initial costs, if the important issue of the sealing capability of the overburden is solved. CO_2 geothermics can form the final step in the use of abandoned coal mines as an energy system. It is a new concept for these mines, and therefore, several matters remain to be solved such as the exact behaviour of impurities on CO_2 phase transitions, the amount and extent of convection in relation to the geometry of the residual space, and the amount of heat that can be extracted relative to the potential heat. Reasons to further explore the opportunities of CO_2 geothermics are its potential to extract low-temperature heat from the sub-surface at relatively low cost, and the use it makes of stored CO_2, that can therefore be regarded as a recycled product.

The case study for the Beringen colliery shows that abandoned mines can be developed in several stages. Each of these has specific benefits, such as the reduced risk of spreading contamination, the production of environmentally friendly energy and/or the sequestration of CO_2. These options do not necessarily interfere with one another. This makes it possible to set up a transparent and phased development plan that highlights the benefits of each step, based on analysis of features, events and processes (FEPs)-(IEA GHG, 2003). CO_2 sequestration forms a fundamental part of this plan and is necessary for upgrading the abandoned Beringen colliery for the production of environmentally friendly energy.

6. Acknowledgments

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