GŁÓWNY
INSTYTUT
GÓRNICTWA

RISK ASSESSMENT OF A POST-COMBUSTION AND AMINE-BASED CO$_2$ CAPTURE READY PROCESS

Alicja Krzemień[1*], Angelika Więckol-Ryk[1], Adam Duda[2], Aleksandra Koteras[2]

[1] *Department of Industrial Risk Assessment, Central Mining Institute (Katowice, Poland)*

[2] *Central Mining Institute (Katowice, Poland)*

* *Corresponding author: e-mail: akrzemien@gig.eu, tel. +48 32 259 25 56, fax. +48 32 259 65 33*

Abstract

CO$_2$ Capture Ready Process, as a part of Carbon Capture and Storage (CCS) technology, is a response to international political pressure and the priority of the European Commission to reduce anthropogenic CO$_2$ emissions since it is connected with concerns regarding global warming. This is currently considered as an option for lessing CO$_2$ emissions into the atmosphere. Many laboratory experiments, as well as pilot projects, have been carried out using different capture systems, but until now no experience from the one-to-one size operational installation has been gained. The energy industry must meet several challenges associated with the start-up of the new full-scale project. This paper investigates the problems that can occur while linking a new technology like the CO$_2$ Capture Ready Process to a working fossil fuel power plant. A Hazard and Operability study (HAZOP) has been used, as it is a structured and systematic examination of a planned or existing process or operation, in order to identify and evaluate problems that may represent risks to personnel or equipment. A case study of a post-combustion CO$_2$ capture system with an aqueous monoethanolamine as a solvent is presented, as it is the most likely system to be used in Polish power plants. Basic problems in the analysis as well as the parameters that should be considered to determine vulnerabilities of the process were successfully identified. Gaining experience about the installation's behaviour while connected to the existing equipment of any power plant is critical for future CCS projects.

1. INTRODUCTION

The main objective of CO$_2$ Capture Ready Process, as a part of CCS technology, is to reduce carbon dioxide emissions into the atmosphere. Many projects that retrofit an existing power plant with a CO$_2$ Capture Ready Process installation are currently being conducted, among them a few large pilot facilities (Global CCS Institute 2013) using different capture systems, but until now no experience from a full size operational installation has been gained. Beginning a new full-scale project seems to be a great challenge for the energy industry. By building or modifying facilities to be Capture Ready we are trying to reduce the amount of carbon dioxide emissions using one of the three leading systems for capturing CO$_2$ from power generation, that is: pre-combustion, oxy-fuel combustion or post-combustion.

All new technologies should be investigated with special care, considering that the lack of information regarding previous incidents or accidents may be a great challenge for an evaluation team. Carrying out any study about CO$_2$ Capture Ready installation is time-consuming and very demanding because it should be done with a stong emphasis on engineering details. The main problem is limited knowledge concerning some technical aspects of the full size installation. Data is available from demonstration facilities, but those projects are far too small to provide an answer regarding full-scale plant problems. Gaining experience about the installation's behaviour while connected to the existing equipment of any power plant can be critical for future CO$_2$ Capture Ready Process projects. All this should lead not only to identifying problems while constructing and operating Capture Ready installations, but also to evaluate the level of risk for any identified deviation, as well as to find credible ways in which they could be overcome.

The main goal of the risk assessment is to identify all possible hazards that can appear within the system. They are not only essential to the system itself, but also they may have much wider influence, for example to the environment. Carrying out the research should give us an answer concerning all possible operability problems within the system. This seems to be quite demanding, especially considering that in the first step of the study all relevant information about the system must be carefully collected. Identifying hazards, analysing and evaluating the risks are the first steps towards successfully managing risk. This is the way to eliminate problems arising from the design or, in case it is impossible, to reduce the magnitude of risks caused by them. Any organi-

zation has to establish its own risk criteria, based on the experience of its working team and some other external indicators of possible hazards that may have the potential to cause negative consequences to the system. In this way unacceptable risks can be found and consequently the right solutions can be applied either by fundamental design changes or by providing protection measures (Macdonald 2004).

