Waste Heat Utilization for CO_2 Capture in the Cement Industry

Udara S. P. R. Arachchige, Dinesh Kawan, Lars-André Tokheim, and Morten C. Melaaen

***Abstract*—The focus of this work is utilization of waste heat in a cement kiln flue gas in an amine-based CO_2 absorption process. The high temperature flue gas from the cement kiln is used to generate steam in a waste heat boiler. The steam is then used to replace some of the steam required in the stripping section of the CO_2 capture plant. The required surface area for heat exchange, the cost of installing this area and the payback time of the installation is calculated. The flue gas capture model was developed using the Aspen Plus simulation software. The available excess heat in the cement manufacturing process is calculated to 18 MW for the base case considered. The heat transfer area is calculated as 3115m^2. The total cost of the heat exchanger was $ 3.9 million, and the payback time is about 1 year, demonstrating the economic feasibility of applying heat integration when implementing an amine-based CO_2 capture process in a cement kiln system.**

***Index Terms*—Carbon dioxide capture, waste heat boiler, flue gas, MEA, cement industry.**

I. Introduction

The concentration of the atmospheric carbon dioxide (CO_2) has risen with the impact of the industrial revolution. The atmospheric CO_2 concentration is calculated as 380 ppmv approximately [1].

One of the main reasons for global warming is the huge impact of fossil fuel combustion in power plants, continuously contributing to the increase in atmospheric CO_2 concentration. However, also industry processes, such as aluminium, steel and cement production, contribute to CO_2 emissions.

Different technologies have been proposed for the purpose of carbon capture [2]. and post combustion chemical absorption is the more mature approach. Amine-based absorption of CO_2 from a cement kiln exhaust gas is considered in this study.

A sketch of a typical kiln system is shown in Fig. 1. The CO_2 is formed in two different processes.

The first Udara S. P. R. Arachchige, Dinesh Kawan, Lars-André Tokheim, and Morten C. Melaaen process is the calcination of calcium carbonate ($CaCO_3$) to produce calcium oxide (CaO). This process is called the process related CO_2 generation. The second source of CO_2 is the combustion of fossil fuels required to heat the kiln system to a sufficiently high temperature to facilitate the chemical reactions. The average carbon dioxide production of cement flue gas varies from 14 to 33% according to the raw material type and other factors [3].

The high energy penalty in the regeneration process is a main disadvantage of the CO_2 capture plant, and minimizing the amount of energy required in the stripper column is important. Therefore, heat integration plays a vital role in carbon capture processes. Such heat integration is possible when a capture plant is coupled with a cement kiln system.

The technical and economic feasibility of installing a waste heat boiler in the cement kiln system, for the purpose of supplying thermal energy to the capture plant, is the topic of this article.

II. Model Development

The flue gas data and other necessary information for model development are taken from the literature. The flue gas capture model is developed in the Aspen Plus simulation software. The CO_2 capture model was previously developed by the authors [4] and the flue gas characteristics from that study is used here as well. A detailed description of the model development and the parameters used in the model development is given in other articles [4], [5]. The flue gas data used to implement the carbon capture model is given in Table I [4], and the basic process flow diagram of the gas absorption process is given in Fig. 2.

TABLE 1: Flue Gas Stream Data [4]

Description	Unit	Base Case
Preheater exhaust gas	Nm³/h	196,834
N_2	vol%	62.3 %
CO_2	vol%	30.3 %
H_2O	vol%	3.7 %
O_2	vol%	3.7 %

TABLE II: Excess Heat Availability in the Waste Heat Boiler [4]

Description	Unit	Reference Case
Re-boiler duty	MW	107.7
Heat availability	MW	18.0
Percentage of available heat	%	17

The temperature of the flue gas leaving the cement pre heater section is typically 350-400 °C, and downstream of the conditioning tower, the temperature is still around 150 °C. The required temperature in the absorption process, on the other hand, is only around 40°C, so the flue gas has to be cooled before it is sent to the capture section. The available

Manuscript received June 12, 2014; revised August 31, 2014.

The authors are with the Telemark University College, Porsgrunn, Norway (e-mail: udara.s.p.arachchige@hit.no, kawandinesh@gmail.com, Morten.C.Melaaen@hit.no, Lars.A.Tokheim@hit.no).

