REDUCING CARBON DIOXIDE EMISSIONS BY UNDERGROUND STORAGE IN AN ABANDONED COAL MINE - AN INITIAL STUDY

SNIŽOVÁNÍ EMISÍ OXIDU UHLIČITÉHO UKLÁDÁNÍM DO OPUŠTĚNÝCH PODZEMNÍCH UHELNÝCH DOLŮ - ZÁKLADNÍ STUDIE

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Abstract

This article is a basic study dealing with the issues of underground storage of carbon dioxide generated from different kinds of activities. Carbon dioxide can be stored underground as a free gas; gas dissolved in water, or can be adsorbed in the rock mass and in the remaining seams. The technology for processing and storage of carbon dioxide is known as Carbon Capture & Storage (CCS). The article focuses on the possibility to store CO2 underground at the Paskov Mine in the Czech Republic.

Abstract

Tento článek je základní studií zabývající se problematikou ukládání oxidu uhličitého, vznikajícího z různých druhů činností, do podzemí. Oxid uhličitý je možno ukládat do podzemí jako volný plyn, plyn rozpuštěný ve vodě nebo může být adsorbován v horninovém masívu a ve zbylých slojích. Technologie zpracování a ukládání oxidu uhličitého je označována jako Carbon Capture & Storage (CCS). Článek se zaměřuje na možnost ukládání CO_2 do podzemí v Dole Paskov v České republice.

Key words: carbon dioxide, Carbon Capture & Storage (CCS), geological storage, abandoned coal mine

1 INTRODUCTION

A number of evidences and studies suggest that one of the causes of global warming may be an increasing concentration of carbon dioxide in the atmosphere. Worldwide CO2 creates more than 60 % of the enhanced greenhouse effect. In industrialized countries, CO2 represents more than 80 % of greenhouse gas emissions. [1] For these reasons, it is desirable to properly dispose of CO2 (so that it does not damage individual components of the environment). One option being verified is to store CO2 back into the ground, from which its increased content originates actually. Also, the project of CO2 storage in deep mines appears and is experimentally verified as one of the many ways to store carbon dioxide into deeper layers of the earth's crust. However, it was demonstrated as well that this method is quite promising for a number of problems that need to be resolved. Significant efforts in this direction is manifested by the Environmental Protection Agency (EPA), which attempts to obtain information about the values of emissions and also initiate programs that would eliminate this negative phenomenon. EPA also applies a uniform classification of proportions of individual gases in the greenhouse effect and expresses it by an CO2 equivalent ($MtCO_2eq$), which means one million metric tons of the CO2 equivalent. For example, in this classification, methane has 20 times higher effect on the greenhouse effect than CO2. [2]

In June 2009, Directive 2009/31/EC of the European Parliament and Council of 23 April 2009 on the geological storage of carbon dioxide entered into force. This new directive, in order to contribute to the fight against climate change, establishes a legal framework for the environmentally safe geological storage of carbon dioxide (CO2) for the purpose of permanent capture. The essence is a relatively new technology consisting in the capture of CO2 from industrial installations, its transport and subsequent intrusion (injection) into a suitable underground geological structure (storage) for the purpose of permanent capture. This method is called Carbon Capture & Storage (CCS). The most difficult part of the process seems to be the very capturing of CO2 from flue gas. The use of CCS is extremely energy-intensive process. The technology consumes about 10-40 % of the energy produced by the plant itself. [4, 15]

In our country, taking into account the reserves of fossil fuels, it is expected to use CCS, particularly in brown-coal burning plants. The local energy company CEZ has already determined in advance a suitable plant for this principal project. The best location seems to be a territory owned by the mining company Moravské naftové doly (MND). In its vicinity, there is a power plant standing in a town of Hodonín, as well as the area of Ledvice in the North Bohemian region where new brown-coal blocks are to be built. The construction of – in this sense – a pioneering power plant is expected in 2015. It is assumed that the costs of construction of this plant will amount to CZK 10 billion. [4] Emissions of gases in CR in the year 2010 are shown in Tab. 1 [5].

