CHEMICAL ENGINEERING TRANSACTIONS
VOL. 56, 2017

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Jiří Jaromír Klemeš, Peng Yen Liew, Wai Shin Ho, Jeng Shiun Lim

ISBN 978-88-95608-47-1; **ISSN** 2283-9216

DOI: 10.3303/CET1756013

Optimisation of Operational Parameter and Economic Analysis of Amine Based Acid Gas Capture Unit

Li Chin Law, Nurhawani Yusoff Azudin, Syamsul Rizal Abd Shukor*

School of Chemical Engineering, Engineering Campus, Universiti Sains Malaysia, 14300 Nibong Tebal, Penang, Malaysia.
chsyamrizal@usm.my

Electricity demand in Malaysia has been projected to escalate and this has led to additional coal-fired power plants being built. Combustion of coal has released greenhouse gases such as CO_2 into the atmosphere. It is predicted that CO_2 emission from coal fired power plants will grow 4.1 % annually to reach 98 Mt by 2020. Greenhouse gases like CO_2 is claimed to be the root of global warming, closely related to the verdict of 2 °C increase in global temperature. To resolve this issue, amine unit has been integrated into the power plant for acid gas removal. Amine is highly preferred due to its characteristic of high selectivity. The drawbacks of this technology are costly operation, energy intensive and exhibits process dynamic. Detailed process simulation utilising Aspen Plus is able to optimise the process and overcome these limitations. In steady state simulation, the optimal operating conditions of absorber and stripper are found. Absorber should be operated at 30 °C (1 atm), while stripper at 120 °C (2 atm). The MDEA to MEA ratio is fixed at 3 : 7 with 40 wt% of amine in the solvent. By comparing the optimised parameters to TNBR's result, acid gas removal rate showed an increment of 5.5 % which resulted in 91.27 % of CO_2 removal rate. 300 % reduction in energy penalty and heat duty cost are achieved when MEA/MDEA is used instead of MEA. A more economical and feasible acid gas removal process with optimum operation is achieved. This has provided better insight for large scale implementation of amine unit in industries with low energy penalty.

1. Introduction

There are 41 % of global electricity worldwide is generated from coal burning due to its low cost and availability resulting in 24.5 % of greenhouse gases emission in 2012 (WCA, 2016). In Malaysia, coal-fired power plant has accounted for 41 % of total electricity generation and is expected to increase in capacity by 2020. Commissioning of the first ultra-supercritical coal technology of 2 GW capacity in Peninsular Malaysia in 2016 (EC, 2016) has provided energy to power the need of 2 million people but at the same time increases the greenhouse gases emission due to the high carbon content of coal. Global warming is hotly discussed publicly relating to the CO_2 emission from coal-fired power plant. No commercial CO_2 capture plant has been built to capture the CO_2 from a coal-fired power plant associated to the high energy penalty in the operation of these technologies. Under some potential climate policies, concern has been arisen regarding the environmental issues associated with coal-fired power plant; a number of researches are prompted to resolve this issue by introduction of highly effective CO_2 capture plant in pilot scale. To this regard, theoretical and experimental researches on the amine unit have been conducted to minimise the energy consumption of the scrubbing and amine regeneration process. Process simulator like Aspen Plus version 8.8 allows the optimisation study for steady state operation of amine unit at lower cost (Dyment and Watanasiri, 2015). In fact, the high energy penalty operation of amine unit is due to the poorly operated acid gas removal and amine regeneration operation (Zurlo, 2013), which causes wastage in energy. Process optimisation is addressed in this paper allowing the study on parameters correlated to amine unit efficiency and economy. Fluctuation in the CO_2 loading and temperature of the flue gas produced by coal combustion due to the variation of coal composition makes the process exhibits dynamic behaviour (Nittaya et al., 2014). A mechanistic dynamic process model and controllability analysis of this post-combustion unit must be developed for achieving a low cost operation of less energy intensive. In order to produce a reliable mechanistic dynamic model for handling of process dynamic, a valid steady-state model must be assembled. Optimisation is done to achieve a target