2. RISK ASSESSMENT

Risk assessment is the first step to prevent incidents or accidents within technical processes. It is important to determine all possible deviations in the system's performance that may lead to a risk (Macdonald 2004). This process can be divided in three main steps: risk identification, risk analysis and risk evaluation, being the most crucial part of the risk management process as shown in Figure 1.
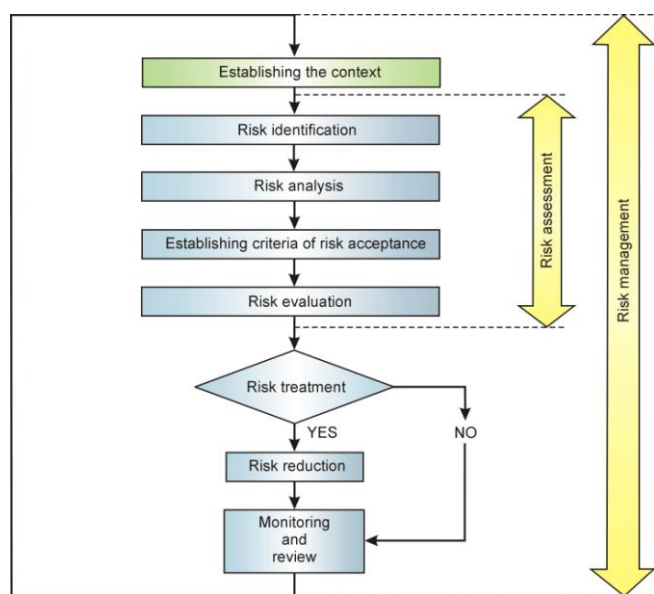

Figure 1. Contribution of risk assessment to the risk management process. Based on ISO/IEC 31010 (2010) and PN-N-18002 (2011)

The most important step within the risk assessment process is to correctly choose an appropriate method to define potential problems. The variety of techniques to identify potential hazards is wide, from checklists to Preliminary Hazard Analysis (PHA), Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis (FTA) and Hazard and Operability study (HAZOP), among others. Some of them are useful when there is not a lot information readily available about the process. On the other hand, techniques like HAZOP require more information regarding the system under consideration (BSI 61882, 2001), being more detailed and time consuming, but in some cases, especially when considering a new technology, remaining indispensable in order to repel threats to the success of a new project.

The right selection of the appropriate tool should be preceded by the definition of the main goal of each study. If a less detailed analysis is needed and we have limited access to information, a PHA may be the best solution, as it still gives an overview of the problem and it is quite easy to conduct. If the nature of the process is under consideration then FMEA is a good option, as it gives an answer regarding all possible interactions between different parts of the system;

FTA should be used when focusing on specific problems related to the technology, like the possibility of explosion, fire or other critical events which may appear. When a detailed and comprehensive study is needed to guarantee that all hazards, together with all deviations and operability problems, are identified and we have access to the technical information about the system like the Piping and Instrumentation Diagram (P&ID), then the best solution seems to be HAZOP (BSI 61882 2001).

A systematic approach to the problem seems to be the biggest advantage of the HAZOP technique, known as a diagnostic tool from the late 1960s and still used for the identification of operational disturbances and deviations within the systems. Over the years, the main HAZOP approach has not changed, but the way of identifying potential operability problems was developed by finding new applications within many industries like power generation, mineral processing and mining. HAZOP, if correctly applied, may indicate and prevent possible deviations in the operation of a processing plant, but can also cover unusual circumstances of the system such as start-up, shutdown and plant maintenance. The first step within the HAZOP study is to analyse the P&ID of the process in order to divide it into specific portions called "nodes", where all parameters describing the system can be identified. It is important to describe the essential features of the plant items, to explain the intended methods of operations and to prepare a process flow chart, so that the study team can improve their understanding of the process dynamics. This part of the study is crucial because any mistake at the early stage of HAZOP can strongly influence the overall analysis. The next step is to combine a series of guidewords with each parameter to create deviations and to capture most of the causes that may lead to risky situations. This is also a good opportunity to identify the possible consequences of each deviation and to discuss among the evaluation team safeguards and recommendations to prevent those events. What is more visible at this stage of the study is that the result of HAZOP depends more upon the experience and attitudes of the team than on the procedures themselves (BSI 61882, 2001; Kletz 1999). It is important to conduct analysis with the support of experts from the organization who may provide information about possible problems in the system's operation.