DOI: 10.7763/IJMO.2014.V4.414

excess heat in the kiln gas can be utilized by replacing the conditioning tower with a waste heat boiler downstream of the pre heater section.

The amount of waste heat available in the process is around 18MW for a calculated base case based on 350 and 150 °C inlet and outlet temperatures. The heat recovery unit should be installed as shown in the Fig. 3.

The steam produced in the waste heat boiler is transferred to the re-boiler unit of the stripper section in the CO_2 capture plant. The waste heat is not sufficient to cover the entire regeneration energy demand, but part of the energy can be replaced with energy generated in the waste heat boiler. The energy requirement in the stripper column as well as excess heat availability in the waste heat boiler is shown in Table II.

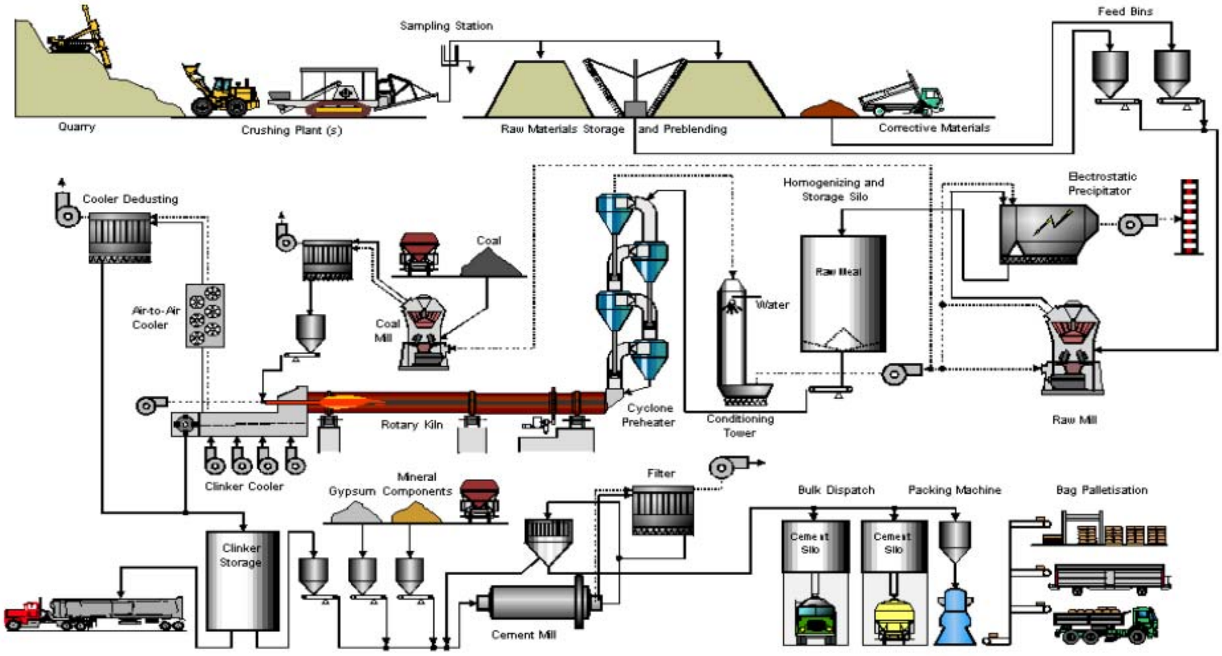

Fig. 1. Typical cement kiln system [6].