Tab. 1 Carbon dioxide emissions from individual sources in the Czech Republic in 2010 [5]

Source of CO_2	**$MtCO_2eq$**
Production of electricity and heat	62
Other emissions from the energy sector	1
Industry	18
Households	10
Services	5
Transport	19
Total emissions in the Czech Republic	115

$MtCO_2eq$... million metric tons of CO_2 equivalent

This paper examines the possibilities of CO_2 storage in abandoned underground mines. This issue, particularly from the area of the Upper Silesian Basin, has already been dealt with by many authors, and laboratory experiments were performed as well. [18, 19, 20] Generally, with an increasing storage depth, pressure and temperature increase as well. In underground mines of the Ostrava - Karviná District, we expect a confining pressure of 12 MPa at a depth of 500 m below the surface, and 25 MPa at a depth of 1000 m. The temperature at a depth of around 1000 m can be more than 30 ˚C. Such conditions significantly determine the state of CO_2. Fig. 1 illustrates the phase diagram of CO_2 [6]. The diagram shows that when storing CO_2 to greater depths, where the pressure may be more than 10 MPa and the temperature higher than 30 ˚C, CO_2 enters the phase of fluid, possibly even supercritical fluid.

Volume LIX (2013), No.1
p. 1-11, ISSN 1802-5420

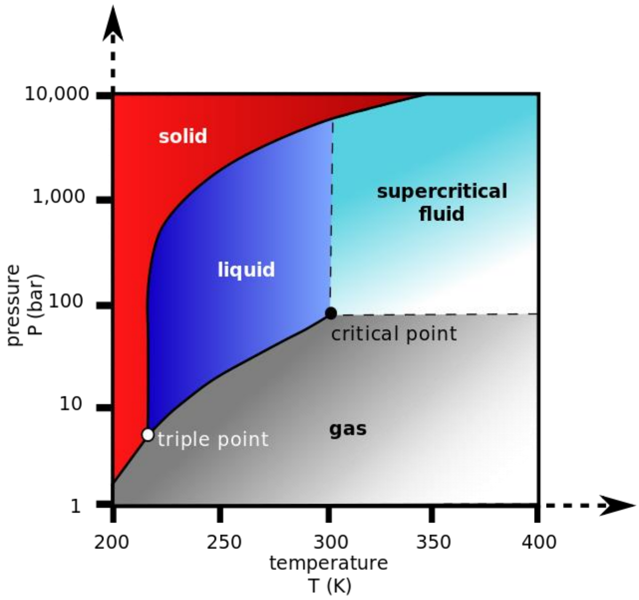

Fig. 1 The phase diagram of carbon dioxide (1 bar = 10^5 Pa) [6]

2 PRINCIPLE OF CARBON CAPTURE & STORAGE TECHNOLOGIES

The Carbon Capture & Storage (CCS) technology itself is not so complex as could be think. In the first step, the carbon dioxide is separated from the flue gas and captured with a special separation unit, which is built near the plant. Subsequently, the separated gas is transported (through pipeline) to the location, which was determined for its permanent storage. As suitable locations, we consider mined deposits of oil or natural gas and underground mines. In these locations, the gas is injected into the ground (of an abandoned working). The disadvantage, however, is that the company producing CO_2 must be built near the appropriate location (excavated sites). Already today, it is possible to permanently store up to 90 % of carbon dioxide emissions to the ground in such a way. [3, 7]

After determining a suitable site, carbon dioxide is injected into an underground reservoir; in the rock mass, it is accumulated in cracks or comes between grains and thus displaces present substances (e.g. water, oil, natural gas). For this reason, appropriate locations are the sites where rocks with high porosity and permeability are present. These requirements meet most sedimentary rocks of the so-called sedimentary basin. In some locations, permeable rocks alternate the impermeable ones. These rocks then act as an impermeable seal. Sedimentary basins are known by a frequent occurrence of oil and natural gas, and possibly natural CO_2. The long-term sealing ability of such rocks is confirmed by that these rocks were able to hold gaseous and liquid hydrocarbons for many years.