Please cite this article as: Law L.C., Azudin N.Y., Shukor S.R.A., 2017, Optimization of operational parameter and economic analysis of amine based acid gas capture unit, Chemical Engineering Transactions, 56, 73-78 DOI:10.3303/CET1756013

of 90 % of CO_2 removal rate or higher (Dyment and Watanasiri, 2015). Up to date, there are limited studies working on the economics and energy aspects of amine unit, especially for the blended amine MEA/MDEA. So, more studies on these areas are highly encouraged to make the commissioning of amine unit economically feasible. Harun et al. (2012) had studied on the steady state simulation of amine unit. Some studies had been done in accordance to high energy penalty of amine unit, as stated by Kaplan (2011), amine unit are very energy intensive and has consumed 35 % of the electricity produced by a typical coal power plant. Kidnay et al. (2011) further emphasises amine regeneration as the major cost determination factor. Solvent selection can significantly reduce the energy penalty, which makes blended amine as one of the approach to make amine unit economically feasible. These provide some insight for the current research.

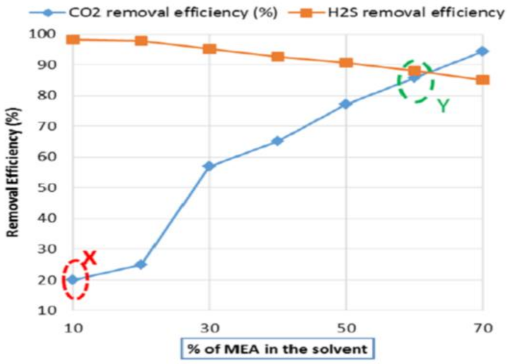

Figure 1: Result for case study done by TNBR (Rani et al., 2015)

Previous studies were focusing on a single amine instead of blended amine. A complete mechanistic model of blended amine MEA/MDEA has not been explicitly addressed in literature. The aim of this paper is to prove that blended amine is able to lower the energy penalty and operational cost of amine unit and then optimisation of CO_2 capture unit using MEA/MDEA is presented and simulated using Aspen Plus (2016). Case study done in TNBR pilot plant is taken as the base case scenario as shown in Figure 1. The structure of this paper is as follows: Section 2 presents the detail of the model used throughout the simulation. Section 3 lists out the base case operating condition and presents the economic analysis of CO_2 capture plant in steady-state mode followed by Section 4, conclusion to summarise the outcome obtained based on this study.

2. Model development and preliminary study

The model used is based on the previous research done by Tenaga Nasional Berhad Research (TNBR) situated in Kajang, Selangor as part of the Advanced Research Low Carbon Power Generation Program in specific area of CCUS, specifically in amine absorption in reducing the CO_2 emission (Rani et al., 2015). Flue gas is produced as the by-product of coal-fired power plant. Table 1 showed the detail information related to flue gas and amine solution.

Table 1: Design information for column sizing

Criteria	Design information
Flue gas density (kmol/m^3)	0.039
Molar flow rate (kmol/h)	1 – 25 (Given by TNBR carbon capture pilot plant)
Space velocity (h^{-1})	14,400 (Chunbo, et al., 2012)
L/D ratio	3.75
Amine solution (kg/h)	45.24 (30 wt%)

Based on the design information provided, absorber had been sized with the dimensions as below. The dimensions for both tray and packed columns are shown in Table 2. This information is used as basic information in steady state simulation. This information was used to carry out preliminary study in choosing the most efficient column type for further simulation studies. Based on the preliminary simulation done, packed column has proven much efficient in acid gas removal with higher removal rate as compared to the case when tray column is used giving 77.75 % of CO_2 removal. This result is in agreement with the information provided by TNBR for the base case operating condition with 77.14 % of CO_2 removal giving less than 1 % of error between both models rendering the simulation model valid to be used for further simulation. Refer to Figure 1 for result provided by TNBR model.

