

MANAGEMENT OF THE CO₂ CAPTURE PROCESS INTEGRATION IN THE GLASS TECHNOLOGY INDUSTRY

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Abstract: The main objective of this study is the development of an inventory system of CO₂ emissions in the processing and manufacturing of the glass, as well as ways to reduce them. Considering the characteristics of these types of processes: energy-intensive and with an increased impact on the environment (e.g. climate change), it is important to know the amount of CO₂ generated in atmosphere. Today, the industrial processes consume more than one third of the global primary energy, while 70 % of this is provided by fossil fuels. Consequently, around 40 % of the globally CO₂ emissions are generated by the industrial processes. One method to reduce the CO₂ emissions is based on the integration in the glass fabrication process of the CO₂ capture post-combustion technology. In this work, the integration of CO₂ capture technology by chemical absorption and its integration effects on the glass technology performance were studied. The CO₂ capture efficiency considered was of 90 %. The weight concentration of monoethanolamine and the CO₂ lean loading solvent presented variations. The values of the thermal heat required for solvent regeneration obtained for cases studied were in the range 2-6 GJ/tCO₂. The heat of waste gases from the glass process was used in two steam turbines, one of medium pressure and one of low pressure. The thermal energy required for solvent regeneration was extracted from the low pressure steam turbine. Initially, the thermodynamic efficiency of the steam turbines cycle was of 30 %, after the integration of the chemical absorption process the efficiency penalty was of 11-26 %. The usage of one system to recovery the heat of the waste gases reduces the negative impact of the chemical absorption process integration in the glass production.

Keywords: glass industry, CO₂ emissions, CO₂ capture technology, chemical absorption process.

1 INTRODUCTION

In industry is important to make the distinction between the emissions generated from the energy production necessary of the process and the emissions generated from the manufacturing process of the products. The process emissions are produced in the chemical reactions due to the raw materials composition, generally this emissions cannot be avoided [1]. The amount of CO₂ provided by the raw materials is directly related to the production of glass and is calculated based on the amount of carbonates in the raw materials [2], [3].

In the glass industry, the stages generation of emissions are the same, regardless of the technological type of process applied. The inventory of the pollution sources from the technological processes of glass manufacturing leads to the separation of the technological process in three stages: handling and mixing of raw materials, melting and shaping, and finishing (Figure 1) [4]. Although the raw materials used to produce different types of glass are mostly natural minerals widespread in nature, which generally do not have a significant impact on environmental factors, the handling of these materials presents a significant potential of dust pollution of the atmospheric air [5]. Thus, the diffuse emissions of particles in the storage and handling areas of the raw materials can vary according to the applied technologies and the technical condition of the equipments used in these technological processes. The glass manufacturing processes also require the use of the fossil fuels for production of the heat required for the melting of raw materials, dyes and organic solvents to perform painted glass products [6]. Generally, the household glass industry uses a very wide range of auxiliary materials that give the products different characteristics. The quantitative value of the final products varies between 75 % (crystals) and 90 % (soda-lime glass) of the raw materials entering in the process according to the physic-chemical processing of the shaping and finishing stages [5]. The ratio of raw and auxiliaries materials used in glass manufacturing technologies varies in a relatively large range depending on the final products obtained.

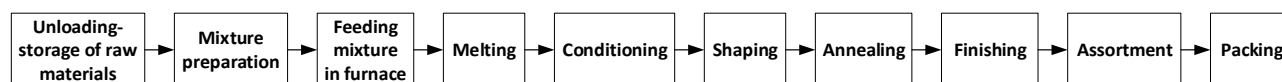


Figure 1: Technological flow of household glass production

The technological process of glass requires an amount of heat in the melting phase of the raw materials. To achieve the glass products the temperature required in the melting furnace is in the range 1500-1800°C [7]. To have the optimal temperature in the melting furnace, an amount of fossil fuel is required (natural gas, oil etc.). The fossil fuel used generates carbon dioxide emissions.