While the figures, which illustrate storing CO_2 underground, depict the rock composition in a simply way (as homogeneous cake layered structure), in fact these are unevenly distributed rock formations, reservoirs and seal rocks that are affected by local faults which together form complex heterogeneous structures. [8]

The European Union has issued a directive on storage of carbon dioxide into the ground and set up a consultation centre at the Technical University of Athens. In this centre, various technical problems are dealt with, associated with environmental risks, issues of management and geological research. The most serious problem in the use of this method, however, still remains its price, which is then reflected in increasing prices for produced electricity, which can grow up to 3 cents per kilowatt hour. The solution to rising prices could be the utilization of the deposited carbon dioxide to displace the oil into the borehole, which would increase the yield of oil fields.

In Europe only, 4 billion tonnes of carbon dioxide per year are discharged into the atmosphere. If commitments to reduce greenhouse gases set by the Kyoto Protocol are to be met by 2012, it will be necessary to realize this project for CO_2 storage in the ground as soon as possible. It is clear that the combined effect of improving energy efficiency and use of renewable energy sources will not be sufficient. [7]

Carbon dioxide can be stored into underground workings as a free gas; gas dissolved in water, or can be adsorbed in the rock mass and in the remaining seams.

The injection of carbon dioxide into the abandoned mine workings, however, is accompanied by many risks. In many areas, there is methane and other toxic volatile gases. The injection of carbon dioxide into the abandoned mine workings may result in the release of dangerous methane into the atmosphere and the consequent threat to the population in the area. [16, 17]

Another risk is the release of heavy metals and other elementary particles which may be present in coal seams and after the release may contaminate underground water, soil, but also air. Since the underground water supplies are strategic sources, the foregoing facts may represent a considerable problem for the storage of CO_2 in the ground. [9] The right selection of a suitable location for a long-term storage of CO_2 underground is a complex process that requires detailed pieces of knowledge on the geological structure of the site and considerable geological experience.

The most important prerequisites for the establishment of underground storage of CO_2 are as follows:

- appropriate porosity, permeability and storage capacity;
- presence of overlying impermeable rock – so-called "sealing rock" (e.g. clay, claystone, marlite, salt), which prevents CO_2 from the migration towards the surface;
- the existence of so-called "structural traps" - phenomena, such as the arched construction of a sealing rock, which can control and regulate the extent of migration of CO_2 in the storage formation;
- storing in a depth of 800 m, where there is a sufficiently high pressure and high temperature to ensure the storage of CO_2 in the compressed liquid phase, so as to ensure maximization of the stored quantities;
- absence of drinking water (CO_2 will not be injected into water intended for consumption and other use by population). [8]

3 POSSIBILITY OF STORING CARBON DIOXIDE AT A SITE IN THE CZECH REPUBLIC

As a default model site, the Paskov Mine in the southern part of the Ostrava-Karvina District was selected. This once original mine, now a plant, still produces a significant amount of residual methane. After the depletion of reserves it could be used as storage for CO_2. During this time period, however, it can only serve as a model example herewith that similar regularities must be examined for each additional convenient location.

The Paskov Plant is not connected with other mines, which this location along with the fact that in 2001 it was finally closed at all accesses with enclosures, predetermines for permanent storage of CO_2 underground. The location and geological profile of that area around the mine are shown in Fig. 2.