Table 2: Specification of packed and tray column to be used for steady-state simulation

Unit Operation Absorber	Specification (Packed column)	Specification (Tray column)
Height of packing	1.50 m	1.5 m
Diameter of column	0.40 m	0.40 m
Column packing	Rasching ring.ceramic.packing (25 mm x 25 mm X 2.5 mm ; 505 kg/m^3 voidage of 0.78 (Pingxiang V-Shion Packing Co., 2014).	
Actual number of trays		7 trays, 0.25 m spacing

3. Optimisation of operational parameters and economic analysis

Through steady state simulation, optimisation is carried out to improve the operability of amine unit. The main objective of carrying out optimisation is to make the commissioning of amine unit economically and environmentally feasible and less energy intensive. The acid gas removal rate and the amine regeneration rate must be studied along with economic analysis. Table 3 showed that variables which are manipulated in steady-state simulation for 2 objective functions of amine unit. Aspen Plus is used throughout the simulation.

Table 3: Manipulated variables and the range

Measured variables (output)	Manipulated variables (input)	Range of manipulated variables
Objective 1: Acid gas (CO_2) removal rate	Lean amine flow rate (kg/h)	0 to 200
	Amine to water ratio	0 to 1
	MDEA to MEA ratio	0 to 1
	Flue gas temperature (°C)	20 to 80
	Lean Amine temperature (°C)	20 to 80
	Absorber pressure (atm)	1 to 2
Objective 2: Amine regeneration rate	Stripper pressure (atm)	1 to 3
	Stripper temperature (°C)	100 to 140

Figure 2 showed the complete simulation layout in Aspen Plus which involves unit operation like absorber, stripper, amine-amine heat exchanger, cooler, mixer and also auxiliary equipment like valves and pumps. Simulation had been run repeatedly to provide the result as shown in Figure 3. All graphs showed the relationship between acid gas removal rate and the manipulated variables. From the graphs, optimal point of removal rate was determined by taking into consideration other factors like cost and surrounding condition. The dotted line shows in the graphs are the optimal point chosen based on some justification.

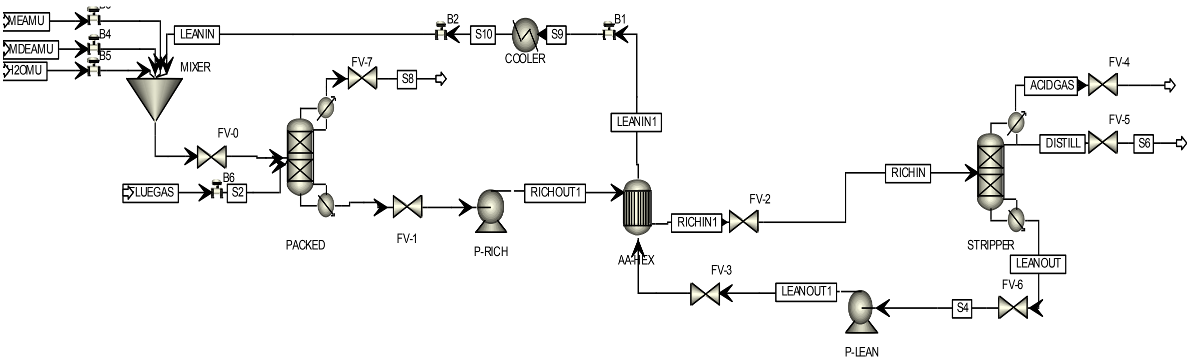

Figure 2: Complete steady-state simulation flowsheet in Aspen Plus

The optimised value for each parameter is listed in table form; the absorber and stripper are optimally operated with the operating conditions as shown in the Table 4 below. The optimised removal rate showed increment as compared to the base case operating condition to 91.27 % CO_2 removal rate with an increment of 5.5 %.

