RESEARCH AND DEVELOPMENT OF CO_2 CAPTURE AND STORAGE TECHNOLOGIES IN FOSSIL FUEL POWER PLANTS

Lukáš Pilař, Pavel Slouka, Jan Hrdlička

ÚJV Řež, a.s, Husinec-Řež130,250 68 Řež, ČVUT Prague, Zikova 1903/4, 166 36 Praha, e-mail: pilar@egp.cz

This paper deals with calculation procedure that has been performed in order to evaluate suitability of a post-combustion CCS technology application in a recent power plant in the Czech Republic. The ammonia CO_2 absorption method and its advantages and disadvantages are described. The technology scheme with key components of the ammonia CCS has been analyzed and more detailed data are provided for each basic component, especially for energy consumption for cooling and compression. The impact of the incorporation of the CCS technology into a 250 MWe power plant fired by pulverized lignite coal was evaluated. The calculations are based on available operation input data of the power plant. Main parameters (e.g. net power output, efficiency or consumptions) are compared for the recent situation and after CCS installation. The main impacts of the ammonia CCS technology application are the decrease of electric efficiency by 11 %, the decrease of net electricity production by 62 MWe, and an increase of wastewater amount and need of consumables. The decrease of efficiency and net electricity production is particularly caused by high energy demands of compression of CO_2 and cooling of CO_2 – ammonia absorber. Also important is the increase of cooling water consumption for the absorbing stage.

Keywords: post combustion; CCS; ammonia

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1. Introduction

The issue of CO_2 emission reduction is currently the target of many research projects. In the Czech Republic, several lignite coal-fired power plants are in operation that should possibly apply the CCS technology. This work is part of a project that studies two methods of CO_2 separation – oxyfuel combustion and chemical absorption – and the storage of CO_2 in the geological structures. While the first method is more suitable for newly constructed plants, the second could possibly be applied in currently running power plants. We discuss in more detail the post combustion method based on chemical absorption of CO_2 and evaluate the key parameters for a given fossil fuel fired power plant.

2. Methods of CO_2 capture from flue gas

The methods of CO_2 removal from flue gas can be classified according to their chemical and physical principles as follows [1–4]:

- Absorption – scrubbing by an absorbing liquid
- Adsorption – adsorption at the surface of a solid matter or extraction by ion liquids
- Physical separation – membrane process, cryogenic separation
- Hybrid approach
- Biologic capture

The methods are currently at different level of their development, from laboratory scale to pilot units. For power plants in the Czech Republic, only the absorption techniques are considered because these are currently the most technically developed.

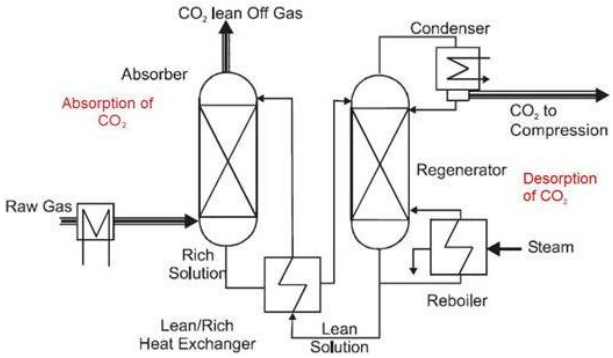

Figure. 1 The principle of absorption methods

The CO_2 is captured either by physical dissolving in a solvent or it undergoes a chemical reaction. The operation principle of the technology is similar for the two methods. The flue gas enters an absorption tower where it is scrubbed in counter-current by an absorption liquid (solvent). The saturated solvent is transferred to another tower where the solvent is regenerated and the dissolved CO_2 is removed at high concentration. During the operation, there are certain losses of the solvent. The losses are caused by unwanted reactions and products. Some solvent also escapes along with the flue gas. Therefore, the solvent is a consumable. At present, the most applied solvents are water solutions of:

