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Original Research

Environmental Hazards Caused by Carbon Capture and Storage (CCS) Technologies

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Abstract

According to European Union requirements and directives, the further development of the power industry based on hydrocarbon fuels is only possible with the application of CCS technologies in power plants. These technologies will greatly reduce carbon dioxide emissions into the atmosphere. Although carbon dioxide is not considered to be a toxic gas and its slight amounts are included in atmospheric air, in big concentrations it can pose a health or even life hazard to both humans and animals. Analyzing the individual stages of CCS technology, it may be concluded that the greatest risk is created by a potential failure of the pipelines transporting CO_2. In the case of failure, huge amounts of CO_2 may get into the surroundings, increasing its concentration in the closest vicinity of the damaged pipeline. This article identifies potential hazards to the environment resulting from these technologies. The gas transportation stage is considered most dangerous one. Sample results of the calculation of the hazard zones around pipelines transporting CO_2 under very high pressure are given. The hazard zones around a pipeline without the safety valves may include an area with a radius of 200 m.

Keywords: carbon dioxide, pipeline transportation, risk

Introduction

The problem of the effect of greenhouse gases on climate changes has been discussed for over 20 years. Although there are still controversies concerning the impact of carbon dioxide on climatic processes, the conclusions of the UN Conference on Environment and Development (UNCED) from 1992, as well as the later Kyoto protocol from 1997, call for a reduction in such emissions. Directive 2009/31 EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of CO_2 [1] regulates a number of legal and organizational measures related to the CCS technologies used in hard- and brown coal-fired power plants. The need of CO_2 capture, transport and storage is now becoming a formal requirement for the planned and now under construction coal-fired power plants with a high capacity of the order of 800-1000 MW. This is an issue of special importance for Poland, where hydrocarbon fuels (hard and brown coal in particular) will remain the main source of energy for many years to come, contributing to the production of huge amounts of CO_2. However, this problem concerns not only Poland but also many other countries whose power sector is based on coal, such as the USA, China, Russia, Japan, India, and Germany. It should be emphasized that the position of Poland is special because the EU policy in this matter is very restrictive and the chances of obtaining energy from renewable sources in our country are limited.

Therefore, in accordance with the above-mentioned European Parliament directive and of the Council, the Polish mining and geological law will have to be amended to account for issues related to CO_2 storage and to the assess-

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ment of the impact of this process on the environment. The CO_2 capture, transport and storage technologies have to be safe at any stage or time of their application [2-6]. Below, the existing CO_2 capture technologies are discussed briefly. The potential hazards to the environment resulting from these technologies are identified, and the area of the hazard zones around pipelines transporting CO_2 under very high pressure is determined. This particular stage is potentially the most dangerous to both humans and animals if they find themselves within the critical zone of a damaged pipeline.

The presented CCS (carbon capture and storage) technologies substantially lower the electricity generation efficiency. Therefore, it is required that they are used in power units with supercritical steam parameters, which may achieve 50% efficiency. The intensive research on the development of all these technologies has raised hope that the new solutions will cause only a slight reduction in the efficiency of the entire power plant, i.e. the application of these technologies will not result in a drastic rise in prices of electricity generated by such plants.

CO_2 Capture Technologies

Analyzing the progress made in research on CO_2 capture, it may be concluded that at present there are at least three technically mature technologies that could be used in the power industry [7]. The first is CO_2 separation based on chemical absorption using a solution of monoethanolamine (MEA). The effectiveness of this process depends to a large extent on the contamination of the flue gases with SO_2, NOx, and dust in particular. Intensive studies are also being conducted on the reduction in the energy consumption of the sorbent regeneration processes, as the use of this technology lowers the electricity generation efficiency in coal-fired power plants by up to 10%. It is anticipated that the application of new generations of sorbents may reduce that loss to a value slightly exceeding 4%. CO_2 capture installations based on this technology are already used in practice, both in experimental and real power plants.

