Ammonia emission from CO₂ capture pilot plant using aminoethylethanolamine

T. Spietz¹ · T. Chwoła¹ · A. Krótki¹ · A. Tatarczuk¹ · L. Więclaw-Solny¹ · A. Wilk¹

Received: 21 December 2016 / Revised: 5 May 2017 / Accepted: 19 July 2017 / Published online: 2 August 2017
© The Author(s) 2017. This article is an open access publication

Abstract Amine post-combustion carbon capture technology is based on washing the flue gas with a solvent that captures CO₂. Thus, a small fraction of this solvent can be released together with the cleaned flue gas. This release may cause environmental concerns, both directly and indirectly through subsequent solvent degradation into other substances in the atmosphere. The paper presents the ammonia emission from CO₂ capture pilot plant (1 tonne CO₂ per day) using 40 wt% aminoethylethanolamine solvent, along with the efficiency of the water wash unit. In addition, the temperature effect of lean amine entering the absorber on ammonia emission was studied. Furthermore, the concentrations of other compounds such as SO₂, SO₃, NO₂, CS₂ and formaldehyde were monitored. The literature review on the NH₃ emission from a pilot plant using aminoethylethanolamine solvent has not been published. The results show that the main source of ammonia emission is the absorber and that emission (in the range 27–50 ppm) corresponds to typical NH₃ release from CO₂ capture pilot plant using an amine solvent. The emission of amines and amine degradation products is a complex phenomenon which is difficult to predict in novel solvents, and for this reason the significance of new solvents testing in a pilot scale has been highlighted.

Keywords Aminoethylethanolamine · Ammonia emission · Carbon dioxide capture · Flue gas · Pilot plant

Introduction

Aqueous solutions of amines are commonly used solvents to remove CO₂ from flue gases in the amine post-combustion capture technology (Bernhardsen and Knuutila 2017; Ma'mun et al. 2007). Some of these amines, such as monoethanolamine (MEA), 2-amino-2-methylpropanol (AMP) and piperazine (PZ), are known to be volatile, and therefore they can be emitted to the atmosphere together with the treated flue gas stream (Khakharia et al. 2015). These amine compounds can react with other compounds in the carbon capture system and the atmosphere to form a wide range of components. The breakdown of amine compounds can result in a very wide range of other emissions. These emissions include ammonia, the primary and secondary short-chain amines (methylamine, ethylamine) as well as acids and aldehydes (i.e. acetic acid, formaldehyde, acetaldehyde) (Gouedard et al. 2012; Strazisar et al. 2003). The recent studies show that the volatile degradation products like ammonia and ethylamine are toxic and they may affect the human health through skin burns and irritation once they are vaporized with a treated flue gas (Låg et al. 2011; Verschueren 2008). Furthermore, the emission of carcinogenic nitrosamines and nitroamines poses large threat, even though the emission of these compounds is relatively low (Zhang et al. 2014; Bartsch and Montesano 1984). These emissions can lead to environmental hazards and solvent losses increasing operating costs (Knudsen et al. 2007).

One of the most emitted products of amine degradation is ammonia, primarily formed as a result of oxidative degradation of MEA. The amount of ammonia discharged to the atmosphere varies and depends on apparatus used for gas treatment (for example, water wash unit), on the kind of utilized solvent and on the process parameters

Editorial responsibility: M. Abbaspour.

✉ T. Spietz
tspietz@ichpw.pl

¹ Institute for Chemical Processing of Coal, Zamkowa 1, 41-803 Zabrze, Poland

(particularly the temperature together with the pressure in the absorber and the liquid-to-gas ratio). According to Khakharia et al. (2014) who have carried out CO₂ capture pilot plant tests, with a capacity of capturing 6 tonnes of CO₂ per day, while using MEA solvent, the emissions of ammonia (after wash section) were in the range of 10–70 mg/m³. Knudsen in his work (Knudsen et al. 2013) demonstrated ammonia emission in the range of 4–7 ppm (3–5 mg/m³). Those tests have been conducted at Aker Clean Carbon's Mobile Test Unit with capturing capacity of 200 kg CO₂ per hour using a novel solvent.