- amines – various kinds (primary, secondary, tertiary, heterocyclic)
- ammonia
- carbonates of alkali metals (sodium or potassium carbonate)
- blended solutions

3. Suitability of the methods

Most literature references deal with detailed descriptions of the most developed absorption methods and usually include pilot plant data. The detailed information can be found about technologies that are currently under intensive development or technologies developed especially for application in existing power plants. We have selected two absorption methods of CO_2 capture that should be suitable for application in the Czech Republic. These two methods are the most advanced in technological development and they are supposed to be the first commercially used. The first method uses amine scrubbing and the second method uses ammonia. The other methods for CO_2 capture are currently under research and development process and do not exceed laboratory scale of application. These two methods are compared from the point of advantages and disadvantages for application in the Czech Republic and also from the point of energy and material demands. The main differences between the two methods are the following:

- **financial demands** – the investment costs are about 20 % lower for the ammonia method; the advantage for operation is the lower price of ammonia compared to amines.
- **chemical properties of the solvent** – both solvents are toxic and corrosive; amines tend toward oxidative degradation. However, more important is the degradation caused by SO_2 and NOx in the flue gas. The amine technology requires less than 30 mg/Nm^3 of SO_2 and NO_x compared to ammonia technology. The amine technology therefore requires additional desulfurization and the use of $DENO_x$ system.
- **operation temperature** – the amine technology works at higher temperatures. It requires higher steam parameters (temperature), while the ammonia method requires steam at about 140 °C. Generally, the heat consumption is higher for the amine method; however, the cooling consumption is higher for the ammonia – besides the cooling water it requires additional cooling supply, because the absorption takes place at approximately 0 °C.
- **CO_2 capture** – it has been found that the ammonia method can absorb three times more CO_2 per kg of solvent than the amine method. This is valid for monoethylene amine. However, research is being carried out to increase this capacity.
- **energy demands** – all information is available only from journal articles, conference proceedings or material from companies. The heat consumption is about 65% lower for the ammonia method. Efficiency decrease for the entire power plant is estimated to be 9 % for the amine method and 4 % for the ammonia method. The efficiency decrease has been calculated for a contemporary power plant using hard coal as the fuel.

Based on the facts mentioned above, the ammonia method was chosen as the reference method for the application in power plants in the Czech Republic.

4. Input parameters of the study and technology proposal

Parameters of a desulfurized flue gas from a reference coal fired power plant that were used in the technology proposal are summarized in Table 1.

Tab. 1 Input parameters

Dry flue gas	Nm^3/h	766 045
CO_2	% vol.	13,94
O_2	% vol.	5,44
N_2	% vol.	80,62
SO_2	mg/Nm^3	155,6
SO_3	mg/Nm^3	12,44
NO_x	mg/Nm^3	207,5
PM	mg/Nm^3	10,4
Water steam	Nm^3/h	218 493
Water (droplets)	kg/h	80
Temperature	°C	62

The ammonia process contains the following main components:

- flue gas cooling and flue gas fan
- CO_2 absorption
- final cleaning of the scrubbed flue gas
- CO_2 desorption
- CO_2 final cleaning
- CO_2 compression
- auxiliary cooling source
- ammonia treatment

More detailed description is provided in the following paragraphs:

- **flue gas cooling** – the absorption process in the ammonia method takes place at low temperatures 5 - 10 °C, therefore the flue gas must be cooled down as much as possible before entering the process. During the cooling condensed water steam is produced. Two stage cooling is proposed; in the first step counter-current water cooling, in the second step compressing cooling. A flue gas fan is proposed to be used after the cooling system to cover all pressure drops along the process.
- **absorption** – the absorber is in principle similar to the equipment used for flue gas desulfurization. The CO_2 is initially dissolved in water and then it reacts with a solution of ammonia and ammonium carbonate. Crystallized ammonium bicarbonate does not react further and it is removed to regeneration. The cooled-down regenerated solvent from the desorption is introduced into the highest level of the

absorption tower. After it exits the absorber, the flue gas passes through ammonia capture. The cleaned flue gas at approx. 10 °C enters a gas-gas heat exchanger, where is it warmed up by the flue gas entering the capture technology to approx. 50 °C. The flue gas is then transported to cooling towers. The suspension from the absorber is transported into a hydro-cyclone to dewater the ammonium bicarbonate to more than 50 % dry matter. The solution is transferred back to the absorber by pump at 3,2 MPa. The suspension passes a regenerative heat exchanger to be warmed up by the solution that returns from desorption. By heating, the crystals are melted and enter the desorption column.