The second technology is based on the gasification of coal before it is actually fired. A power unit using this technology is composed of 2 parallel processing lines containing a gasifier, a gas turbine and a heat recovery steam generator. The coal is pre-dried, pulverized and fed into the gasifier, where the temperature is 1,400ºC. The produced gas is purified and fed into the gas turbines. The flue gases from the gas turbines are fed further into the heat recovery steam generators. The steam generated by them is then used in the steam turbine. In installations designed to reduce CO_2 emissions, the hot gas from the generator is cooled with injected water. In an appropriate installation, a catalytic conversion of CO to H_2 and CO_2 occurs, and then CO_2 is separated. The efficiency of CO_2 capture exceeds 90%, depending on the installation type.

The third technology is based on what is referred to as Oxy-Combustion (oxygen combustion with CO_2 recirculation). In a boiler designed for oxy-combustion, oxygen is fed into the furnace chamber instead of air. The result is that the flue gases contain practically no nitrogen but CO_2 in the first place. A part of this gas is re-circulated into the furnace chamber, where together with the fed oxygen it ensures appropriate combustion conditions. The resulting flue gases are in practice pure carbon dioxide, which can now be captured, transported, and stored. This technology requires adding oxygen-producing facilities to the power plant, which will also lower the electricity generation efficiency by approximately 10%.

CCS Technical Risk

The assessment of risk related to the carbon dioxide capture and sequestration technology has to be carried out for each stage of the process, i.e. for the capture, transport, injection, and storage of CO_2. Individual CO_2 removal installations may employ different technologies of gas capture and different methods of transport, as well as different storage methods. The assessment of risk should take account of the social and economic aspects, but also the technical and geological factors that have a direct or indirect impact on the level of risk of the entire CCS technology. According to the definition of risk, the probability of its occurrence and its consequences should be assessed for each hazardous event scenario. Due to the complexity of the process of CO_2 sequestration and due to the different effects it might produce, the consequences of hazardous events may be expressed in monetary units and also in terms of hazard to the health and life of humans and in relation to environmental impact.

The first step in risk analysis is to define the scenarios of hazards that may occur at different stages of the CO_2 sequestration process. For example, depending on the applied CO_2 capture technique, the potential hazards are as follows:

- fire hazard or risk of explosion during oxygen combustion
- fire caused by leakage of amines
- fire caused by an uncontrolled leakage of syngas

The following might occur at the transport stage:

- leakage of CO_2 from transport pipelines, presenting a hazard to humans and animals in the area of the released gas cloud
- risk of exposure to the jet of gas with a very low temperature
- leakage of CO_2 from the installation and from intermediate storage points
- during sea transport, leakage from the CO_2 storage tanks in ports
- CO_2 leakage from ship tanks, which may pose a threat to the ship's crew

During CO_2 injection, leakage is possible from the installation and from the equipment used for gas injection.

Risk Related to CO_2 Storage

The main hazard related to underground storage of CO_2 is leakage of the gas from the storage site, its migration into other layers and – eventually – leakage into the atmosphere. The geological formations for the storage of CO_2 are composed of many layers with a different thickness, porosity, and permeability, and with a different chemical composition. All these factors decide about the possibility of safe storage of CO_2. It is anticipated that in practice the following structures may be suitable for storage purposes (Fig. 1):

- deep saline aquifers at depths exceeding 800 m with sandstone as reservoir rock
- structures formed from entirely or partially depleted oil or gas deposits that have already been used for oil or gas storage, and frequently also for the storage of accompanying CO_2 (oil recovery is often enhanced with carbon dioxide injection)
- unmined, deep coal beds containing methane (in this case, the injected CO_2 allows methane recovery)

All the above-mentioned geological structures may be used as CO_2 storage sites provided that their capacity is significantly higher than the anticipated amount of CO_2 to be injected. Moreover, these structures have to meet the requirements related to the minimum porosity of at least 10%, to the collector thickness of above 20 m, and to the appropriate permeability and size of the sealing overlayer.

It is estimated that in Poland there are at least 27 structures in saline aquifers and more than 80 depleted hydrocarbon deposits that may be taken into consideration as potential CO_2 storage sites. In any storage case, potential risk has to be taken into account. The risk may be classified into three main areas: environmental hazard, health hazard and economic hazard.