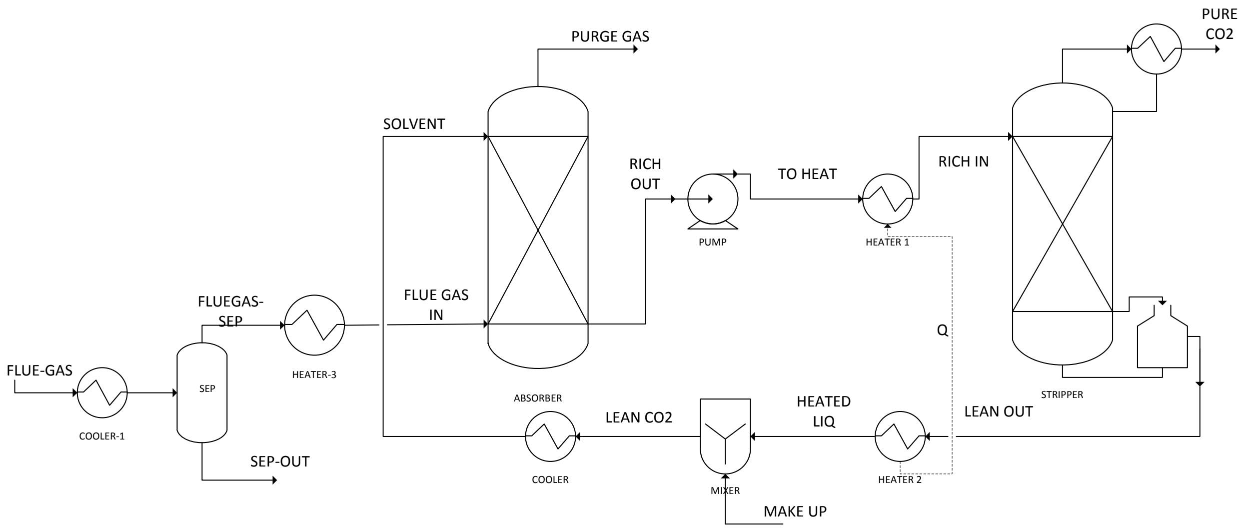

Fig. 2. Process flow diagram [4].

As described above, a significant amount of the required re-boiler energy can be provided by heat integration with the cement kiln process. However, the physical size as well as the installation costs and operational costs should be determined in order to evaluate the feasibility of such a waste heat boiler system. A brief description of the calculation procedure is given in the following section. The purpose of the calculation is to evaluate the required surface area of the cooling tubes to exchange the available heat in the flue gas and to use the heat exchange area as a basis for calculating the investment costs. Next, the payback time for the installation can be determined by calculating the savings in energy costs.

III. Heat Transfer Area Calculation

The main steps in the calculation procedure are briefly discussed here. The calculation can be subdivided into four main parts:

- Evaluate the excess energy availability in the process.
- Calculate the required water flow rate for the heat exchange in the waste heat boiler.

- Calculate the overall heat transfer coefficient of the waste heat boiler.
- Calculate the required surface area for heat transfer.

The heat availability was calculated as 18MW in the simulation studies [4], [5], or simply carrying out a heat balance by hand calculations.

The required water flow rate can be calculated by a simple energy balance and is found to be 28862 kg/hr. The system has to operate at 120-130 °C and 2.5 bars to comply with the temperature requirements of the re-boiler.

The slightly superheated steam coming from the waste heat boiler has a temperature of 130°C and a pressure of 2.5 bar The steam is sent to the re-boiler, where it can replace 18% of the regeneration energy demand of the stripper. The steam condenses to water in the re-boiler, and water at about 120 °C is returned to the waste heat boiler where it is heated, converted to steam and slightly superheated, before being sent to the re-boiler for another cycle.