One method to reduce the amount of CO₂ emissions generated by glass production consists of the integration of CCS technology (Capture and Storage CO₂). More technologies for the separation the carbon dioxide were developed in the

last years. The most developed technology for separating the CO₂ is the chemical absorption process [8], [9]. The main advantage of this technology is that it can be applied to separate the carbon dioxide provided from many sources, as the CO₂ from fossil fuel combustion, the CO₂ from different industries (glass, cement, iron, etc.). The main drawback of the chemical absorption process using amines consists of the thermal heat required for solvent regeneration [10]. In the case, the chemical absorption process is integrated into a power plant, the steam required for solvent regeneration is taken by low pressure body turbine leading to a decrease in the global efficiency with 10-20 % [11], [12]. In the glass production, the waste gases have a high temperature. The waste gases are cooled down to 50 °C, the temperature of the chemical absorption process. The heat of the waste gases can be used to cover the heat required for regeneration the chemical solvent [13].

In this article, we studied the post-combustion integration of chemical absorption process using monoethanolamide (MEA) into a glass factory with recovery the heat of the waste gases from glass production, to supply the necessary heat for chemical solvent regeneration.

2 METHOD

The highest emissions potential in the atmospheric air of the raw and auxiliary materials is in the melting phase [3]. The pollution substances are generated due to the following processes: the melting of raw and auxiliary materials introduced in the furnace and the combustion of fossil fuels (oil or natural gas) to obtain the heat required for melting of the raw materials. The carbon dioxide is generated from the fossil fuels combustion process and from the decomposition of carbonates of the batch materials (sodium carbonate and limestone). In the real melting phase, the following processes take place [3]:

- The evacuation of the free water contained in the mixture (the moisture content of the mixture);
- The decomposition of carbonates, sulfates and nitrates (with forming the gaseous compounds such as CO₂, SO₃, SO₂, N₂ and O₂) as well the elimination of crystallization water from raw materials containing it;
- The formation of liquid phases by melting some components, including the eutectics that can result from the initial mixture or from certain local separations of its components;
- The mutual dissolution of the liquid phases formed with obtaining a glass melting without crystals but still containing gases;
- The volatilization of some components of the glass and mixture;
- The dissolution of gases in liquid glass (fuel, air, flue gases, CO₂, SO₂, etc. from raw materials).

As it is observed, the carbon dioxide emissions are generated only in two processes.

The determination of the emissions resulted of technological processes from glass industry can perform in two methods: the first method by direct determination, continuous measurement and monitoring, and the second method is by calculation using the emission factors. In this study, we used the second method by calculation the amount of the carbon dioxide generated in the manufacturing glass process.

2.1 Determination of the CO₂ emissions by mass balance

In this section, we calculated the CO₂ emissions produced at household glass manufacturing. In Tables 1 and 2 there are presented the compositions of the raw materials used to produce glass and the oxide composition of the glass resulted. The amount of raw materials considered was of 100 kg. In addition, the shards (30 kg) and the water, as moisture (1.28 kg) was added at raw materials presented in Table 1. Thus, the total losses with the water and the decomposition gases are of 16.7 kg/100 kg_{glass}.

Table 1: Raw materials

Raw materials	Gravel	Al(OH) ₃	CaMg(CO ₃) ₂	CaCO ₃	Na ₂ CO ₃	NaNO ₃	K ₂ CO ₃	Sb ₂ O ₃	Total
Amount, [kg]	51.17	1.39	12.96	1.09	16.04	2.3	0.51	0.14	85.6
Losses, [kg]	0	0.48	6.19	0.48	6.66	1.46	0.16	0	15.43

Table 2: Glass oxide composition

SiO ₂	Al ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	Sb ₂ O ₃	Shards	Total
[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
51.17	0.91	4.55	2.8	10.08	0.35	0.14	30	100

The reactions that take place in the manufacturing of glass are shown in Table 3. As can be seen the CO₂ emissions are produced at the raw materials decomposition. Based on the chemical reactions listed in Table 3 and the amounts of the raw materials listed in Table 1, the amounts and volumes of the gases and water vapors that are produced by melting can

be calculated using the stoichiometric calculation. The results obtained for the household glass defined are presented in the Table 4.