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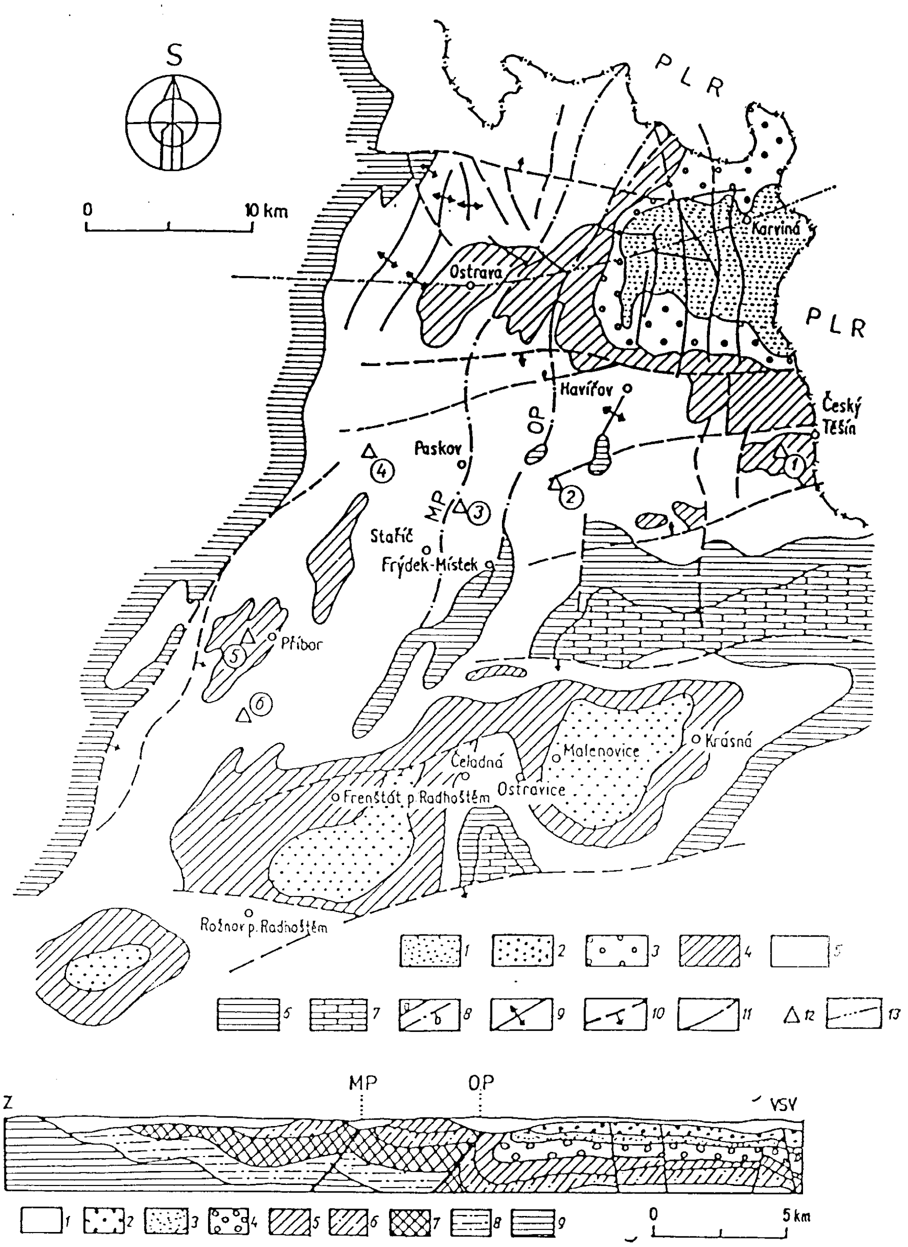

Fig. 2 Exposed geological map of the Carboniferous system in the Czech part of the Upper Silesian Basin and a geological section through the Ostrava ridge of OKR [12, 14]

Explanatory notes to the map: 1-3 - Karviná Formation - layers: 1 - Doubrava and Suchá, 2 - Suchá, Saddle including Prokop Seam, 3 - Saddle including Prokop Seam, 4-5 - Ostrava Formation - layers: 4 - Poruba and Jaklovec, 5 - Hrušov and Petřkovice, 6 - dinant (kulen), 7 - devon and dinant (carbonates), 8 - Michálkovice (MP) and Orlová (OP) fault: and mines-verified course, b - expected course, 9 - major anticline axes, 10 - breaks of fundamental importance, 11 - other faults, 12 - significant gas deposits, 13 - geological cut lines. Numbers (circled) next to gas deposits: 1 - Žukov, 2 -. Bruzovice, 3 - Staříč, 4 -Krmelín, 5 - Příbor - North, 6 - underground gas reservoir Příbor - South.

Explanatory notes to the cut: 1 - cover, 2-8 - Upper Carboniferous: 2-4 - Karviná Formation - layers: 2 - Doubrava, 3 - Suchá, 4 - Saddle, 5-8 - Ostrava Formation - layers: 5 - Prokop and Poruba seams, 6 - Jaklovec, 7 - Hrušov, 8 - Petřkovice, 9 – dinant.