But what to do when a system does not exist and it is still in an investigation phase? This is the right moment to implement a HAZOP approach to check if the P&ID was correctly prepared and to study all possible deviations that may appear within the future system's operation. Strong support of an interdisciplinary group of experts is needed, so that all possible problems with the initial design can be identified. Also laboratory test and demonstrational projects, although developed in a smaller scale compared with the industrial needs would be a good source of information concerning process behaviour and the complications which may appear with its application to a full scale project.

3. POST-COMBUSTION AND AMINE-BASED CO_2 CAPTURE READY PROCESS

Chemical absorption processes based on organic solvents such as amines are currently the preferred option for post-combustion CO_2 capture. The most widely-studied solvent

for post-combustion CO_2 capture is an aqueous solution of monoethanolamine (MEA) (Abu-Zahra et al. 2007; Amann, Bouallou 2009; Global CCS Report 2012; Harun et al. 2012; IPCC 2005; Johnson, Reddy, Brown 2009; Notz, Mangalapally, Hasse 2012; Rao, Rubin, Berkenpas 2004; Reddy, Gilmartin 2008; Sønderby et al. 2013; Tenaska 2012). Systems using commercially available chemical solvents like MEA (mostly 30 wt % solution), with inhibitors to prevent degradation and equipment corrosion, are the best near-term option for CO_2 capture from power plants.

In general we can say that in a post-combustion system, CO_2 is captured from flue gas by passing it through equipment which separates most of the CO_2. The biggest advantage of this system is its ability to capture the carbon dioxide at the end of the flue gas production chain. In this way it is possible to retrofit any existing power plant with a capture unit. There are several commercially available process tech-

nologies which can be used for CO_2 capture from flue gases: chemical absorption, physical absorption, adsorption (pressure/temperature swing), gas membrane separation and cryogenic distillation (IEAGHG 2012). In Poland the most likely to be used in the near future is one based on chemical absorption, it was used in the Bełchatów Project which although was cancelled due to economic problems, had a great chance to be the first full scale CO_2 Capture Ready Installation.

Among the most commercially available technologies for chemical absorption of CO_2 the following five should be mentioned: Fluor's Econamine FG+, Mitsubishi Heavy Industries KS solvent, Cansolv Technologies, Aker Clean Carbon and Alstom's Chilled Ammonia Process (Global CCS Report 2012; IPCC 2005). In this paper we will focus on Capture Ready Post-Combustion Process based on aqueous MEA (30 wt % solution) as a solvent (Fig. 2), where CO_2 is removed from flue gas stream at low-pressure.
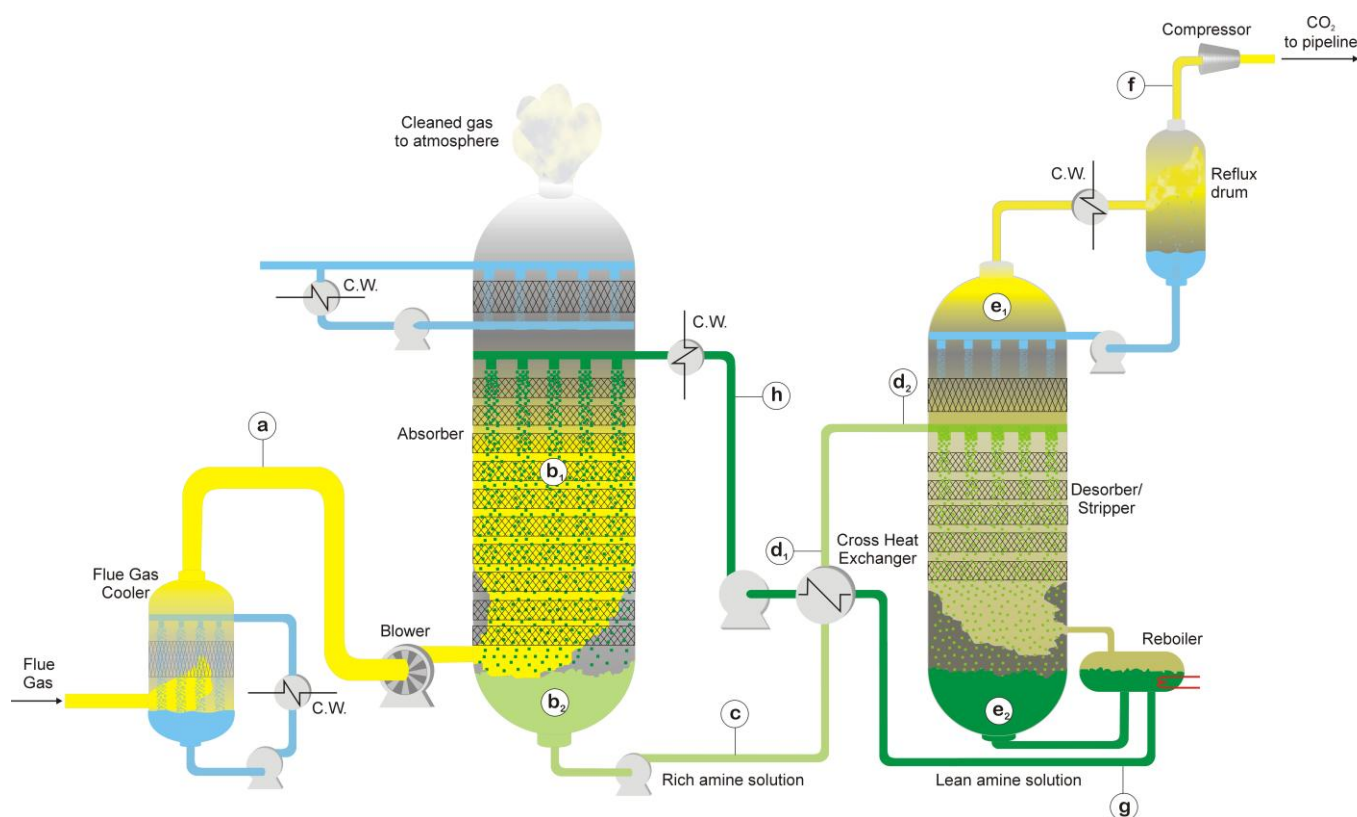