Three mechanisms of emission contribute to the release of amines and their volatile degradation products to the atmosphere. These emissions are: gas-phase emissions (vapour emission), mist emissions and liquid entrainment. Gas-phase emission is related to solvent evaporation and depends on volatility of the used amines, and also on CO₂ loading, and the temperature in the absorption column. The vapour pressure of the solvent increases with the temperature; however, it decreases with an increased CO₂ loading. Thus, formation of amine salts (both carbamate and bicarbonate) reduces the solvent volatility (Nguyen et al. 2011; Kolderup et al. 2011).

Liquid entrainment is a result of absorption liquid droplets being carried by gas flow. This phenomenon is well known and occurs wherever there is a contact between gas and liquid.

The most undesirable phenomenon related to the amine emission is the formation of mist (aerosol). Mist is caused by small droplets of water (or other liquid) that are suspended in a gas. Amine mist may be formed in the absorber when vapour phase amine is absorbed into fine water droplets. The suitable conditions to form mist occur, especially near the liquid distributors where a hot gas contacts with a cold stream of solvent. Due to the tiny size of the liquid particles, they tend to penetrate wash sections and conventional demisters.

A significant temperature difference between the gas and liquid phase results in a supersaturated environment, and thus amine emission in the form of aerosol increases as the temperature bulge increases (temperature bulge is the place in the absorber where the temperature reaches its maximum). Numerous studies indicate that aerosol-based emissions can be significant (Kamijo et al. 2013; Mertens et al. 2014; Khakharia et al. 2014). It is worth mentioning that mist formation depends in high extent on the presence of condensation nuclei, such as particulate matter, soot, SO₂, NO₂, H₂SO₄. These fine particles contribute to the heterogeneous nucleation being a dominant mechanism of aerosol formation in most industrial gas cleaning processes (Kamijo et al. 2013; da Silva et al. 2013; Khakharia et al. 2013).

In order to reduce the emission of amines and volatile degradation products, the washing systems such as water washing sections, acid wash and demisters are applied. Mitsubishi Heavy Industries, Ltd., implemented the first optimized washing system within an absorber column in 1994 and developed a proprietary washing system in 2003 (Kamijo et al. 2013).

A water wash section consists of a packed bed with a continuous recycle of water that is aimed at condensing and absorbing the volatile compounds and thus reducing their emissions. Demister consists of a wired mesh which can remove droplets larger than 10 µm with 99.99% efficiency. As it has been studied and described in the papers (Khakharia et al. 2014), the water wash and a demister are not effective in removing aerosol-based emissions as the aerosol droplets are typically much smaller than 10 µm. Thus, MEA emission after the water wash can exceed the permitted values. One of the applied solutions to reduce mist emission is an employment of Brownian demister unit. It consists of a candle filter elements which are composed of millions of fibres. Therefore, it is able to remove very fine droplets by means of impingement and diffusion mechanisms (Khakharia et al. 2014). Aker Clean Carbon have developed a novel concept for reduction of amines emission and volatile degradation products, consisting of the combination of antimist design and a pH-controlled polishing step (Knudsen et al. 2013).

The paper presents ammonia emission from CO₂ capture pilot plant (1 tonne per day CO₂) depending on the process parameters. The aim of this work was to evaluate the efficiency of the water washing section placed on the top of the absorber to reduce ammonia emission from a post-combustion CO₂ capture process. Current state-of-the-art shows that NH₃ emission from a pilot plant using aminoethylethanolamine (AEEA) solvent has not yet been presented in the literature. Furthermore, there is limited information on ammonia emission from post-combustion carbon capture (PCCC) pilot plants (Mertens et al. 2013; Knudsen et al. 2013; Khakharia et al. 2014). However, Saeed (Saeed et al. 2017) published interesting laboratory research related to thermal degradation of 2-aminoethylethanolamine (AEEA). The authors found that AEEA is unstable in the presence of CO₂ and the most abundant degradation product is 1-(2-hydroxyethyl)-2-imidazolidinone (HEIA). Therefore, in further investigations, it will be important to verify this finding at the pilot scale.