3.1 Mining and geological situation of the Paskov Plant

Fig. 3 shows the mining area. It illustrates geological strata and coal seams. The mining area was formed by the Carboniferous cluster with a total mining area of 19.6 km^2. The dimension of the inlet of pits (mining and upcast) at the surface is +250.8 m B. p.v. (Balt after settlement). From the deepest level at an elevation of -630 m, dip workings were headed up to the elevation of -761 m. The mine was made available from the surface by 4 pits, from a total of which 2 are in the central part of the mining field and 2 in the marginal eastern and western parts. The highest first level was set at an elevation of -150 m.

Rocks of sets of superincumbent beds of carbon reach a thickness from 300 m up to 900 m and are nearly impermeable for the release of CH_4 from the mine area. This impermeableness was not violated either by undertaken excavations. In the period since the mine's establishment, mining areas of the order of 9.2 million m^3 were released by mining activities. With regard to their subsequent compression, collapse and consolidation over a certain time horizon, the remaining free volume can be deduced from the regularities of compression of the rock material. The compressibility for this case (in the long term horizon, i.e. years and over) from 25 % to 40 % can be a priori determined. This is a free volume of mining area from 2.3 million m^3 to 3.6 million m^3.

Technological factors participate in the decisions on possibilities of filling this area with the stored gas, as well. It is also necessary to take into account the fact that a number of existing mine workings (cross-cuts, corridors) was filled with various kinds of dams from simple dam counters to explosion-proof dams. These counters are designed for a maximum pressure of 1 MPa. Due to the distortion of rocks in their vicinity and the expected pressure in the reservoir (15 to 22 MPa), sealing dams thus do not affect the communication of gas throughout the space of the mine being damped down.

The mine operation in the period of its existence was marked by the emergence of coal and gas outbursts. This was associated with a high gas bearing property of the location and low permeability of any its parts. In the past period, theoretical and practical pieces of knowledge were obtained that can be used in the project and the assessment of the suitability of the proposed CO_2 storage. These include especially gathering a large set of values of permeability of the rock layers and the gas flow under these conditions.