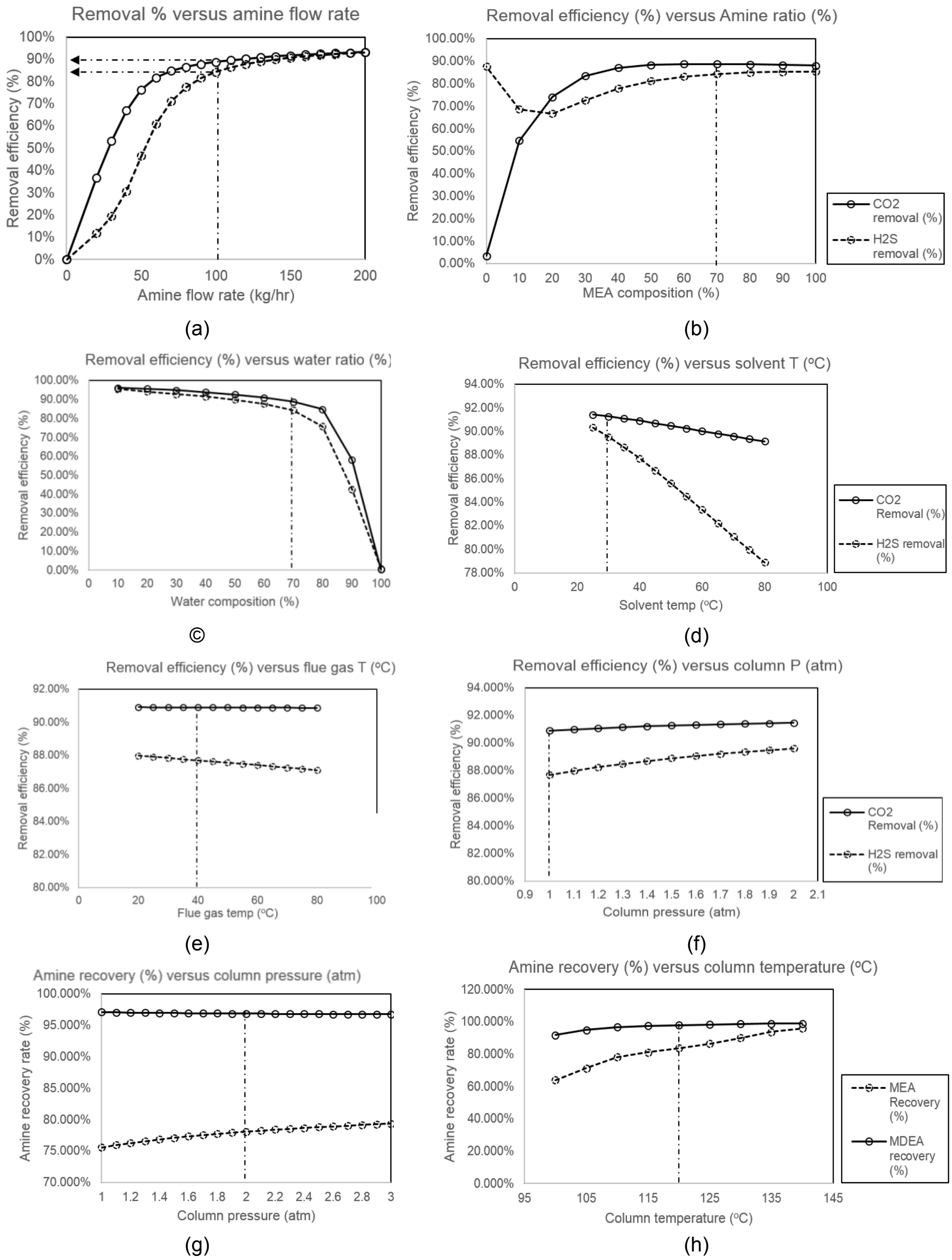

Figure 3: (a) – (h) Graphs showing the relationship between removal rate or amine recovery rate and various manipulated variables