Figure 2. Simplified Amine "Capture Ready" Process flow diagram based on (Sanpasertparnich et al. 2010)

In the first step of this process flue gas from the Flue-Gas Desulfurization (FGD) unit is delivered to the cooler where it is cooled by circulating water at a temperature of about 40°C (other parameters of this process are presented in Table 1). In case of a high level of impurities in the flue gas, which may contain SO_2 and SO_3, it is necessary to scrub it by using a desulfurizing solution. The flue gas exits through the top of the cooler and is sent to a blower where it is slightly compressed. Then the gas enters at the bottom of the absorber, while at the same time MEA enters at the top of the absorber. CO_2 is removed from the feed gas by the lean amine solvent. Treated flue gas, consisting mainly of N_2 and O_2, is washed with a circulating water stream before leaving through the top of the absorber. When the amine stream is loaded with CO_2, as it is the case with the stream that leaves through the bot-

tom of the absorber, it is known as rich amine stream. The rich amine stream leaves from the bottom of the absorber and it is pumped to the cross-heat exchanger in order to exchange the heat with the lean stream from the desorber. Then the lean stream is further cooled, bringing its temperature down to around 40°C and it proceeds to the absorber. By that time a rich amine enters at the second stage of the desorber and flows down the column, going in the direction of the vapours from the reboiler. The overhead vapour from the desorber is cooled and most of the water is condensed out of the low pressure CO_2 product. The majority of the condensed water reflux returns to the top of the desorber, while the balance returns to the absorber. The remaining low pressure CO_2 product is routed to the compression section (Reddy, Gilmartin 2008; Sanpasertparnich et al. 2010; Tenaska 2012).

Table 1. Basic parameters of a post-combustion process based on MEA

Nº	Component	Pressure [kPa]	Temperature [ºC]	Flow rate [kg/s]	Medium
a	Pipeline from the FGD unit to the cooler	101	45	725	Flue gas before CO_2 removal
b_1	Absorber	109	40	–	Flue gas + amine
b_2	Absorber	109	57	–	Flue gas + amine
c	Pipeline with rich amine to cross-heat exchanger	109	57	3009	Rich amine
d_1	Pipeline from cross-heat exchanger to desorber	109	107	3009	Rich amine
d_2	Pipeline from cross-heat exchanger to desorber	109	103	3009	Rich amine
e_1	Desorber	186	103	-	Amine + CO_2
e_2	Desorber	186	123	-	Amine + CO_2
f	Pipeline from reflux drum to compressor	183	40	151	CO_2
g	Pipeline from reboiler to cross-heat exchanger	109	123	2858	Lean amine
h	Pipeline from cross-heat exchanger to lean amine cooler	109	67	2858	Lean amine