Table 3: Reactions of glass production [14]

Raw materials decomposition	Glass formation	Clearing glass
$\text{Na}_2\text{CO}_3 \rightarrow \text{Na}_2\text{O} + \text{CO}_2$ $2\text{NaNO}_3 \rightarrow \text{Na}_2\text{O} + \text{NO}_2 + \text{NO} + \text{O}_2$ $\text{K}_2\text{CO}_3 \rightarrow \text{K}_2\text{O} + \text{CO}_2$ $\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$ $\text{CaMg}(\text{CO}_3)_2 \rightarrow \text{CaO} + \text{MgO} + 2\text{CO}_2$ $2\text{Al}(\text{OH})_3 \rightarrow \text{Al}_2\text{O}_3 + 3\text{H}_2\text{O}$	$2\text{Na}_2\text{O} + \text{CaO} + 3\text{SiO}_2 \rightarrow$ $2\text{Na}_2\text{O}.\text{CaO}.3\text{SiO}_2$ $\text{Na}_2\text{O} + 2\text{SiO}_2 \rightarrow \text{Na}_2\text{O}.2\text{SiO}_2$ $\text{Na}_2\text{O} + 2\text{CaO} + 3\text{SiO}_2 \rightarrow$ $\text{Na}_2\text{O}.2\text{CaO}.3\text{SiO}_2$ $\text{Na}_2\text{O} + 3\text{CaO} + 6\text{SiO}_2 \rightarrow$ $\text{Na}_2\text{O}.3\text{CaO}.6\text{SiO}_2$	$\text{Sb}_2\text{O}_3 + \text{O}_2 \rightarrow \text{Sb}_2\text{O}_5$ - which takes place at the nitrates decomposition with the oxygen released by them, and at temperatures above 1200 °C, the reaction takes place: $\text{Sb}_2\text{O}_5 \rightarrow \text{Sb}_2\text{O}_3 + \text{O}_2$ - releasing oxygen, which helps refining glass.

Table 4: Gases resulting by melting stages

Component	CO ₂	NO ₂	NO	O ₂	H ₂ O
Amount, [kg]	13.49	0.62	0.41	0.43	1.28
Volume, [m ³ _N]	6.9	0.3	0.3	0.3	2.2

The fuel used for generated the heat required in the melting furnace contains CH₄ in volumetric concentration of 96.96 %. The low heating value of fuel is of 8813.72 kcal/m³ and the CO₂ emission factor is of 55.75 t_{CO2}/TJ. The results for household glass melting furnace are presented in Table 5.

Table 5: Results melting furnace

Parameter	Value		
Time cycle, [h]	0.8		
Number batches, [batch/24 h]	72		
Combustion air flow in melting furnace, [m ³ _N /h]	4100		
Fuel consumption in melting furnace, [m ³ _N /h]	285		
Flue gases composition from melting furnace, [%]	CO ₂	O ₂	CO
	8	6	0.55
Glass flow extracted, [kg/h]	972		
Flue gases flow from melting furnace, [m ³ /h]	28000		
Flue gases temperature from melting furnace, [°C]	1470		

The calculation of the process emissions [2]:

$$m_{CO_2}^{mp} = FE_{mp} \times m_{gl} \quad (1)$$

where: $m_{CO_2}^{mp}$ - is the CO₂ emissions from the melting process, [kg_{CO2}/h]; FE_{mp} - is the CO₂ emission factor (determined based on stoichiometric chemical reactions), [kg_{CO2}/t_{glass}]; m_{st} - is the product of glass, [t_{glass}/h].

The calculation of the combustion emissions [2]:

$$m_{CO_2}^{fuel} = FE_{fuel} \times LHV_{fuel} \times m_{fuel} \quad (2)$$

where: $m_{CO_2}^{fuel}$ - is the CO₂ emissions from fuel combustion, [kg_{CO2}/h]; FE_{fuel} - is the CO₂ emission factor of fuel (determined on the basis of elementary/chromatographic analysis), [kg_{CO2}/MJ]; LHV_{fuel} - is the low heating value of fuel, [MJ/m³_N]; m_{fuel} - is the fuel consumption, [m³_N/h].