Table 4 showed the comparison between the optimised parameters to the one operated in TNBR. Based on the result, economic and energy penalty analysis were done using Aspen Plus. Economic aspect of acid gas removal using amine is determined by the stripper cost, stripper installation cost, utilities cost, operating cost and the cost due to the amine degradation. Economic analysis mainly focuses on the stripper unit as stripper unit is the unit which is accounted for more than 80 % of the total operating cost (Alptekin et al., 2009). By studying on the stripper's economic aspect, cost saving can be achieved. Reboiler in the stripper is the major contributor to the plant operating cost (Slagle, 2013). Heat duty of the reboiler is specified by the user in the Aspen Plus simulation, which impact on the amine regeneration as well as amine circulation rate. According to Slagle (2013) the circulation rate is corresponded to the reboiler duty, the higher the amine circulation rate, the higher is the reboiler duty. This parameter must be carefully studied as it directly influences the operational cost and amine loss. In addition, the amount of MEA and MDEA lost through the absorber (CLEANGAS stream), and stripper (CO_2 and DISTILL streams) must be topped up into the absorber along with the lean amine circulation stream. These has accounted for some cost. In this analysis, Aspen Plus with its activated analysis was used for the economics and energy analysis. In carrying out this analysis, economics button was activated; next, mapping, sizing, evaluation and investment analysis were done accordingly. By doing so, the total capital cost and utilities cost were obtained. The equipment cost and installation cost of all equipment were available in the investment analysis file. Analysis and comparison were done based on the result obtained.

Table 4: Table of comparison between optimised parameters TNBR base case base case condition

Manipulated variables	TNBR	Optimised value
Lean amine flow rate (kg/h)	100	100
Amine to water ratio	3 : 7	4 : 6
MDEA to MEA ratio	5 : 5	3 : 7
Flue gas temperature (°C)	30	30
Lean Amine temperature (°C)	70	30
Absorber pressure (atm)	1	1
Stripper pressure (atm)	2	2
Stripper temperature (°C)	112	120

In comparing the operating cost between the case when blend amine is used as the solvent to the case when only MDEA or MEA is used as the solvent, reboiler heat duty is fixed at 20,000 W at first. By referring to Table 5, when the heat duty is fixed, the utilities cost is almost the same for all cases. Cost of amine losses is dependent on the type of amine used. For MDEA case, least amount of amine is lost as MDEA which is tertiary amineis easier to be regenerated. This accounts for the lowest operating cost among the 3 cases. The case when MDEA is used alone, the acid removal rate is also the lowest, which is 22 % lesser that the case when blended amine was used. This explains why MDEA is not suggested to be used as the only solvent. Operating cost for the case when blended amine was used has shown some cost saving.

Table 5: The operating cost for different amine used

Amine type (20,000 W)	Total amine loss cost (USD/y)	Total utilities cost of stripper (USD/y)	Total capital cost (stripper) (USD)	Total operating cost (USD/y)	CO_2 removal rate (kmol/s)
MEA only	766.76	6,140.86	411,500.00	6,907.61	0.00002898
MDEA only	247.99	6,140.86	411,500.00	6,388.85	0.00001819
MEA+MDEA	635.95	6,086.47	411,500.00	6,722.42	0.00002799

Next, comparison was made for the case when the heat duty was not fixed, but cost of amine losses was fixed at an amount of 640 – 770 USD/y as shown in Figure 4. In this case the heat duty of 6,000 W is enough to minimise the cost due to amine losses to 645.11 USD/y. Compare with the case when MEA is used alone, 20,000 W of heat duty was supplied yet the cost due to amine losses was still very high at 766.76 USD/y. The reduction in the heat duty requirement has shown that, cost and energy could be saved by more than 300 % when blended amine was used instead of MEA only. The usage of blended amine is able to reduce the energy penalty (%) (Aroonwilas and Veawab, 2009) and operating cost. This emphasise on the importance of using blended amine in amine unit and the necessity to study the process of MEA/MDEA absorption.

4. Conclusion

This paper presented a mechanistic steady state model of an amine unit using blended amine MEA/MDEA as absorbent for removing CO_2 from flue gas. This model is proposed in accordance to the pilot scale amine unit operation in TNBR. The main objective of this unit is to maintain the acid gas removal rate at 90 % and above.

In steady-state simulation, optimisation of the operating condition and sensitivity study had been carried out.