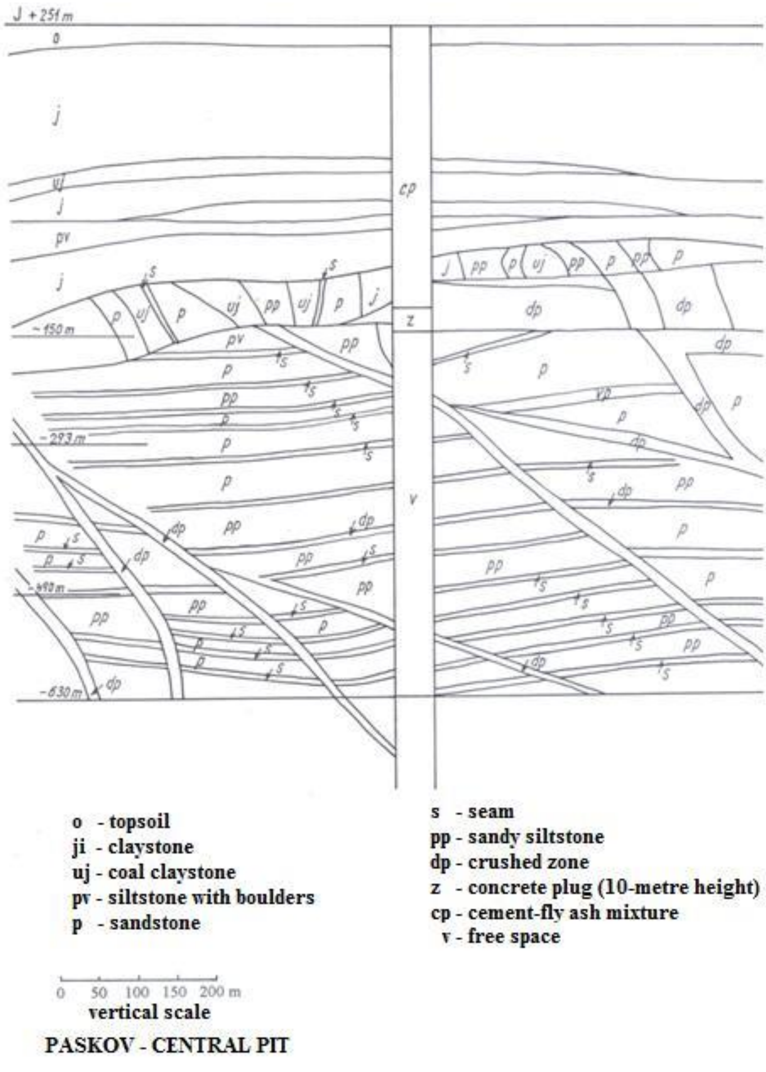

Fig. 3 The adjusted geological profile of the Paskov Mine with rendering the layers between the surface and the -150 m dimension [12, 14]

The average thickness of the mined seam reached 0.9 m. Accompanying rocks are composed of sandstone (about 40 %), siltstone (40 %) and clays (20 %). The firmest rocks reached the maximum compressive strength of 70 MPa (sandstone). Their thickness does not exceed 20 mA and due to tectonic segmentation no tremors of rocks have ever occurred in the Paskov locality. In terms of stability of the mine it is a quiet area without seismic activity. Activity induced by tremor phenomena can be excluded as well.

An important condition for the storage of CO_2 is an estimate to calculate the time period of flooding of individual levels of the mine. After the completion of mining activity at the mine the inflow of mine water is determined for about 259 m^3 per day at the tendency of flooding to a dimension of -30 to -50 m of the absolute depth, which is the position of the piezometric level of the detrital aquifer. If during a period of 23.7 years the mine area would be flooded to the third level (-630 m), there is still a free volume of 5.3 million m^3 for 56.7 years, and the additional volume of 1.5 million m^3 for 17.1 years. Because the consolidation of rocks will be gradual, the actual time period of flooding may be further increased (indicatively up to 40 years).

3.2 Permeability between the underground and the surface

To determine the critical point of the project, i.e. the possibility of gas leak from underground to the surface, the calculation of linear filtering according to the Darcy's theory was used (Equation 1).

$$Q = \frac{S \cdot (p_s - p_0) \cdot k_p}{2 \cdot \eta \cdot h} \qquad (1)$$

Where:

S calculation was made for the area S = 400 m^2 which corresponds to the area of the subsidence trough above excavations

p_s anticipated pressure of 15 MPa in the tank

p_0 atmospheric pressure at the surface of 0.1 MPa

k_p permeability coefficient for topsoil 10^{-8}, claystone $5 \cdot 10^{-18}$, claystone coal 10^{-14}, coal seam 10^{-10}, siltstone with boulders 10^{-14}, geologically very diverse layer just above the level – 150 m 10^{-16}, excavations 10^{-10} (m^2). Using the arithmetic mean depending on the thickness of each layer, „k_1“ between the level of -150 m and the surface $k_1 = 10^{-16}$ m^2 was found out.

h critical distance between the top level and the surface of 400 m

η_{CH4} dynamic viscosity of CH_4 $10{,}26 \cdot 10^{-6}$ Pa·s (at 0˚C)
η_{CH4} dynamic viscosity of CO_2 $13.9 \cdot 10^{-6}$ Pa·s (at 0˚C)
γ specific mass for CO_2 1,9 kg/m^3 (at 0˚C)

The permeability of layers was investigated in-situ for the subject area in the earlier works like [10, 11].

The result of the equation is the total volumetric flow rate Q of gas that can escape from the mine to the surface with a surface area of 400 m^2. The volume flow rate of carbon dioxide amounts according to the equation to 5.35·10-5 $m^3 \cdot s^{-1}$, which is a slight flow rate indeed, but in a year this leak could achieve a volume of 1,687 m3. It is difficult to see how this theoretical leakage of CO2, which is 4.22 cubic meters per square meter of the area per year, could affect vegetation, as shown in [9].