4. THE USE OF HAZOP FOR RISK ASSESSMENT OF CO_2 CAPTURE READY PROCESS

According to the USA Standard for process safety management (OSHA 1910.119, 1992), a Preliminary Hazard Analysis technique (PHA) is recommended for certain types of chemical facilities. This is way it has become a widely accepted technique for other industrial processes as "CO_2 Capture Ready" installations, although they are not mentioned within this regulation. This technique seems to be a good option for planned facilities but in some cases it may not be sufficient while analysing a new technology. That is why a HAZOP study might be a better and more effective solution. HAZOP analysis identifies the potential operability problems, but also other safety related risks as well as environmental hazards, which is the great added value of this study (Tenaska 2012).

While conducting a HAZOP analysis of the installation, 41 parts (nodes) were identified. All of them were reviewed in sequential order following a P&ID, so possible problems with the intended design would be found; equipment failures and safety hazards among them. The most important system parameters taken into account were: temperature, pressure, flow rate, material corrosion, composition, integrity and material properties.

Some of the possible deviations identified within the study are mentioned below, showing the complexity of the problem:

● material corrosion, resulting from the use of wrongly selected material, not resistant to monoethanolamine corrosive properties and CO_2 influence. Some cases of valves corrosion – due to the lack of stainless steel usage - are known from post-combustion tests, as well as some traces of condensation that were observed within the CASTOR project (Kittel et al. 2006), demonstrating that at a specific height in the gas pipeline a risk of local corrosion can appear (the corrosion rate of carbon steel was considerable in the "lean amine areas", at the outlet of the desorbed and at the inlet of the absorber);

● monoethanolamine degradation:
  – carbamate polymerization is the most common mechanism of amine degradation and it may appear in the desorber and in the reboiler with the presence of CO_2 and high temperature (over 100°C)
  – oxidative degradation leads to the formation of high molecular weight degradation products (Goff, Rochelle

2004). It can appear in the absorber when O_2 concentration in the flue gas is over 5% or when heat stable solids are formed (Davidson 2007; Yu, Huang, Tan 2012). The degradation could be mainly catalysed by the presence of iron and copper but also by nickel and chromium (Goff, Rochelle 2003)

  – thermal degradation leads to the formation of high molecular weight degradation products. It only takes place around the desorber, the cross-heat exchanger or the reboiler, where temperature is above 205°C (Davidson, 2007)

● decrease of flow rate or lack of flow rate to the absorber, both flue gas and MEA, caused by a pipeline blockage, an equipment failure or human error

● loss of solvent and/or flue gas, as a consequence of pipeline leakage

● overflow or reversed flow due to human errors or equipment failures (valves, pumps etc.)

● increase of pressure caused by an excessive accumulation of gas within the system (for example, caused by a gas outlet obstruction in the absorber)

● change in the flue gas composition (high level of impurities) as a consequence of a gas supply system failure or pipeline corrosion

Some other examples of "nodes" taken into consideration together with deviations analysed by the experts' team are presented in Figure 3. While conducting a HAZOP study the main problem which has to be overcome is the need to demonstrate system capabilities in a power plant setting where the quantities of CO_2 to be captured are typically several times larger than at any currently operating demonstration plant.

Nº	PART/"NODE"	PARAMETER	GUIDE WORD	DEVIATION	POSSIBLE CAUSE
92	Pipeline from blower to absorber	Flow	NO	No flow rate of flue gas to the absorber	Failure of the gas supply system to the blower and/or failure of the blower
93	Pipeline from blower to absorber	Flow	LESS	Decreased flow rate of flue gas to the absorber	Failure of the gas supply system to blower and/or failure of blower
94	Pipeline from blower to absorber	Integrity	NO	Loss of containment of the pipeline with flue gas	Mechanical damage to the pipeline (for ex. rupture)
95	Pipeline from blower to absorber	Integrity	NO	Loss of containment of the pipeline with flue gas	Installation error
96	Pipeline from blower to absorber	Integrity	NO	Loss of containment of the pipeline with flue gas	Materials defect
97	Pipeline from blower to absorber	Composition	PART OF	Presence of impurities in the flue gas	Failure of the gas supply system to the absorber
98	Pipeline from blower to absorber	Composition	PART OF	Presence of impurities in the flue gas	Pipeline corrosion
99	Pipeline from blower to absorber	Corrosion	AS WELL AS	Pipeline corrosion	Presence of acid impurities in flue gas and use of non-stainless steel
100	Absorber	Integrity	NO	Loss of containment in the absorber	Mechanical damage to the absorber
101	Absorber	Integrity	NO	Loss of containment in the absorber	Installation error
102	Absorber	Integrity	NO	Loss of containment in the absorber	Improperly selected material
103	Absorber	Flow	NO	No flow rate of flue gas in the absorber	Failure of the gas supply system to the absorber
104	Absorber	Flow	NO	No flow rate of the MEA in the absorber	Failure of the MEA solution supply system to the absorber
105	Absorber	Flow	NO	No flow rate of the MEA in the absorber	Lack of the MEA solution in the MEA storage tank