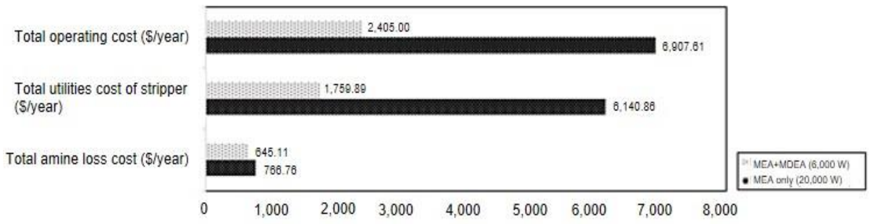

Figure 4: Chart of operating cost for different type of solvents which are MEA/MDEA, MEA and MDEA

This result had been compared to the base case scenario in TNBR. The comparison had proven that optimisation has improved the effectiveness of amine unit in removing acid gas by 5.5 % giving CO_2 removal rate of 91.27 % which is much higher than the targeted 90 % of CO_2 removal. The objective of this study has been achieved. While economic study further proves the suitability of blended amine MEA/MDEA in saving the operating cost by as much as 300 %. This proven that utilisation of blended amine in acid gas capture unit makes the installation of amine unit more promising with lower energy consumption. In future study, a mechanistic dynamic model can be designed based on the outcome of this study to tackle the dynamic of this process.

Acknowledgement

This study has been supported by Fundamental Research Grants Scheme (FRGS-PJKIMIA/6071255) and special thanks to TNBR for the shared data and technical expertise which had made this research a success.

References

Alptekin G., Jayaraman A., Copeland R., Dietz S., 2009, A Low Cost High Capacity Regenerable Sorbent for Post Combustion CO_2 Capture, AIChE Annual Meeting, 4 November 2013, San Francisco, United States, 341764.

Aroonwilas A., Veawab A., 2009, Integration of CO_2 capture unit using blended MEA–AMP solution into coal-fired power plants, Energy Procedia 1, 4315-4321.

Aspen Plus v8.8, 2016, Aspen Technology Inc., Massachusetts, United States.

Chunbo Y., Guangwen C., Quan Y., 2012, Process Characteristics of CO_2 Absorption by Aqueous Monoethanolamine in a Microchannel Reactor, Chinese Journal of Chemical Engineering 20 (1), 111-119.

Dyment J., Watanasiri S., 2015, Acid Gas Cleaning using Amine Solvents: Validation with Experimental and Plant Data, Aspen Technology, Massachusetts, United States.

EC (Energy Comission), 2016, Year In Review – 2015, Peninsular Malaysia Electricity Supply Industry Outlook 2016, Suruhanjaya Tenaga (Energy Commission), Putrajaya, Malaysia.

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 10, 295-309.

Kaplan S., 2011, Power Plants: Characteristics and Costs, DIANE Publishing, Collingdale, USA.

Kidnay A.J., Parrish W.R., McCartney D.G., 2011, Fundamentals of Natural Gas Processing, 2nd Ed., CRC Press, Boca Raton, Florida, USA.

Nittaya T., Douglas P.L., Croiset E., Ricardez-Sandoval L.A., 2014, Dynamic Modelling and Controllability Studies of a Commercial-Scale MEA Absorption Processes for CO_2 Capture from Coal-Fired Power Plant, Energy Procedia 63, 1595-1600.

Rani N.H.A., Muda N., Shukor S.R.A., 2015, Syngas Clean Up System Using Amine for Gas Turbine Applications, 5th International Conference on Environment 2015 (ICENV 2015), 18-19 August 2015 Penang, Malaysia, 577-584.

Slagle J.C., 2013, Improve Your Gas Plant's Performance in the Middle East Part 1: The Amine Plant, Arab States, Gas Processors Association – Gulf Cooperation Council 21st Technical Conference, 8 May 2013, Doha, Qatar, 1-17.

WCA (World Coal Association), 2016, Coal and Electricity, <www.worldcoal.org/coal/uses-coal/coal-electricity> accessed 20.08.2016.

Zurlo J., 2013, Optimisation of Amine Units and Improve Refinery Profitability, Gulf Publishing Company, Texas, USA.