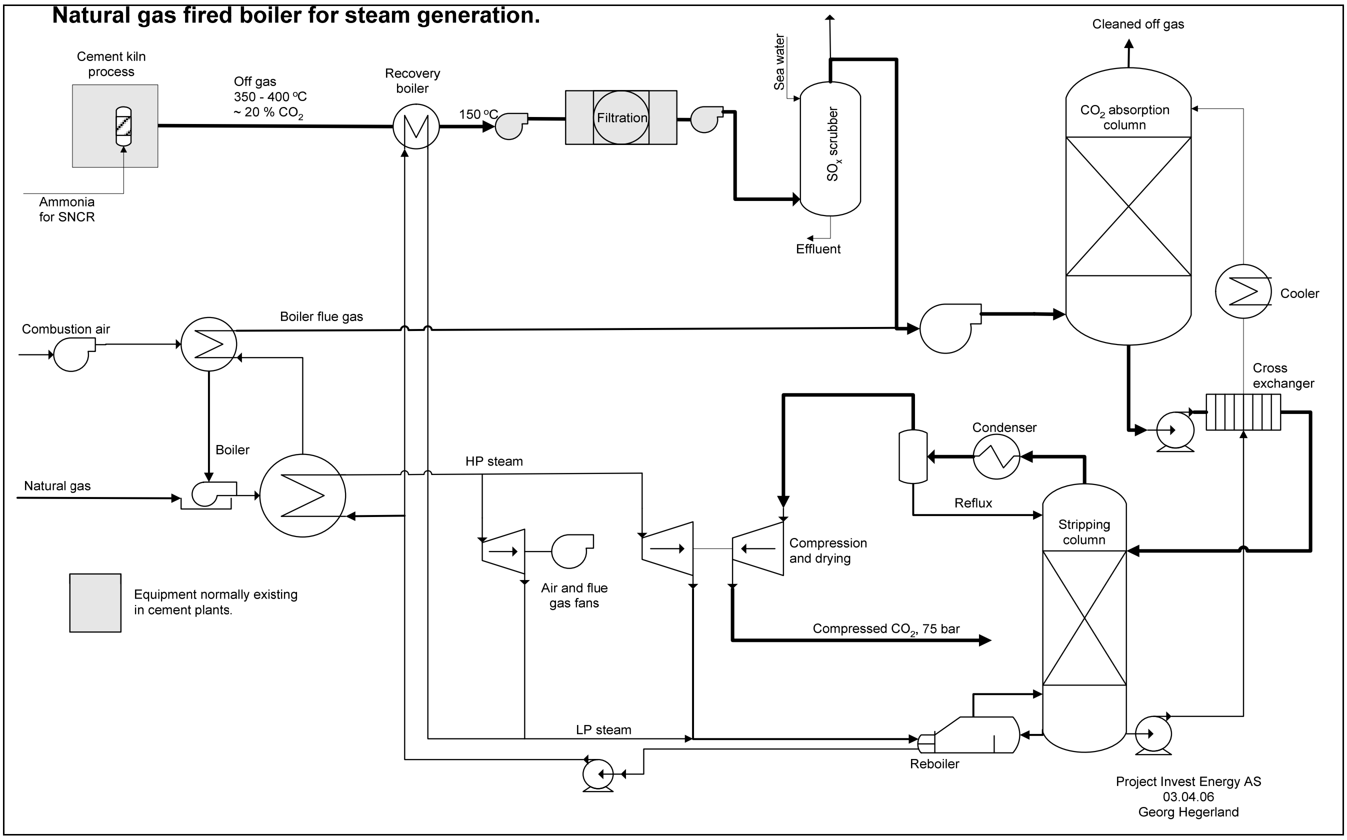

Fig. 3. Block diagram for NOx, **SOx** and CO_2 removal from cement plant off gases [7].

The overall heat transfer coefficient can be calculated by equation 1 [8].

$$U = \frac{1}{\frac{1}{h_1} + \frac{r_1}{k_A}\ln\frac{r_2}{r_1} + \frac{r_1}{k_B}\ln\frac{r_3}{r_2} + \frac{r_1}{r_4}\frac{1}{h_4}} \quad (1)$$

Here,

h_1= convection heat transfer coefficient for the water side [W/(m^2·K)]

h_4= convection heat transfer coefficient for the air side [W/(m^2·K)]

r_1=inner radius of the water tube [m]

r_2= outer radius of the water tube without dust layer [m]

r_3= outer radius of the water tube with dust layer [m]

k_A= thermal conductivity of the tube material [W/(m·K)]

k_B= thermal conductivity of the dust layer [W/(m·K)]

The convection heat transfer coefficient on the water side (inside the tubes) can be calculated by Nusselt number correlation.

The convection heat transfer coefficient on the gas side (outside the tubes) can be calculated by Nusselt number correlation.

Nusselt number correlation is given by: $Nu = \frac{h \times L}{k}$,

where, Nu=Nusselt number; h=convective heat transfer coefficient; L=Characteristic length; k = thermal conductivity.

Input values used for the calculation are given in Table II, and the resulting overall heat transfer coefficient is 85 W/(m²·K).

TABLE III: Input Values for Calculation of Overall Heat Transfer Coefficient

Parameter	Unit	Value
Thickness of the water tube	mm	2
Thickness of the dust layer	mm	2
Diameter of the tube	mm	10
Flue gas inlet temperature	°C	360
Flue gas outlet temperature	°C	140
Water inlet temperature	°C	120
Water outlet temperature	°C	134

The required area can be calculated from equation 2: $Q = UA(\Delta T)_{lm}$

The required surface area for heat transfer is calculated as 3115 m^2.