All the test results reported in this paper are based on test campaigns conducted in October, 2015, at the post-combustion CO₂ capture pilot plant located at the Łaziska Power Plant (Silesian voivodeship, Poland) owned by TAURON Polska Energia S.A., the second largest electricity producer in Poland (Tatarczuk et al. 2013).

Materials and methods

The CO₂ capture plant received its flue gas from 225 MWe hard coal-fired boiler. The flue gas stream was extracted downstream the power plant's desulphurization unit. The typical flue gas parameters were as follows: flue gas flow 200 m³/h (cubic metres at standard conditions in volume flow rate unit—1013 hPa, 273 K); CO₂ content 12–14 vol%; SO₂ content, max. 200 mg/m³; temperature range 70–95 °C and atmospheric pressure.

At first, flue gas was cooled down and dedusted in a direct water scrubber and sweetened in a desulphurization column, where SO₂ was removed. Sodium bicarbonate aqueous solution was mainly used as a solvent for desulphurization, and it maintained SO₂ concentration in flue gas below 10 mg/m³. Afterwards, the gas entered the absorber bottom and flowed upward through packing, where CO₂ chemically reacted with a lean amine solution to remove most of the CO₂. The 40 wt% aqueous solution of N-(2-aminoethyl)ethanolamine (that is also commonly named as aminoethylethanolamine) was used as CO₂ capture solvent. The AEEA (≥ 99 , 5% purity, CAS: 111-41-1) was obtained from Brenntag Polska Sp. z o.o. and was used without any further purification. The potable water was used to prepare an aqueous solution of 40 wt% AEEA. The final concentration of solvent was checked by acid–base titration (Weiland and Trass 1969).

The absorption tower was of 14 m height and 0.33 m diameter, including two sections of structured packing: Mellapak 350Y (5.1 m height) and Mellapak 500Y (3.3 m height). Desorption column (the stripper) was of 15 m height, and it contained two kinds of packing: structured Mellapak 750Y (0.28 m diameter, 4.3 m height) and random C-Ring 1" within the internal heat exchanger (0.5 m diameter, 5 m height) (Stec et al. 2015a).

Treated gas was passed through a one stage water washing section which is an integral part of the column (as shown in Fig. 1) and vented through the top of the absorber. The water washing section included 3 packed beds, 0.27 m each with a structured packing Mellapak 750Y. A low amount of fresh water (approx. 5–10 dm³/h) was added into the washing water recycle stream to avoid a high accumulation of amine recovered in the washing water and to compensate water losses. The average flow rate of circulating wash water was 50 dm³/h.

The flow sheet of the CO₂ capture process for the pilot plant and more technical details have been previously described in other paper (Stec et al. 2015b).

A Fourier Transformed Infrared (FTIR) analyser Gasmet DX4000 was used to analyse the gas leaving the absorber (Fig. 1). Additionally, the unit was equipped with a ZrO₂ sensor for accurate oxygen measurement. Gasmet DX 4000

is a portable analyser which is typically used in stack emissions monitoring, comparison measurements, catalytic process control and other applications where multiple gas compounds need to be accurately monitored in hot and humid sample gases. To avoid water condensation and thereby loosing water-soluble components, the gas sample was heated to 180 °C using a heated transfer line wherein the volatile compounds of the aerosol phase were vaporized and therefore they could be analysed. This system utilized hot and wet measurement principle, which ensures that the analysis was carried out on a representative sample. Previous studies showed that this technique was suitable for monitoring both inorganic and organic emissions from pilot plants (da Silva et al. 2013; Khakharia et al. 2014; Mertens et al. 2013). Unfortunately, AEEA emission measurements were impossible due to FTIR gas analyser limitations. The AEEA spectra are not available in the manufacturer's library, and thus that component has not been measured ("IR Spectrum Collection—Gasmet Technologies Inc.").

During the sampling, the pilot plant was operated at steady state conditions. Nonetheless, the flue gas composition varied slightly depending on coal-fired boiler parameters and finally resulted in fluctuations of measured concentration (that is clearly visible in the plots).