The environmental hazard relates mainly to the leakage of CO_2 which, by getting into the air, destroys the effect of any activities striving to reduce the concentration of this gas in the atmosphere. Moreover, carbon dioxide migrating in geological structures might contaminate the clean water reservoirs. Storage in the immediate vicinity of seas or lakes poses a serious potential threat of the gas getting into these water basins and thus upsetting the marine flora and fauna. The penetration of CO_2 into hydrocarbon deposits and a possibility of initiation of seismic activity of certain geological structures also could be dangerous [8].

The health hazard, related to the impact of CO_2 on humans and animals, concerns the effects of a high concentration of CO_2 on the one hand, and the effects of a decreased concentration of oxygen on the other. In higher concentrations, carbon dioxide has an adverse impact on human behavior and health. 1% concentration causes drowsiness and the value of 1.5% is the maximum concentration permissible in some professions, for example for submarine crews. Concentrations exceeding 2% have a slightly narcotic effect and result in higher blood pressure

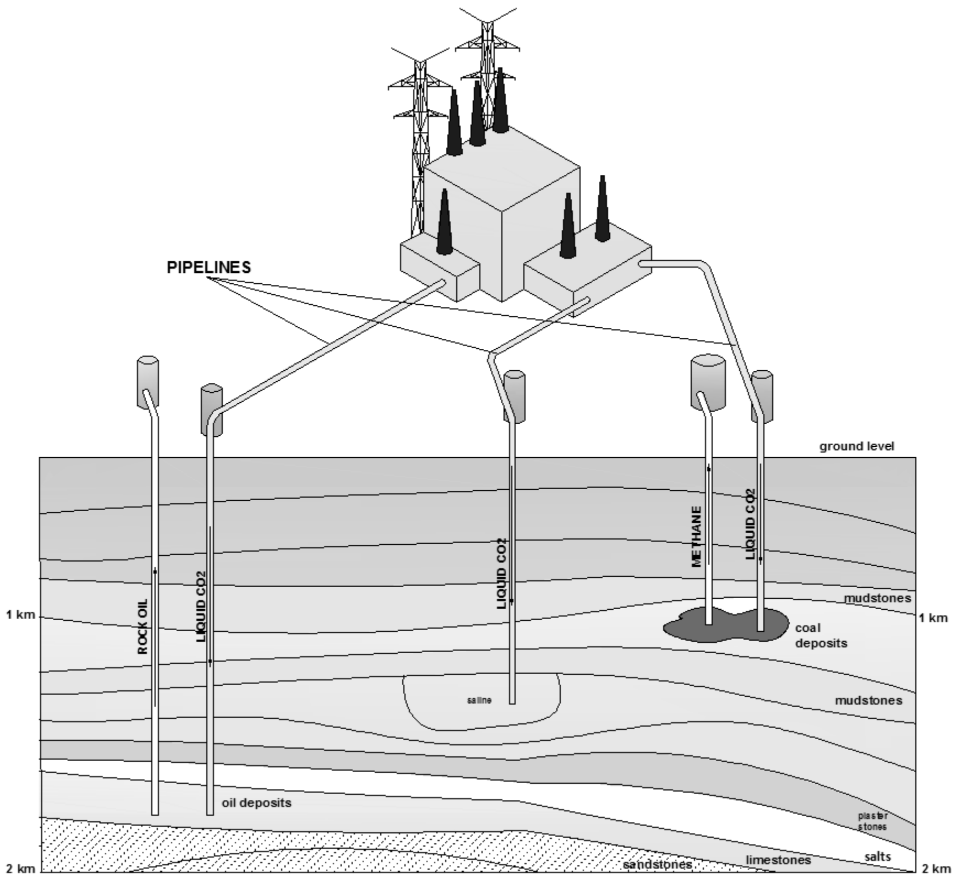

Fig. 1. Possibilities of underground CO_2 storage.

and pulse. Carbon dioxide also affects hearing acuity. In concentrations ranging from 3 to 5% it impedes breathing, raises blood pressure significantly, and causes dizziness and headaches. It multiplies the heart beat and it may bring about fits of panic. Additionally, at concentrations higher than 10%, loss of consciousness may occur and longer exposure results in suffocation. The hazard to humans is also related to the risk involved with the operation of the equipment and installations used for CO_2 capture, transport, and injection. A sudden leakage of gas streams with a very low temperature from damaged installations can cause burns.