IV. Heat Exchanger Cost Calculation

The area-specific capital cost of heat transfer water tubes, C_P^0, is taken as 140 $/$m^2$ [8]. The bare module cost of the heat exchanger, C_{BM}, is given by equation 2 [9].

$$C_{BM} = C_P^0 \left[B_1 + B_2 F_M F_P \right] \quad (2)$$

Here,

B_1 and B_2 are constants taken as 1.63 and 1.66, respectively, for U - tube heat exchangers [9].

FM = material factor, taken as 2.7 [9].

FP = Pressure factor which is calculated from the equation 3 [9] given below.

$$\log_{10} F_P = C_1 + C_2 \log_{10} P + C_3 (\log_{10} P)^2 \quad (3)$$

Here,

C_1, C_2, C_3 are constants.

FP is calculated as 1 due to the low system pressure. The bare module cost is calculated as 856 $/$m^2$.

Total cost of heat exchanger is calculated as the product of the area and the area-specific cost, and is found to be $ 2,665,506. This value is calculated according to 2001 cost values and must be converted to 2014 data using relevant inflation factors. The total cost of heat exchanger for 2014 is then calculated as $ 3.9 million.

All direct and indirect costs related to the construction and installation of the heat exchanger unit is included in the bare module cost. Examples of direct costs are equipment cost, material cost and labor cost, and examples of direct cost are freight, overhead and engineering costs. The input values for calculation is given in the Table IV.

TABLE IV: Input values for Calculation of Heat Exchanger Cost

Parameter	Value
B1	1.63
B2	1.66
FM	2.7
C_P^0	140 $/$m^2$

TABLE V: Input Values for Calculation of Steam Cost

Parameter	Value
Heating value of Methane [10]	50 MJ/kg
Latent heat of steam	2.26 MJ/kg
Energy loss	15%

V. Steam Cost Calculation

The cost of the gas purchased for generating steam in regenerating process is around 1.1 NOK/Sm^3 according to the price at 2001[7]. The amount of energy can be replaced by installing waste heat boiler is calculated as 18 MW. The equivalent amount of steam recovered by installing waste heat boiler is calculated as 28862 kg/hr. The payback time period is calculated.

The input values used for calculation procedure is given in the Table V. Assume 15% of the energy losses during the heat transferring to steam generating.

Amount of steam generated by methane gas = 42.5 / 2.26 = 18.8 kg steam/ kg of gas.

Required amount of gas to generate steam recovery by waste heat boiler = 28862 / 18.8 = 1535 kg/hr (2326 m^3/hr).

Total amount of gas to generate amount of steam recovery per year (considering 7000 operating hours per year) = 16.28 million m^3.

Cost of the savings by steam recovery is around 26.4 million NOK / yr according to the current price. The equivalent amount of dollar is 4.4 million $.

The payback time period is approximately 10.5 months.

VI. Conclusion

The amount of energy available in the cement kiln exhaust gas is around 18MW for case considered in this study. This will cover 18% of the total energy requirement in the stripper regeneration process. The equivalent amount of steam generated by installing a waste heat boiler in the cement kiln system is 28862 kg/hr. The required heat exchange area is calculated as 3115m^2. The total cost of the waste heat boiler installation is calculated as 3.9 million dollars. The installation cost for the waste heat boiler is paid back through a reduction in consumption in externally generated steam. The payback time is calculated approximately as 1 year. Therefore, heat integration with the cement kiln system by installing a waste heat boiler may be economically very attractive when implementing an amine-based carbon capture process in the cement industry.

Acknowledgement

The support of Nils Henrik Eldrup, clarifying possible improvements to obtain more accurate results and instructions to the calculation of equipment cost, is gratefully acknowledged.

References

[1] *Intergovernmental Panel on Climate Change (IPPC), Summary for policymakers, Climate Change 2007, The Physical Science Basis*, Cambridge University Press, 2007.

[2] L. Faramarzi, "Post- combustion capture of CO_2 from fossil fueled power plants," Ph.D thesis, Technical University Of Denmark, Denmark, 2010.

[3] K. Thambimuthu, J. Davison, and M. M. Gupta, "CO_2 capture and reuse," in *Proc. IPCC Workshop on Carbon Capture*, Regina, Canada, pp. 26-44, 2002.