Results and discussion

Figure 2 presents an ammonia emission, water and CO₂ content in the treated gas at standard operating conditions of the absorber. The standard operating conditions were as follows: the flue gas flow entered the absorber of 280 kg/h, CO₂ content within the range of 13.1–13.3 vol%, with SO₂ below 3 ppm and finally with the absorber pressure of 130 (absolute) kPa. The lean solvent temperature was maintained at 40 °C. Typical fresh water make-up to water washing section was 6 m³/h.

Figure 2 shows that the NH₃ emission in treated flue gas is estimated to be 45 ppm (30.4 mg/Nm³), and it is kept at the constant level. The flue gas is heated up along the column due to exothermic reaction of the concentrated amine (AEEA 40 wt%) with CO₂. Therefore, treated flue gas temperature is relatively high (64 °C). The contact between gas and solvent at this condition results in a gas saturation and mist formation, and hence the water content in treated gas is high, approximately 17 vol%.

The solvent regenerated by heating in the stripper (desorber) results in CO₂ releasing. To verify the purity of obtained CO₂ stream, which can be utilized in further processes, the FTIR analyser was connected to CO₂ line, downstream the condenser (as shown in Fig. 1). Figure 3 shows the ammonia, carbon dioxide and water vapour

Fig. 1 Scheme of absorption and desorption column. The sampling points have been highlighted (Szczypiński et al. 2013)

Fig. 2 Ammonia emission and water vapour content in treated flue gas

content in CO₂ stream. Other measured components and remaining parameters are shown in Table 1. It can be observed that purity of CO₂ stream is very high as the CO₂ reaches 96.6 vol%. The other major component of this gas stream is water (3.3 vol%) which is related to water evaporation in the stripper and leads to gas saturation with water vapour because the temperature of CO₂ downstream the condenser is much lower than the treated flue gas temperature (i.e. 20 °C in comparison with 62 °C); for that reason, the water content also is lesser.

It is worth noting that the ammonia emission from desorption column is very low (below the detection limit).

Moreover, both SO_x and NO_x contents in CO₂ stream are also very low (below 1 ppm). Therefore, the CO₂ stream after dedicated purification and dehumidification can be successfully used in the further processes (Cuéllar-Franca and Azapagic 2015). These low concentrations of sulphur and nitrogen oxides result from that the flue gas before entering the pilot plant was sweetened in a wet scrubbers of desulfurization unit of power plant (FGD). Additionally, the flue gas was pre-treated in the water scrubber and in the desulphurization column of pilot plant where acid compounds and dusts were removed in sodium bicarbonate aqueous solution and in a cold water, respectively.

Fig. 3 Ammonia and water vapour content in CO₂ stream **Table 1** Measured components in treated gas and in the CO₂ gas stream at various conditions

Test	CO ₂ (vol%)	O ₂ (vol%)	CO (ppm)	NO ₂ (ppm)	NO (ppm)	NH ₃ (ppm)	SO ₂ (ppm)	SO ₃ (ppm)	CS ₂ (ppm)	Water vapour (vol%)	HCHO (ppm)
Treated gas at standard parameters ^a	3.39	7.66	33.34	0.24	85.61	44.50	0.75	0.20	0.26	16.85	0.11
Stream of CO ₂ at standard conditions	96.59	0.04	1.80	0.00	0.58	0.58	0.01	0.84	2.49	3.31	0.85
Treated gas fresh water flow rate 10 dm ³ /h	3.08	7.84	31.66	0.19	86.17	34.89	0.00	0.67	1.08	17.47	0.00
Treated gas fresh water flow rate 14 dm ³ /h	2.65	7.95	21.02	0.17	85.65	27.35	0.00	0.66	0.24	18.33	0.00
Treated gas lean amine temperature 50 °C	2.46	9.66	9.28	1.29	83.57	48.99	0.00	1.14	1.64	20.58	0.00
Treated gas lean amine temperature 30 °C	2.00	11.90	6.90	1.03	79.95	30.56	0.00	0.50	0.65	10.66	0.00

^a Water make-up (to water washing section) 6 dm³/h, the lean amine temperature 40 °C

In order to reduce the amine and ammonia emission, the water wash, being integral part of the absorber, has been employed. To evaluate the efficiency of the water wash, the fresh water flow rate (water make-up to washing section) was altered and then ammonia emission was measured. The results are shown in Fig. 4.