The economic hazard of CCS technology is mainly related to a substantial rise in the price of energy generated with this technology. This in turn translates into higher prices of other products, making them non-competitive in markets that offer goods whose production is based on electricity generated by coal-fired power plants that do not use the CCS technology. The economic hazard also involves the costs of potential failures of the CCS installations, including the CO_2 transport installation. Additional losses may results from CO_2 leakage from storage sites. They will then be related to higher taxes on extra emissions of carbon dioxide into the atmosphere. It should also be mentioned that in high concentrations carbon dioxide intensifies the deterioration and corrosion processes in concrete and reinforced concrete structures, causing concrete carbonation and corrosion and deterioration due to the impact of CO_2. It also has an adverse effect on some plastics, e.g. it dissolves elastomeric seals.

Pipeline Transport Safety

Carbon dioxide transport via high pressure ground pipelines is the most effective form of CO_2 transportation [9-11]. Nowadays there are more than 6 thousand kilometres of CO_2 transport pipelines worldwide; most of them are in the USA and Canada. The diameters of these pipelines range from 0.3 to 0.7 m, and the pressure of the transported gas – from 10 to 20 MPa. In Europe such pipelines can be found in Holland and Norway. Most of them are located in poorly populated or totally uninhabited areas, which does not pose any threat to humans. The planned new pipelines for CO_2 transport from power plants will have to go across densely populated areas. Therefore, the assessment of the risk of an uncontrollable leakage of CO_2 from such a pipeline becomes an essential problem. Statistical data on the frequency of failure of pipelines transporting potentially hazardous substances such as natural gas together with the data concerning the failure rate of CO_2 pipelines indicate that the failure rate calculated per the pipeline unit of length and per unit of time is similar in both cases, although statistical data concerning CO_2 pipelines are much more limited. The data suggest that the main causes of damage to CO_2 pipelines are leaking valves, poor quality of weld seams, corrosion, and external factors such as human errors during excavation work carried out in close proximity to pipelines. The experience gained during the operation of these pipelines makes it possible to formulate a few remarks on the following aspects of their safety:

- the need to dry CO_2 to prevent corrosion
- avoidance of elastomeric seals in the CO_2 installation, as CO_2 can dissolve such materials
- the fact that in the presence of CO_2 some lubricants lose their properties and the gas itself features very poor lubricating properties, which has to be taken into account when designing compressors and pumps
- the need to account for the possibility of brittle cracking and crack propagation in the pipeline at the designing stage.

Another important element of safety of the pipelines transporting CO_2 is the correct placement of safety valves together with automatic gas leak detection systems. If the pipeline is damaged, the two valves neighboring the leak location close, thus limiting the amount of gas that gets into the surroundings to the amount of gas contained in between the valves. The optimum arrangement and the number of such valves are especially important in densely populated areas. These factors determine the size of the hazard zone around such a pipeline. Another measure to improve safety is carbon dioxide odorization, which facilitates the identification of the gas leak location. It results from the remarks presented above that the key element that prevents the adverse effects of uncontrollable CO_2 leakage is the determination of the hazard zones around the pipeline. These zones depend on the potential concentration of CO_2.

Modeling CO_2 Leakage from a Damaged Pipeline

In order to assess the potential hazard zones around a damaged pipeline, it is necessary to perform numerical simulations of the phenomenon of the CO_2 leakage through a hole in a broken gas pipeline. Assuming that carbon dioxide is transported in the liquid state [12] and that it features the parameters corresponding to Point A in Fig. 2, when the