Taking into account that the free space in the mine, the premises of which occupy 2.3 to 3.6·106 m^3, can be filled with the amount of carbon dioxide proportional to this volume, then the ratio between the stored and leaked gas is significantly positive in respect to the protection of the atmosphere.

To verify the value calculated according to Equation 1, the Fluent calculation program of the Institute of Economics and Management Systems, VSB-TU Ostrava, was used. The input data for this model was deliberately limited to the rock formation between -150 mA and the surface. The resulting values were then adjusted as different areas of the mine may have different values of permeability.

3.3 Verification of the opportunities and risks when storing CO_2 in the location of the Paskov Mine using the Fluent program

The permeability of individual layers occurring in the area has been selected as follows:

- Topsoil $1 \cdot 10^{-6}$ m^2
- Claystone $1 \cdot 10^{-14}$ m^2

- Coal claystone $1 \cdot 10^{-12}$ m^2
- Siltstone with boulders $1 \cdot 10^{-13}$ m^2
- Sandstone $1 \cdot 10^{-11}$ m^2
- Siltstone $1 \cdot 10^{-10}$ m^2
- Seam $1 \cdot 10^{-8}$ m^2
- Crushed zone $1 \cdot 10^{-7}$ m^2
- Cement-fly ash mixture in the borehole $1 \cdot 10^{-5}$ m^2

Pressure acting underground is 10 MPa. It corresponds to a geostatic pressure at a given depth below the surface. The shoed depth is 450 metres. The gas permeability of cement - fly ash mixture in the borehole is irrelevant as it is closed on all sides. We can, therefore, assume that there is an airtight mixture in the borehole. The model of geological layers is shown in Fig. 4.

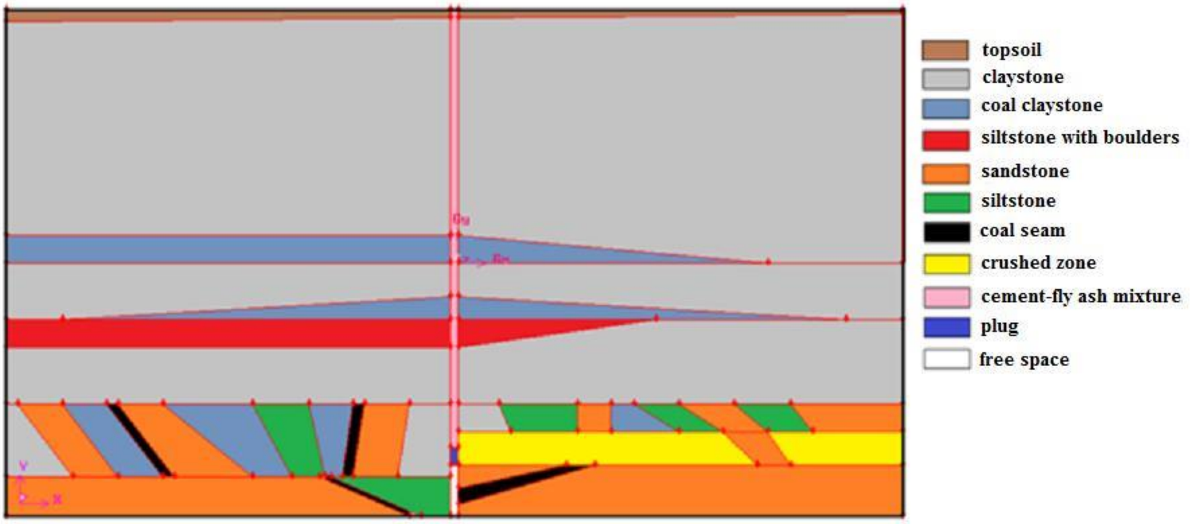

Fig. 4 Model of geological layers for the Fluent program [13]