Figure 3. Example of a HAZOP worksheet for some elements of a post-combustion and amine-based CO_2 Capture Ready Process

Also we must remember that an amine-based post-combustion system may introduce a number of environmental risks that must be evaluated. They could result from process emissions to the air and land, but also from big system changes in mass and energy flows when a capture unit is added to a power plant (IRGC 2009).

5. CONCLUSIONS

CCS technology is relatively young and is of interest to many researchers all over the world, but is still being developed within a process of technology changes. Many laboratory experiments, as well as pilot projects, have been undertaken using different capture systems, but until now no experience from full-size operational installations has been gained. The energy industry must meet several challenges associated with the start-up of new full-scale projects, which may introduce new technical problems. Most of them are related with the properties of the materials used and the technologies applied, and can be identified at the first stage of the project if the appropriate tool is implemented. That is why a HAZOP analysis seems to be a good option for identifying potential operability problems and further risk assessment, as industrial process operations are never completely risk-free.

The main goal of any risk assessment is to identify all possible failures of the intended design, so that safeguards and actions required for improving the safety of the process could be implemented when scaling up the technology to a constructible design at a commercial size. All this can only be done properly in the context of a particular power plant, employing a specific Capture Ready Technology. Although it seems that Capture Ready Technology has little potential to cause major hazards both to the environment and humans, at the same time the complexity of the process and the specific instrumentation introduce a wide range of possible deviations in the operation of a full-size plant. This makes a HAZOP analysis very complex and time-consuming, but it is the only approach to guarantee that everything possible was done to prevent accidents and other harmful consequences.