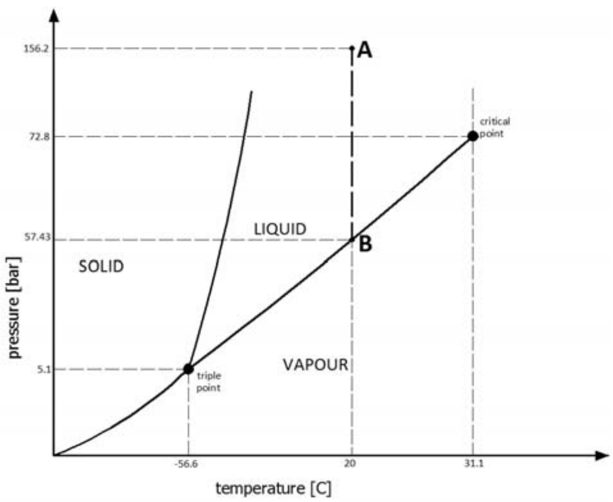

Fig. 2. Phase diagram of carbon dioxide.

pipeline is damaged, there is an abrupt drop in pressure, and a relatively slight change in temperature to the values corresponding to the parameters on the saturation curve (Point B).

Now evaporation and a two-phase flow proceed in the breakage zone, encompassing bigger and bigger areas of the pipeline. The carbon dioxide that gets into the atmosphere expands abruptly, which is accompanied by a significant decrease in gas temperature (Fig. 3).

Some example calculation results of the drop in temperature of CO_2 after it flows out of the gas pipeline are shown in Fig. 4. Fig. 4 presents the change in temperature depending on the distance from the outflow for two different pipeline diameters of 0.2 and 0.5 m. The pipeline of such diameters can be used to transport gas from the power units of medium and large power. The assumed pipeline length is 200 km. This length is the average length of pipeline transporting CO_2 in Polish conditions. In the calculations the following initial parameters of CO_2 in the pipeline before damage are assumed: temperature 20ºC, pressure 156.2 bar. Flowing out, the gas forms a cloud around the pipeline, which may be moved by the wind (Fig. 3). Due to the fact that carbon dioxide is heavier than air, the cloud will fall to the ground and will travel further, touching it. An example change in CO_2 concentration in the centre line of the cloud depending on time is shown in Fig. 5.

The areas of maximum concentration values of the gas for both diameter variants are shown in Figs. 6 and 7. The marked areas in the figures relate to CO_2 concentration values of 5 (risk to human health), 10 and 20% (risk to human life). The presented results of CO_2 outflow simulation are performed using the PHAST v.6.7 software package [13], with an implemented Unified Dispersion Model [14], assuming the Gaussian distribution of the concentration of released gases in the air.

The performed analyses show that for pipelines with diameters of up to 0.2 m and gas pressure p=15 MPa, the range of areas with a concentration higher than 10% (i.e. a concentration which is hazardous to the health and life of humans and animals), reaches 75 meters and encompasses an area of about 278 m². For pipelines with diameters of 0.5 m and pressures of 15 MPa the range is 225 m, encompassing an area of 3,457 m². The calculated sizes of the zones presenting potential hazard to humans are comparable to the hazard zones around pipelines transporting natural gas.

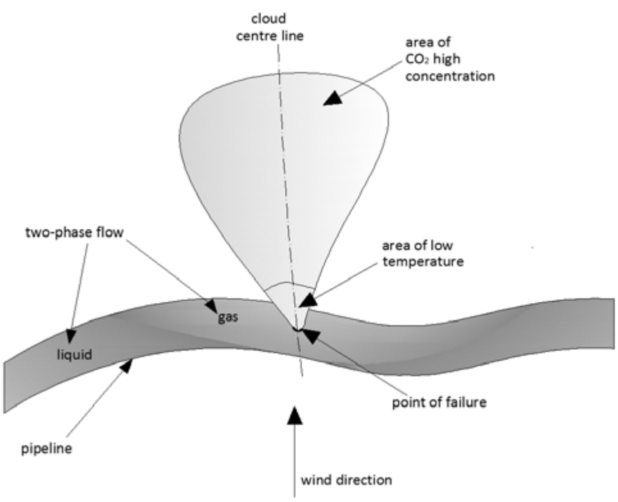

Fig. 3. Gas outflow from the damaged pipeline.

