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

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Abstract

This paper presents the results of a research project on the suitability of post-combustion CCS technology in the Czech Republic. It describes the ammonia CO_2 separation method and its advantages and disadvantages. The paper evaluates its impact on the recent technology of a 250 MWe lignite coal fired power plant. The main result is a decrease in electric efficiency by 11 percentage points, a decrease in net electricity production by 62 MWe, and an increase in the amount of waste water. In addition, more consumables are needed.

Keywords: post-combustion, ammonia, fossil fuel.

1 Introduction

A key goal of many current research projects is to reduce CO_2 emissions. Several lignite coal fired power plants are operated in the Czech Republic where CCS technology might be applied. This work is a part of a project that studies two CO_2 separation methods: oxyfuel combustion and chemical absorption, and storage in geological structures. While oxyfuel combustion is more suitable for a newly-constructed plant, chemical absorption might be applied in power plantsthat are already in operation. This paper offers a detailed discussion of a post-combustion method based on chemical absorption of CO_2, with an evaluation of key parameters for a given fossil fuel fired power plant.

2 Methods of CO_2 capture from flue gas

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

- Absorption — scrubbing by an absorbent liquid
- Adsorption — absorption on the surface of solid matter or extraction by ion liquids
- Physical separation — membrane process, cryogenic separation
- Hybrid approaches
- Biological capture

These methods are currently at different levels of development, from laboratory scale to pilot units. For power plants in the Czech Republic, only absorption techniques are under consideration, because these are currently the most technically developed. In this case, the CO_2 is either captured by dissolving it physically in a solvent, or it is absorbed by a chemical reaction. However, these technologies have a similar operation principle. The flue gas enters an absorption tower, where it is scrubbed in a countercurrent 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 solvent, e.g. due to unwanted reactions and products, or the solvent is released along with the flue gas. The solvent is therefore a consumable. At present, the solvents that are most widely applied are water solutions of:

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

3 Suitability of the methods

The most developed absorption methods have been described in great detailin the literature, and there are reports on the operation of pilot plants. Detailed information can be found about technologies that are currently under intensive development, or that are being specially developed for application in current power plants. We have selected two absorption methods for CO_2 capture that are considered to be suitable for application in the Czech Republic. These two methods are in the most advanced stage of technological development, and they are supposed to be the first commercially built. The first method uses amine scrubbing, and the second uses ammonia as the solvent. Other methods for CO_2 capture are currently in the research and development process, but have not yet gone beyond laboratory-scale application. The advantages and disadvantages of these two methods are compared from the point of view of application in the Czech Republic, and also from the point of view of energy and material demands. The main differences between the two methods are as follows:

- **financial demands** — the investment costs are about 20 % lower for the ammonia method. An advantage when operating the plant is that ammonia is cheaper than amines.
- **chemical properties of the solvent** — both solvents are toxic and corrosive. Amines tend toward oxidative degradation, but the degradation caused by SO_2 and NO_x in the flue gas is a more important issue. The amine technology requires less than 30 mg/Nm^3 of SO_2 and NO_x in the flue gas from the combustion system compared to ammonia method. The amine technology therefore requires additional desulfurization, and the $DENO_x$ system alsoneeds to be used.
- **operation temperature** — the amine technology works with 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 method — besides the cooling water, it requires an additional cooling supply, because 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, studies are being carried out to increase this capacity.
- **energy demands** — information is available only from journal articles, conference proceedings and companymaterials. The heat consumption is about 65 % lower for the ammonia method. The decrease in efficiency for an entire power plant is estimated to be 9 percentage points for the amine method, and 4 percentage points for the ammonia method. The decrease in efficiency was calculated for a current power plant using hard coal as the fuel.

On the basis of the considerations discussed here, the ammonia method was chosen as the reference method for application in power plants in the Czech Republic.

4 Input parameters of the study, and a technology proposal

For the technology proposal, parameters of the flue gas after the desulfurization process from a reference coal-fired power plant were used. The parameters are summarized in Table 1.

The ammonia process consists of the following main components:

- flue gas cooling and the 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

A more detailed description is provided in the following paragraphs:

- **flue gas cooling** — the absorption process for the ammonia method takes place at low temperatures (5–10 °C), so the flue gas must be cooled down as much as possible before entering the process. Condensed water steamis produced during the cooling process. Two-stage cooling is proposed; the first step involves counter-current water cooling, and the second step involves com-

Table 1: Input parameters

Dry flue gas	Nm^3/h	766 045	NO_x	mg/Nm^3	207.5
CO_2	% vol.	13.94	PM	mg/Nm^3	10.4
O_2	% vol.	5.44	water steam	Nm^3/h	218 493
N_2	% vol.	80.62	water (droplets)	kg/h	80
SO_2	mg/Nm^3	155.6			
SO_3	mg/Nm^3	12.44	temperature	°C	62

pression cooling. A flue gas fan is proposed after the cooling system to cover all pressure drops in the course of the process.