The resulting values of static pressure calculated in the Fluent program from the specified input parameters are shown in Fig. 5. The results show that in the environment modelled in Fig. 5, the static pressure is divided in the left and right parts of the model, depending on the configuration of geological layers. Just below the surface it reaches a value of 0.5 MPa which causes that the mass flow rate of CO_2 reaches 0.026 kg/s above ground. When compared with the result in accordance with the equation (1), the value is 3 orders higher, and it would probably cause significant problems. However, it must be counted with such contingency for the final draft. The negative value in the model at the surface (in the layer of topsoil) means that there is a pressure by 134 Pa lower than the atmospheric one, so that the surface pressure should be 101,200 Pa. [14]

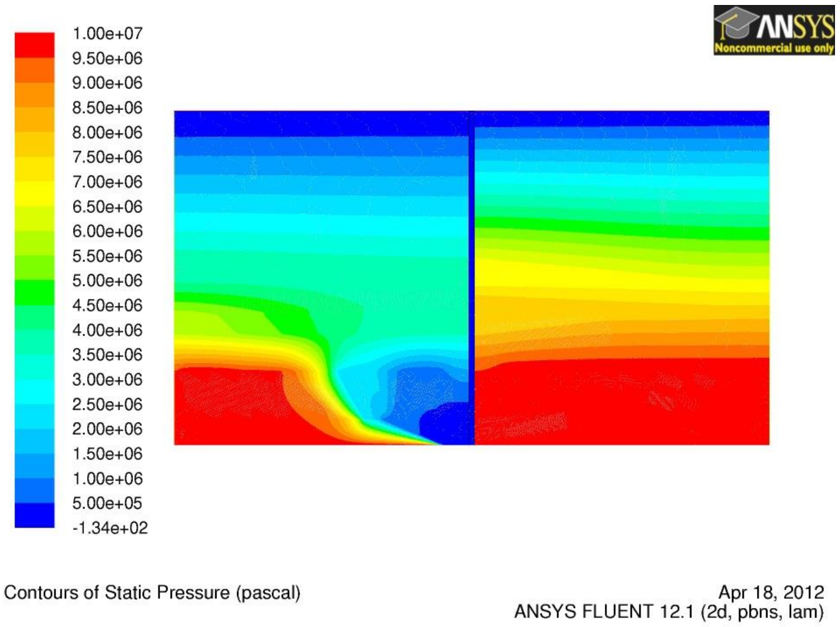

Fig. 5 Results of the distribution calculation of static pressure [13]

4 CONCLUSIONS

Even although there is no consensus of the scientific community, whether it is provable global warming is caused by increased carbon dioxide emissions, yet many individuals and organizations efforts are developed, this phenomenon not to be underestimated and timely implementation of measures to be realized to reduce the concentrations of CO2 in the atmosphere. As part of this activity, a number of scientific studies were performed and also some practical projects were implemented. Most suggestions look for a way to reduce the CO_2 content in a way of storing it underground. The procedure is quite logical, because most human activity of produced carbon dioxide comes from fossil fuels, which occurred in underground environments of the Earth. Also there are certain reservations to how it is stored underground. In any case, it would be advisable to invest not only into the CCS technology, but also into the technologies for generating energy from renewable resources. The article dealt with the possibility of storing CO_2 underground at the abandoned Paskov Mine. This is only a conceptual idea. To implement such a storage method, it is necessary to acquire a large range of input data, in particular the data on the geological survey of the site position and situation at the mine. It is also necessary to determine the properties of the rock mass, strength characteristics and in particular the data on gas permeability of layers, seams and the environment that was affected by mining activities.

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RESUMÉ

Tento článek se zabýval pouze základní studií možnosti uložení odpadního CO_2 do podzemních prostor již uzavřeného Dolu Paskov. Studie ukázala, že je nutno získat velkou škálu vstupních údajů. Jsou to především geologická pozice lokality a to ze širšího pohledu oblasti i užší situace na předmětném dole. Dále je nutno zjistit vlastnosti horninového masivu, pevnostní charakteristiku a zejména údaje o plynopropustnosti (permeabilitě) vrstev, slojí i prostředí, které bylo ovlivněno hornickou činností. Stávajícími matematicko – fyzikálními zákonitostmi bylo teoreticky řešeno, zda pod tlakem uložený oxid uhličitý bude nebo nebude mít možnost unikat na povrch.