- **flue gas final cleaning** – passing from the absorber, the flue gas enters the ammonia removal (scrubbing) device to remove the ammonia slip before the gas is released into the atmosphere.
- **desorption** – decomposition of ammonia bicarbonate to ammonia and CO_2 takes place here. The ammonia remains dissolved under pressure and CO_2 is released in gaseous form. The process takes place at 3 MPa and 120 °C. All reaction heat must be returned and additional heat to warm up the solution to 120 °C must be supplied. This heat is supplied by steam extracted from the turbine. The CO_2 stream is collected at the head of the column at approx. 115 °C and passes a cooler to cool down to 30 °C. Condensed water droplets are removed in a separator, and pure CO_2 is compressed to the pressure required for transport (10 MPa and temperature 50 °C). It means that the CO_2 is in supercritical state and liquid.
- **CO_2 compression** – a two stage radial compressor with an intercooler (integrally geared compressor) is proposed. The output temperature from the compressor will be 117 °C and further cooling is planned. This study proposes to integrate a separate cooling loop to utilize the heat from compressed CO_2 cooling.
- **auxiliary cooling source** - Two cooling sources will be used for the cooling. The first one (with the highest power) is a cooling loop with cooling tower. However, the required temperature around 0 °C cannot be reached here. For example, in summer the temperature would probably not be lower than 23 °C. Therefore, a compressing cooling is proposed with ammonia working fluid. The ammonia loop parameters typically reach -12 °C which is far sufficient for this purpose.
- **ammonia treatment** – it is necessary for storage and feeding of ammonia. Storage in liquid state is proposed.

5. Impacts on the existing power plant

The addition of the proposed technology will have negative impacts on the economy of the current power plant. The most important impacts are:

- **Increase of water consumption** – the proposed cooling demands a high amount of water. The proposed water consumption is calculated in Table 2. The calculation assumes the temperature difference in the cooling tower at 10 °C. The system is designed as closed with cooling water supply and dense salt water removal, according to the needs.
- **increase of energy self-consumption** – electricity need of main drivers are already known (compressor, flue gas fan, compression cooling). The self-consumption is estimated to be approx. 50 MWe and is calculated in Table 2.

Tab. 2 Energy consumption

Device		Value
Flue gas fan	MWe	2,03
Compression cooling	MWe	36,82
Compressor	MWe	6,32
Other	MWe	4,52
Sum	MWe	49,69

- **steam consumption** – steam is required in the desorption process to heat up the suspension. Approx. 20.7 kg/s – 50.0 MWt of steam is required. The steam extraction for CCS is supposed to take place between the middle- and the low-pressure sections of the turbine. At this point the steam has parameters suitable for the CCS technology.
- **consumption of demineralized water** – demineralized water is required for the absorber to sustain the required concentration and amount of the solvent.
- **efficiency decrease** – for this case, the post-combustion CO_2 capture technology decreases the power plant's efficiency by approx. 11 %. At the nominal power output of 250 MWe, the efficiency will be 28 %.
- **wastewater** – this studied technology produces wastewater that contains ammonia. All acid components of the flue gas (SO_2, SO_3, HCl, HF and NO_x) undergo reactions with ammonia in water environment. The products are ammonium sulphite, sulphate, chloride, fluoride, nitrite and nitrate. The proposed treatment of the flue gas before CO_2 capture makes them appear in the condensate from flue gas cooling. The residual acid components would be converted in the absorption-desorption cycle of CO_2. In any case, in the entire process these components will be fully captured and removed dissolved in water. This wastewater must be then treated. From economic and ecological perspectives, it is desirable to minimize the amount of ammonium compounds. This can be accomplished either by NO_x reduction by primary measures in the boiler, or by the application of a high-efficiency $DENO_x$ system, alternatively combined with desulfurization. Both approaches require higher investment and higher operation costs;

they are higher for the second option. It is therefore essential to make a cost analysis of the ammonium salts removal.