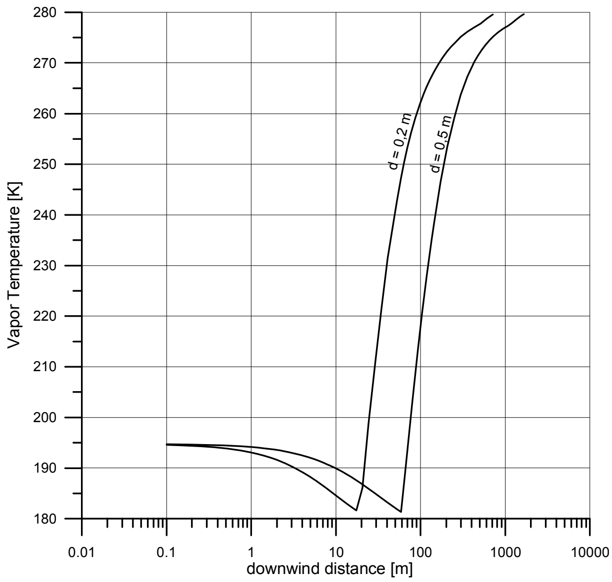

Fig. 4. Change in CO_2 temperature depending on distance from the outflow.

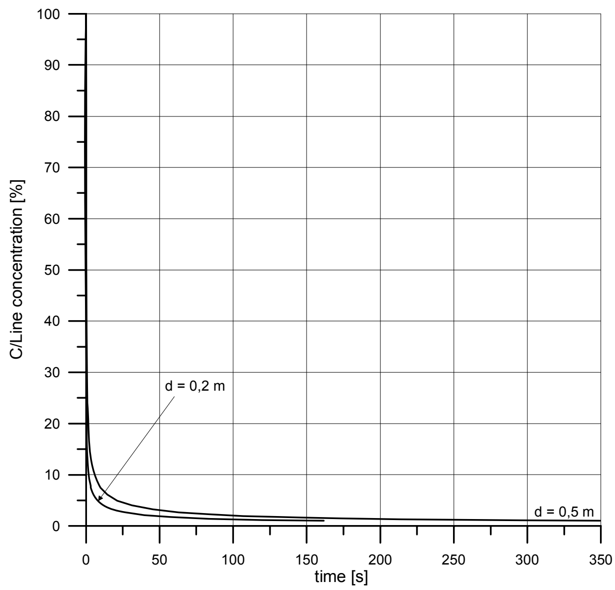

Fig. 5. Change in CO_2 concentration depending on time.

Conclusions

According to European Union requirements and directives, the further development of the power industry based on hydrocarbon fuels is only possible with the application of CCS technologies in power plants. These technologies will greatly reduce carbon dioxide emissions into the

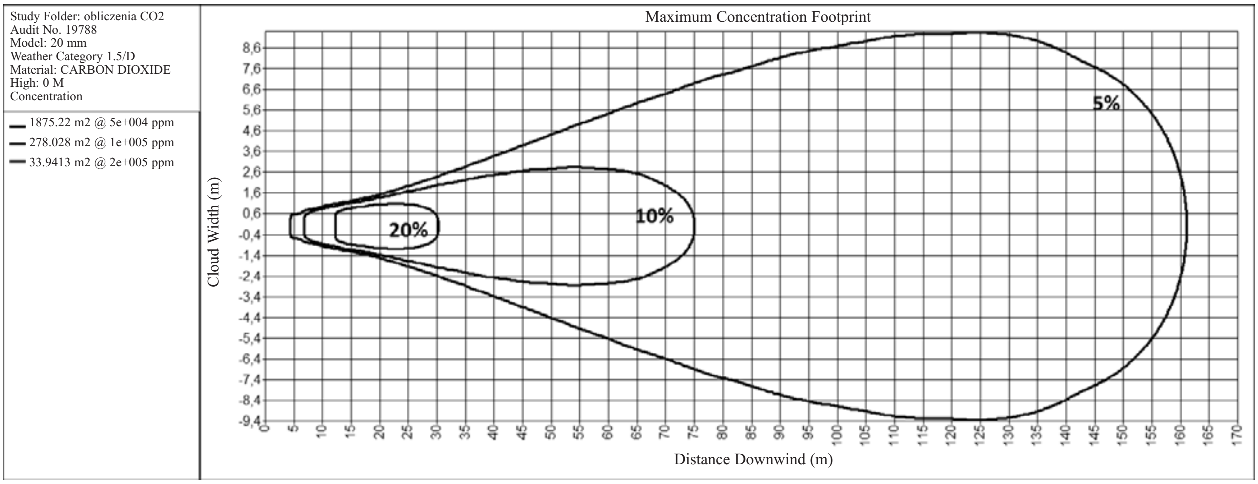

Fig. 6. CO_2 concentration areas for a 0.2 m diameter pipeline.