The ammonia emission at a make-up water flow rate of 6 dm³/h is approximately 43 ppm and the amount of water vapour is 17 vol%. An increase in water make-up to 10 dm³/h decreases the ammonia emission by 18% (from 42.5 to 34.5 ppm). In this case, it can be seen that the water content in the treated gas are kept at constant level (due to constant treated gas temperature during both tests). Further increase in flow of fresh water reduces the ammonia emission to about 27 ppm. That is nearly 36% decrease with respect to the initial ammonia emission. The sulphur

and nitrogen oxides content does not change considerably. The fluctuations in measured CO₂ concentration at various water flow rates are related to the variable composition of the flue gas that enters the absorber.

The effect of lean amine temperature on the ammonia emission is shown in Fig. 5. At a standard lean solvent temperature (i.e. 40 °C) the emission of ammonia is in the range of 40–48 ppm. An increase in lean amine temperature to 50 °C causes an increase in the ammonia emission to approximately 50 ppm. The value of ammonia emission decreases from ca. 50 to 30 ppm as the lean solvent temperature decreases from 50 to 30 °C. Furthermore, the water vapour decreases from 20.6 to 10.7 vol% as well as CO₂ decreases from 2.46 to 2.0 vol%. The temperature of treated flue gas decreases by 5–8 °C as a result of decreasing the lean amine temperature by 10 °C. In the

Fig. 4 Effect of increasing water dosing in the water washing section on the ammonia emission. Vertical lines indicate a change in the water dosing

Fig. 5 Effect of change in lean amine temperature on the ammonia emission. Vertical lines indicate a change in the lean amine temperature

consequence the treated gas contains less water vapour as well as other volatile and water-soluble compounds (lower partial pressure is observed). The CO_2 content also is reduced with lean amine temperature because the solvent absorption capacity increases at a lower temperature. Nonetheless, the kinetics of chemical absorption is reduced, and finally possibly results in inferior CO_2 capture efficiency. In addition, when colder lean solvent is fed into the absorber, the more energy has to be spent in the stripper to heat up and regenerate the solvent. Given this, the most favourable temperature of lean amine entering the absorber, in terms of CO_2 removal efficiency, is estimated to be 40 °C.

Conclusion

In this work, the experimental research was carried out in the CO_2 capture pilot plant using AEEA as a solvent. Ammonia emission, water vapour and CO_2 concentration together with other compounds were measured. Furthermore, the efficiency of water washing section located at the absorber top was evaluated. The experimental data are summarized in Table 1.

The results show that the main source of ammonia emission is the absorber. Emissions of ammonia were in the range 27–50 ppm, and it corresponds to typical emission from CO_2 capture pilot plant using an amine solvent

(Spietz et al. 2015; Khakharia et al. 2014). The content of sulphur oxides, nitrogen dioxide, carbon disulphide and formaldehyde is very low, approximately the detection limit.

In addition, the effect of lean solvent temperature on ammonia emission was investigated. Ammonia emission increases from 30 to 50 ppm with increasing lean solvent temperature (from 30 to 50 °C). However, considering the energy demand and CO₂ removal efficiency, the optimum lean amine temperature was estimated to be 40 °C.

The water wash is effective in ammonia removal, and thereby it can also reduce other volatile and water-soluble compounds. An increase in water make-up to wash water section from 6 to 14 dm³/h affected the ammonia emission reduction by 35.7% (from 42.6 to 27.4 ppm).

The CO₂ stream leaving the stripper has a high purity as the CO₂ accounts to 96.6 vol%. The other major component is water vapour, and thereby released CO₂ can be used in the further processes, after a slight purification.

However, the ammonia emissions for AEEA solvent have not been presented before in the literature. Therefore, the data obtained in the paper can be useful, especially considering that in the near future the amine emission reduction will be a critical requirement for all amine-based CO₂ capture plants.