The CO₂ total emissions are obtained by summing up the process emissions and the combustion emissions:

$$m_{CO_2}^{total} = m_{CO_2}^{mp} + m_{CO_2}^{fuel} \quad (3)$$

The CO₂ total emissions was calculated using Eq. 1-3 and was obtained the following results: the amount of CO₂ from melting stage is of 134.9 kg_{CO2}/h, the amount of CO₂ from fuel combustion is of 586 kg_{CO2}/h , and the total amount of CO₂ is of 720.9 kg_{CO2}/t_{glass}, the all results obtained are for one tone of glass produced.

2.2 Chemical absorption process description

In this section, we studied the integration of chemical absorption process in the glass production. The chemical absorption processes consists by the passing the gases that contains CO₂ by an absorption unit. The waste gases from the glass production are introduced in the absorption unit at the bottom and the chemical solvent at the top. The chemical solvent consists of water and one type of amine. In this study, we used monoethanolamide in different concentration in the chemical solvent. After the chemical absorption process takes place, the chemical solvent rich in CO₂ get out at the bottom of the absorption unit. The gases treated leaves the absorption unit at the top. The regeneration of the chemical solvent occurs in the desorption unit at of temperature of 120 °C [15]. In this work, the thermal heat required for solvent regeneration is taken from the heat of waste gases. After the desorption process, the pure carbon dioxide is evacuated at the top of desorption unit to be compressed and storage. The chemical solvent lean in CO₂ is recirculated, but not before to transfer a part of its heat to the chemical solvent rich in CO₂. The pressure of the chemical solvent is maintained by using pumps. The process was simulated in the software Chemcad 6.01. The thermodynamic packages used for simulation the processes (glass production and chemical absorption process) were SRK (Soave-Redlich-Kwong) and Amine packed. In figure 2 is presented the scheme used in Chemcad program.

The gases from the glass manufacturing and the combustion fuel have a high temperature, approximately 1700 °C. The optimal temperature for the chemical absorption is of 50 °C [16], therefore the gases was cooled up to this temperature. It can see that the heat of the gases resulted from process was used to produce power, by two steam turbine, one of medium pressure and one of low pressure. A part of the steam produced was taken from the low pressure steam turbine at five bar for regeneration of the chemical solvent. The CO₂ capture efficiency was maintained of 90 % and the weight concentration of MEA was varied, also it was varied the lean loading solvent to determine the effect on the power produced.