References
1. Abu-Zahra M.R.M., Niederer J.P.M., Feron P.H.M., Versteeg G.F. (2007): CO_2 capture from power plants: Part II. A parametric study of the economical performance based on mono-ethanolamine. International Journal of Greenhouse Gas Control, 1(2), 135–142. DOI: http://dx.doi.org/10.1016/S1750-5836(07)00032-1
2. Amann, J.-M.G., Bouallou C. (2009): CO_2 capture from power stations running with natural gas (NGCC) and pulverized coal (PC): Assessment of a new chemical solvent based on aqueous solutions of N-methyldiethanolamine + triethylene tetramine. Energy Procedia, 1(1), 909-916. DOI: http://dx.doi.org/10.1016/j.egypro.2009.01.121
3. BSI 61882 (2001). STANDARD. Hazard and operability studies (HAZOP studies) – Application guide: IEC.
4. Davidson R.M. (2007): Post-combustion carbon capture from coal fired plants – solvent scrubbing. Vol. CCC/125, pp. 58: IEA Clean Coal Centre.
5. Global CCS Institute (2013): The Global Status of CCS: 2013 Melbourne, Australia, (pp. 204).
6. Global CCS Report (2012): CO_2 Capture Technologies. Post Combustion Capture (PCC). Australia: The Global Carbon Capture and Storage Institute http://www.globalccsinstitute.com.
7. Goff G.S., Rochelle G.T. (2003): Oxidative degradation of aqueous monoethanolamine in CO2 capture. In: International Test Network for CO_2 Capture: report on 5th workshop. Vol. Report PH4/22, pp. 202–222. USA: IEA Greenhouse Gas R&D Programme.
8. Goff G.S., Rochelle G.T. (2004): Monoethanolamine Degradation: O_2 Mass Transfer Effects under CO_2 Capture Conditions. Industrial & Engineering Chemistry Research Vol. 43(20), pp. 6400-6408. DOI: 10.1021/ie0400245
9. Harun N., Nittaya T., Douglas P.L., Croiset E., Ricardez-Sandoval L.A. (2012). Dynamic simulation of MEA absorption process for CO_2 capture from power plants. International Journal of Greenhouse Gas Control Vol. 10(0), pp. 295–309. DOI: http://dx.doi.org/10.1016/j.ijggc.2012.06.017.
10. IEAGHG (2012): CO_2 Capture at Gas Fired Power Plants. Vol. 2012/08: The International Energy Agency Greenhouse Gas R&D Programme. http://www.ieaghg.org.
11. IPCC (2005): IPCC Special Report on Carbon Dioxide Capture and Storage: Prepared by Working Group III of the Intergovernmental Panel on Climate Change. B. Metz, O. Davidson, H.C. de Coninck, M. Loos, and L.A. Meyer (eds.). IPCC, Cambridge University Press, Cambridge, United Kingdom and New York, USA, 442 pp. Vol. 2.
12. IRGC (2009): Power plant CO_2 capture technologies. Risks and risk governance deficits (Concept Note). International Risk Governance Council. http://www.irgc.org.
13. ISO/IEC 31010 (2010): STANDARD. Risk management – Risk assessment techniques. Geneva: ISO/IEC.
14. Johnson D.W., Reddy S., Brown J.H. (2009): Commercially Available CO_2 Capture Technology. Power. Retrieved from POWER website: http://www.powermag.com/commercially-available-co2-capture-technology/
15. Kittel J., Pasquier D., Ropital F., Boudou C., Bonneau A. (2006): Corrosion experiments for CO_2 solvents. Paper presented at the 8th International Conference on Greenhouse Gas Control Technologies.
16. Kletz T.A. (1999): Hazop and Hazan – Identifying and Assessing Chemical Industry Hazards. Rugby, UK, Institution of Chemical Engineers.
17. Macdonald D. (2004): Practical hazops, trips and alarms: Newnes.
18. Notz R., Mangalapally H.P., Hasse H. (2012): Post combustion CO_2 capture by reactive absorption: Pilot plant description and results of systematic studies with MEA. International Journal of Greenhouse Gas Control, Vol. 6(0), pp. 84–112. DOI: http://dx.doi.org/10.1016/j.ijggc.2011.11.004.
19. OSHA 1910.119 (1992): STANDARD. Process safety management of highly hazardous chemicals.
20. PN-N-18002: 2011 System zarządzania bezpieczeństwem i higieną pracy. Ogólne wytyczne do oceny ryzyka zawodowego.
21. Rao A.B., Rubin E.S., Berkenpas M.B. (2004): An Integrated Modelling Framework for Carbon Management Technologies. Volume 1 – Technical Documentation: Amine-Based CO_2 Capture and Storage Systems for Fossil Fuel Power Plant. Pittsburgh, Pennsylvania: Carnegie Mellon University.
22. Reddy S., Gilmartin J. (2008): Fluor's Econamine FG PlusSM Technology for Post-Combustion CO_2 Capture. Paper presented at the GPA Gas Treatment Conference, Amsterdam, The Netherlands.
23. Sanpasertparnich T., Idem R., Bolea I., deMontigny D., Tontiwachwuthikul P. (2010): Integration of post-combustion capture and storage into a pulverized coal-fired power plant. International Journal of Greenhouse Gas Control Vol. 4(3), pp. 499–510. DOI: http://dx.doi.org/10.1016/j.ijggc.2009.12.005.

24. Sønderby T.L., Carlsen K.B., Fosbøl P.L., Kiørboe L.G., von Solms N. (2013): A new pilot absorber for CO_2 capture from flue gases: Measuring and modelling capture with MEA solution. International Journal of Greenhouse Gas Control Vol. 12(0), pp. 181–192. DOI: http://dx.doi.org/10.1016/j.ijggc.2012.10.010.

25. Tenaska (2012): Final Front-End Engineering and Design Study Report. Report to the Global CCS Institute. Retrieved from http://cdn.globalccsinstitute.com.

26. Yu C.-H., Huang C.-H., Tan C.-S. (2012): A review of CO_2 capture by absorption and adsorption. Aerosol Air Qual. Res. Vol. 12, pp. 745–769.