Acknowledgements The results presented in this paper were obtained during research co-financed by the National Centre of Research and Development in the framework of Contract (No. SP/E/1/67484/10)—Strategic Research Programme—Advanced technologies for energy generation: development of a technology for highly efficient zero-emission coal-fired power units integrated with CO₂ capture. The results presented in this paper were obtained during the research project entitled “Development of the gas separation and the treatment technology in respect of the gas further utilization” (ICHPW No. 11.16.010), financed by the Ministry of Science and Higher Education.

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

References

- Bartsch H, Montesano R (1984) Relevance of nitrosamines to human cancer. *Carcinogenesis* 5:1381–1393
- Bernhardsen IM, Knuutila HK (2017) A review of potential amine solvents for CO₂ absorption process: absorption capacity, cyclic capacity and pKa. *Int J Greenh Gas Control* 61:27–48. doi:10.1016/j.ijggc.2017.03.021
- Cuéllar-Franca RM, Azapagic A (2015) Carbon capture, storage and utilisation technologies: a critical analysis and comparison of their life cycle environmental impacts. *J CO₂ Util* 9:82–102. doi:10.1016/j.jcou.2014.12.001
- da Silva EF, Kolderup H, Goetheer E, Hjarbo KW, Huizinga A, Khakharia P, Tuinman I, Mejdell T, Zahlsen K, Vernstad K, Hyldbakk A, Holten T, Kvamsdal HM, van Os P, Einbu A (2013) Emission studies from a CO₂ capture pilot plant. *Energy Proc* 37:778–783. doi:10.1016/j.egypro.2013.05.167
- Gouedard C, Picq D, Launay F, Carrette P-L (2012) Amine degradation in CO₂ capture. I. A review. *Int J Greenh Gas Control* 10:244–270. doi:10.1016/j.ijggc.2012.06.015
- IR spectrum collection—Gasmeter Technologies Inc. [WWW Document], n.d.. IR Spectr. Collect—Gasmeter Technol. Inc. URL <http://www.gasmet.com/technology/spectra>. Accessed 19 Dec 2016)
- Kamijo T, Kajiya Y, Endo T, Nagayasu H, Tanaka H, Hirata T, Yonekawa T, Tsujiuchi T (2013) SO₃ impact on amine emission and emission reduction technology. *Energy Proc* 37:1793–1796. doi:10.1016/j.egypro.2013.06.056
- Khakharia PM, Brachert L, Mertens J, Huizinga A, Schallert B, Schaber K, Vlught TJH, Goetheer ELV (2013) Investigation of aerosol based emission of MEA due to sulphuric acid aerosol and soot in a post combustion CO₂ capture process. *Int J Greenh Gas Control* 19:138–144
- Khakharia PM, Kvamsdal HM, Da Silva EF, Vlught TJH, Goetheer ELV (2014) Field study of a Brownian Demister Unit to reduce aerosol based emission from a post combustion CO₂ capture plant. *Int J Greenh Gas Control* 28:57–64
- Khakharia P, Brachert L, Mertens J, Anderlohr C, Huizinga A, Fernandez ES, Schallert B, Schaber K, Vlught TJH, Goetheer E (2015) Understanding aerosol based emissions in a post combustion CO₂ capture process: parameter testing and mechanisms. *Int J Greenh Gas Control* 34:63–74. doi:10.1016/j.ijggc.2015.01.001
- Knudsen JN, Jensen JN, Vilhelmsen P-J, Biede O (2007) First year operating experience with a 1 t/h CO₂ absorption: pilot plant at Esbjerg coal-fired power plant. *Proc Eur Congr Chem Eng* 16:20
- Knudsen JN, Bade OM, Anheden M, Bjorklund R, Gorset O, Woodhouse S (2013) Novel concept for emission control in post combustion capture. *Energy Proc* 37:1804–1813
- Kolderup H, da Silva T, Mejdell A, Tobiesen A, Haugen G, Hoff KA, Josefsen K (2011) Emission Reducing Technologies H&ETQP Amine6, SINTEF A18095. ISBN 978-821405-024-0
- Låg M, Lindeman B, Instanes C, Brunborg G, Schwarze P (2011) Health effects of amines and derivatives associated with CO₂ capture. *Nor Inst Public Health*. ISBN 978-828082-462-2
- Ma'mun S, Svendsen HF, Hoff KA, Juliusen O (2007) Selection of new absorbents for carbon dioxide capture. *Energy Convers Manag* 48:251–258. doi:10.1016/j.enconman.2006.04.007
- Mertens J, Lepaumier H, Desagher D, Thielens M-L (2013) Understanding ethanolamine (MEA) and ammonia emissions from amine based post combustion carbon capture: lessons learned from field tests. *Int J Greenh Gas Control* 13:72–77. doi:10.1016/j.ijggc.2012.12.013
- Mertens J, Brachert L, Desagher D, Schallert B, Khakharia P, Goetheer E (2014) Predicting amine mist formation based on aerosol number concentration and size measurements in flue gas. In: *Energy procedia, 12th international conference on greenhouse gas control technologies*, vol 63, pp 893–901. doi:10.1016/j.egypro.2014.11.099
- Nguyen T, Hilliard M, Rochelle G (2011) Volatility of aqueous amines in CO₂ capture. In: *Energy procedia, 10th international conference on greenhouse gas control technologies*, vol 4, pp 1624–1630. doi:10.1016/j.egypro.2011.02.033
- Saeed IM, Lee VS, Mazari SA, Ali BS, Basirun WJ, Asghar A, Ghalib L, Jan BM (2017) Thermal degradation of aqueous 2-aminoethylethanolamine in CO₂ capture; identification of degradation products, reaction mechanisms and computational studies. *Chem Cent J* 11:10. doi:10.1186/s13065-016-0231-7