- **absorption** — the absorber is in principle similar to that 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 is removed for regeneration. The regenerated solvent from desorption, which must also be cooled down in advance, is introduced into the highest level of the absorption tower. After the absorber, the flue gas passes through ammonia capture. The cleaned flue gas at approximately 10 °C enters the gas-gas heat exchanger, where is it warmed by the flue gas entering the capture technology to approximately 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 pumped back to the absorber at 3.2 MPa. The suspension passes a regenerative heat exchanger to be warmed by the solution that returns from desorption. The crystals are melted by heating, 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 it is released into the atmosphere.
- **desorption** — decomposition of ammonia bicarbonate to ammonia and CO_2takes placehere. The ammonia remains dissolved under pressure, and the CO_2 is released in gaseous form. The process take place at 3 MPa and 120 °C. All reaction heat and additional heat must be returned to warm the solution to 120 °C. This heat is supplied by steam extracted from the turbine. The CO_2 stream is collected at the head of the column at approximately 115 °C and passes a cooler to be cooled to 30 °C. Condensed water droplets are removed in the separator, and pure CO_2 is compressed to the pressure required for transport, which is 10 MPa and temperature 50 °C. This means that the CO_2 is in a supercritical and liquidstate.
- **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 proposed. In this study, a separate cooling loop will be integrated to utilize the heat from compressed CO_2 cooling.
- **auxiliary cooling source** — two cooling sources will be used for cooling the technology. The first (with the highest power) is a cooling loop with a cooling tower. However, the required temperature of around 0 °C cannot be attained there. For example, in summer the temperature will probably not be lower than 23 °C. Compression cooling with ammonia as the working fluid is therefore proposed. The ammonia loop parameters typically reach −12 °C, which is fully sufficient for our purposes.
- **ammonia treatment** — this is necessary for ammonia storage and feeding. Storage will be in the liquid state.

5 Impacts on the current power plant

The proposed technology will basically have a negative influence on the whole power plant. The most important impacts are:

- **increased amount of water** — the proposed cooling requires a large amount of water. The proposed water consumption is calculated in Table 2. The calculation assumes a temperature difference of 10 °C in the cooling tower. The system is designed as a closed system, filling with cooling water and removing dense salt water as needed.

Table 2: Calculated amount of water

Device	Removed heat	Cooling water	Evaporation	Condensate	Salt removal
	MWt	t/h	t/h	t/h	t/h
1st cooling stage	105.68	9 086.46	121.43	138.55	
Cooling of desorbed CO_2	8.68	746.35	9.97		
Compressor cooling CO_2 (1st stage)	2.03	174.69	2.33		
Total		**10 007.5**	**133.73**	**138.55**	**66.87**
Cooling of the compressor cooler	9 8.18	8 441.69	112.81		56.40

- **increased energy self-consumption** — the electricity needs of the main drives are already known (compressor, flue gas fan, compression cooling). The self-consumption is estimated at approx. 50 MWe, and is calculated in Table 3.

Table 3: Energy consumption

Device		**Value**
Flue gas fan	MWe	2.03
Compression cooling	MWe	36.82
Compressor	MWe	6.32
Other	MWe	4.52
Total	**MWe**	**49.69**

Table 4: Summary

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
CO_2emissions	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**

- **steam consumption** — steam is required for the desorption process, to heat up the suspension. Approximately 20.7 kg/s of steam is required.
- **consumption of demi water** — demineralized water is required for filling into the absorber to sustain the required concentration and the required amount of solvent.
- **decreased efficiency** — for this case, the post-combustion CO_2 capture technology decreases the power plant's efficiency by approximately 11 percentage points. At a nominal power output of 250 MWe, the efficiency will be 28 %.
- **waste water** — the waste water contains residues of salts, and the total amount of waste water will increase.
- **required area** — according to the literature, approximately 25 000 m^2 of free area is required for a 600 MWe power plant. This is a very high requirement.

Table 4 summarizes all important calculated data for a reference 250 MWe power plant running on lignite coal. The table is divided into the current situation and the situation after CCS construction with ammonia scrubbing.

6 Conclusion

The study presented here has shown that the ammonia post-combustion CO_2 capture method is suitable from the technological point of view for a current 250 MWe power plant 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 decreases the total efficiency of the power plant by nearly 11 %. This means that the net electricity production decreases by approx. 62 MWe, mostly due to the self-consumption of the new technology. It also means that the electric efficiency of the power plant falls from the current level of 38.4 % to just 27.9 %. Further negatives are increased production of waste water, and the addition of new consumables.

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