- **required area** –It can be found in the literature that for a power plant of 600 MWe the required area is very large (approx. 25 000 m^2.)

Tab. 3 Summary – clean gas

Parameter	Unit	Value
Dry flue gas	Nm^3/h	669 937
CO_2	% vol.	1.59
O_2	% vol.	6.22
N_2	% vol.	92.19
Water steam	kg/h	8489.15
Temperature	°C	50 *)

**) The temperature 50 °C refers to the gas that exits the gas-gas heat exchanger. Flue gas exiting the CCS absorber has temperature 10°C and must be heated before it enters the stack*

Table 4 summarizes all important calculated data for a reference power plant of 250 MWe running on lignite coal. It is separated by current situation and after CCS construction with ammonia scrubbing.

Tab. 4 Summary for 250 MWe reference power plant

Parameter	Unit	Current situation	With CCS
Power output	MWe	250	238
Coal consumption	t/h	214	214
Energy in fuel	MWt	588	588
Self-consumption	MWe	24	24
CO_2 production	t/h	211	211
Captured CO_2	t/h	0	190
Emissions of CO_2	t/h	211	21
Consumption of CCS	MWe	0	50
Net electricity generation	MWe	226	164
Total efficiency	%	38.4	27.9
Efficiency decrease	%	0	10.5

To lower the CCS impact on current technology, the heat from CO_2 compression (5.28 MWt) can be used in the steam cycle. The low potential waste heat will be utilized for preheating of the steam turbine condensate in the heater, which is placed in parallel to the low pressure heater n. 1. This arrangement results in 330 kWe increase in electricity output and total efficiency increase by 0.06 %.

When using this method of CO_2 capture, there are no other ways to reasonably utilize waste heat for the overall efficiency increase.

6. Conclusion

The presented study has shown that the ammonia post-combustion CO_2 capture method is, from a technology point of view, applicable for existing 250 MWe power plants running on lignite coal. The technology is quite well known and available. However, the impact is very significant. The calculations have shown that the addition of CCS technology reduces the total efficiency of the power plant by nearly 11 %. It means that the net electricity production decreases by approx. 62 MWe. The decrease is mostly caused by self-consumption of the new technology. It also means that the current electric efficiency of the power plant 38.4 % decreases to only 27.9 %. In addition, there are other negatives such as increased production of wastewater and addition of new consumables to the technology.

The study of the technical aspects of the proposed CO_2 separation and the study of its impacts on the existing power plant were completed last year. The economic aspects of the addition of the CO_2 separation unit will be examined this year.

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Summary

Lukáš Pilař, Pavel Slouka, Jan Hrdlička
ÚJV Řež, a.s., ČVUT

Research and Development of CO_2 Capture and Storage Technologies in Fossil Fuel Power Plants

The presented study has shown that the ammonia post-combustion CO_2 capture method is, from a technology point of view, applicable for current 250 MWe power plants running on lignite coal. The technology is quite well known and available. However, the impact of the capture method is very significant. The calculations have shown that the addition of CCS technology decreases the total efficiency of the power plant by nearly 11 %. It means that the net electricity production decreases by approx. 62 MWe. The decrease is mostly given by self-consumption of the new technology. It also means that the current electric efficiency of the power plant 38.4 % decreases to only 27.9 %. In addition, other negatives such as increased production of wastewater and addition of new consumables to the technology occur.