- Spietz T, Stec M, Tatarczuk A, Więclaw-Solny L (2015) Reduction of amines emission and their volatile degradation products. *CHEMIK* 69:625–634
- Stec M, Tatarczuk A, Więclaw-Solny L, Krótki A, Ściążko M, Tokarski S (2015). Pilot plant results for advanced CO₂ capture process using amine scrubbing at the Jaworzno II Power Plant in Poland. In: *Fuel*, the 10th European conference on coal research and its applications, vol 151, pp 50–56. doi:[10.1016/j.fuel.2015.01.014](https://doi.org/10.1016/j.fuel.2015.01.014)
- Stec M, Tatarczuk A, Więclaw-Solny L, Krótki A, Spietz T, Wilk A (2015b) Demonstration of a post-combustion carbon capture pilot plant using amine-based solvents at the Łaziska Power Plant in Poland. *Clean Technol Environ Policy*. doi:[10.1007/s10098-015-1001-2](https://doi.org/10.1007/s10098-015-1001-2)
- Strazisar BR, Anderson RR, White CM (2003) Degradation pathways for monoethanolamine in a CO₂ capture facility. *Energy Fuels* 17:1034–1039. doi:[10.1021/ef020272i](https://doi.org/10.1021/ef020272i)
- Szczypiński T, Tatarczuk A, Grudnik K (2013) Optimization of amine-based CO₂ capture from flue gas by flowsheet modification. *Przem Chem* 92:106–110
- Tatarczuk A, Ściążko M, Stec M, Tokarski S, Janikowski J (2013) Carbon capture, towards comprehensive knowledge: our common objective. *Chem Int* 67:897–902
- Verschueren K (2008) *Handbook of environmental data on organic chemicals*, 5th edn. Wiley, Hoboken
- Weiland RH, Trass O (1969) Titrimetric determination of acid gases in alkali hydroxides and amines. *Anal Chem* 41:1709–1710. doi:[10.1021/ac60281a024](https://doi.org/10.1021/ac60281a024)
- Zhang Yuanyuan, Xu J, Zhang Yu, Zhang J, Li Q, Liu H, Shang M (2014) Health risk analysis of nitrosamine emissions from CO₂ capture with monoethanolamine in coal-fired power plants. *Int J Greenh Gas Control* 20:37–42. doi:[10.1016/j.ijggc.2013.09.016](https://doi.org/10.1016/j.ijggc.2013.09.016)