[4] U. S. P. R. Arachchige, D. Kawan, L. A. Tokheim, M. C. Melaaen, "Impact of kiln thermal energy demand and false air on cement kiln flue gas CO_2 capture," *International Journal of Energy and Environment*, vol. 1, no. 5, pp. 45-52, 2014.

[5] U. S. P. R. Arachchige, D. Kawan, L. A. Tokheim, and M. C. Melaaen, "Model development for CO_2 capture in cement industry," *International Journal of Modeling and Optimization*, vol. 3, no. 6, pp. 535-540, 2013.

[6] J. I. Bhatty, F. Miller, and S. Kosmatka, "Innovations in Portland Cement Manufacturing," Portland Cements Association, Illinois, USA, 2004.

[7] G. Hegerland, J. O. Pande, H. A. Haugen, N. Eldrup, L. A. Tokheim, and L. M. Hatlevik, "Capture of CO_2 from a cement plant – technical possibilities and economical estimates," in *Proc. the 8th International*

Conference on Greenhouse Gas Control Technologies: GHGT -8, Trondheim, Norway, 2006.
[8] F. P. Incropera, D. P. Dewitt, T. L. Bergman, and A. S. Lavine, *Fundamentals of Heat and Mass Transfer*, John Wiley & Sons. Sixth edition. 2007.
[9] R. Turton, R. C. Bailie, W. B. Whiting, J. A. Shaeiwitz, and D. Bhattacharyya, "Analysis Synthesis and design of chemical processes," Pearson Education Inc. Fourth edition, 2013.
[10] International Energy Agency. Key World Energy Statistics. (2010). [Online]. Available: http://www.iea.org/textbase/nppdf/free/2010/key_stats_2010.pdf.

Udara S. P. R. Arachchige received his B.Sc degree (2007) in chemical and process engineering from University of Moratuwa, Sri Lanka and M.Sc degree (2010) in energy and environmental engineering from Telemark University College, Porsgrunn, Norway. He is presently pursuing his Ph.D in carbon dioxide capture from power plants-modeling and simulation studies at Telemark University College. He has presented and published 14 papers in international conferences and journals.

Dinesh Kawan received his B.E degree (2010) in electronics and communication engineering from Khwopa Engineering College, Purbanchal University, Nepal. He is presently pursuing his master degree in system and control engineering in Telemark University College, Porsgrunn, Norway.

He is also working as a research assistant at Faculty of Technology in same university college. Mr. Kawan has research interest in carbon capture, modeling and simulation, and control systems in process industries.

Lars-André Tokheim has a PhD degree in combustion (Telemark University College (TUC), Porsgrunn, Norway, 1999), a MSc degree in industrial environmental technology (TUC, 1994) and a BSc degree in chemistry (TUC, 1992). He is an associate professor at TUC since 2006, where he teaches gas purification and heat & mass transfer, supervises MSc and PhD students, and coordinatesmaster study programmes in Process Technology and Energy & Environmental Technology as well as a PhD study programme in Process, Energy & Automation Engineering. He has industrial experience from Norcem/HeidelbergCement since 1994: as a research scholar (1994-1998), as a process engineer in the Production Department (1998-2001), and as the head of Department of Process Development and Environmental Matters (2001-2006). Prof. Tokheim's main research interests include use of alternative fuels in cement clinker production, calciner technology and gas pollution reduction, in particular CO_2 captureand NO_x reduction.

Morten Chr. Melaaen is a professor in process technology at Telemark University College, Porsgrunn, Norway. He is also the dean of Faculty of Technology, Telemark University College and has a part time position at the local research institute Tel-Tek. Earlier, he has worked as a research engineer in Division of Applied Thermodynamics, SINTEF, Norway and as an associate professor at Norwegian University of Science and Technology (NTNU).

He has worked on research projects as a senior research scientist in Norsk Hydro Research Centre Porsgrunn, Norway. He started to work as a professor at Telemark University College in 1994 and became Head of Department, Department of Process, Energy and Environmental Technology in 2002. He received his MSc in Mechanical Engineering in 1986 and his Ph.D in 1990, both from NTNU. His research interests are CO_2 capture, modeling and simulation, fluid mechanics and heat and mass transfer. Professor Melaaen has more than 100 scientific papers published in the above mentioned related fields in international journals and conferences.