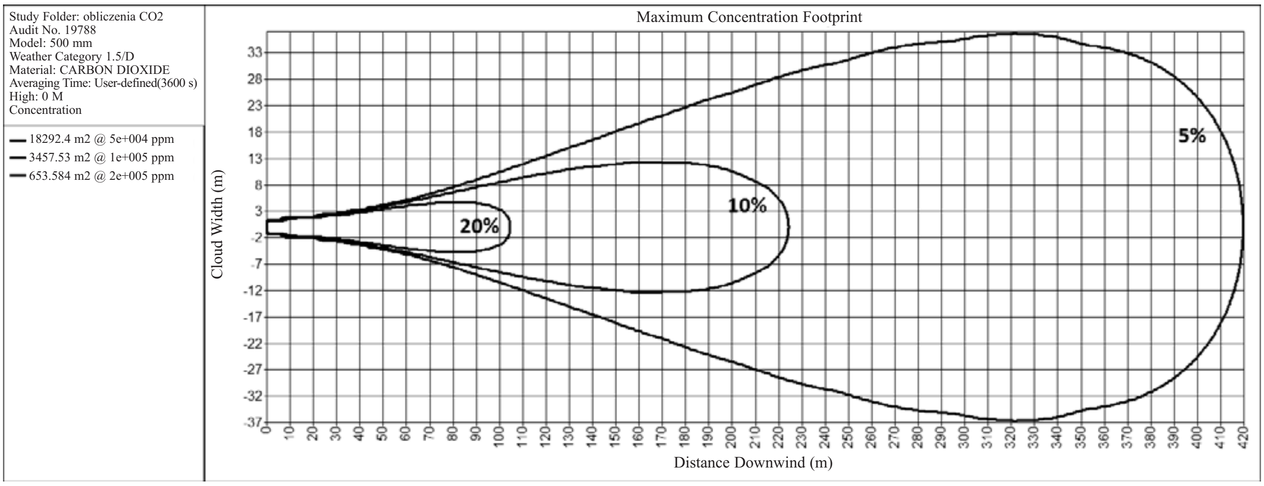

Fig. 7. CO_2 concentration areas for a 0.5 m diameter pipeline.

atmosphere. And this, according to the current stage of knowledge, should prevent the negative changes in climate. On the other hand, attention should be drawn to the hazards that these technologies involve and which could affect both humans and the environment. Although carbon dioxide is not considered to be a toxic gas and its slight amounts are included in the atmospheric air, in big concentrations it can pose a health or even life hazard to both humans and animals. Analyzing the individual stages of the CCS technology, it may be concluded that the greatest risk is created by a potential failure of the pipelines transporting CO_2. This results from the fact that transport via pipelines is carried out at extremely high pressures and that the pipeline diameters have to be relatively large, due to the amount of the transported gas. Consequently, in the case of failure huge amounts of CO_2 may get into the surroundings, increasing its concentration in the closest vicinity of the damaged pipeline.

The hazard zones given above depend of course on the amount of CO_2 that might get into the surroundings, i.e. on the damaged pipeline capacity. Therefore, in order to limit the impact of such a failure, CO_2 leak detectors and safety valves connected to them should be used so that the damaged section of the pipeline can be cut off if leakage occurs. This will limit the amount of the released gas and decrease of the critical areas.

The estimation of zones where a significant rise in the CO_2 concentration is possible after a pipeline failure should be made at the stage of planning the run of pipelines transporting CO_2. The calculations of such zones presented in the paper correspond to the dimensions of the pipelines and to the parameters of the gas that may be featured by the CCS installations to be built in Polish power plants.

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