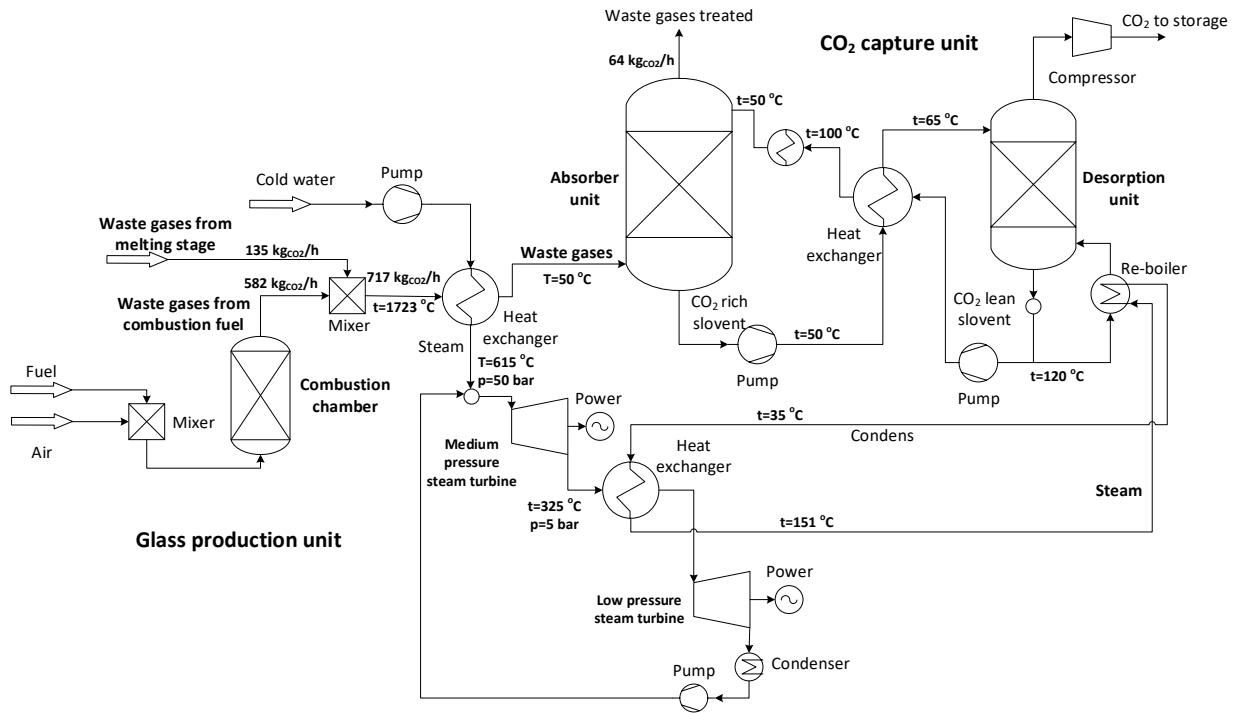


Figure 2: Simulation of the glass process and the chemical absorption process in Chemcad [17]

The thermodynamic efficiency of the cycle before and after the integration of the chemical absorption process was calculated using the following equation:

$$\eta_t = \frac{P_t \cdot \eta_m \cdot \eta_g}{Q_{fuel} \cdot Q_{mp}} \cdot 100 \quad (4)$$

where: η_t - is the thermodynamic efficiency of the cycle, [%]; P_t - is the power produced of the steam turbines, [kW]; η_m - is the mechanical efficiency, 98.5 %; η_g - is the steam generator efficiency, 99.1 %; Q_{fuel} - is the heat of the fuel, [kJ/s]; Q_{mp} - is the heat of the gases from melting process, [kJ/s];

Also, it was calculated the CO₂ emission factor before and after integration of the separation technology like as rapport between the amount of the CO₂ released in the atmosphere and the power produced of the cycle.

3 SIMULATION RESULTS AND DISCUSSION

In this study, we analyzed the integration of the chemical absorption process in the glass production. The amount of the carbon dioxide generated from the glass process resulted by simulation of the process was validated with the results obtained based on the calculation of CO₂ emissions by mass balance. The amount of carbon dioxide from fuel combustion is higher than the amount of carbon dioxide from raw materials decomposition. The molar concentration of CO₂ in the gases from fuel combustion is of 7.8 %, after the gases are mixed with the waste gases from melting boiler, the molar concentration increases up to 9.4 %.

The performances of the chemical absorption process depend on the established value of more parameters. In this study, for the CO₂ capture efficiency of 90 %, and for all absorption process parameters established all cases studied have been compared. The weight concentration of MEA in the chemical solvent was varied, respectively we considered three cases: MEA in weight concentration of 10, 20 and 30 %. The lean loading solvent is an important parameter of the chemical absorption process, the value of these influences the amount of heat required for solvent regeneration. In the specialty literature, the value of the lean loading solvent is of 0.21 kmol_{CO₂}/kmol_{MEA} [11]. In our study, the lean loading solvent was varied between 0.16-0.24 kmol_{CO₂}/kmol_{MEA}. The heat duty for chemical solvent regeneration was between 1400-4000 MJ/h. In Table 6 there are presented the main results obtained for the chemical absorption process.

Table 6: The main results for chemical absorption process

Glass production	
Flow fuel, [kg/h]	215
Flow air, [kg/h]	4500
Excess air, λ , [-]	1.32
Glass produced, [kg/h]	972
Temperature of waste gases, [°C]	1723
CO ₂ from melting stage, [kg/h]	135
CO ₂ from fuel combustion, [kg/h]	582
CO ₂ total, [kg/h]	717
Power, [kW]	1027
CO ₂ emission factor, [kg/MWh]	700
Thermodynamic efficiency, [%]	31
Chemical absorption process	
Temperature of chemical absorption process, [°C]	50
Temperature of desorption process, [°C]	120
Waste gases flow, G, [kg/h]	4878
Chemical solvent flow, L, [kg/h]	6000-17000
L/G ratio, [kg _{w.g} /kg _{c.s}]	1.23-3.32
MEA wt. concentration, [%]	10-30
CO ₂ lean loading solvent, [mol _{CO₂} /mol _{MEA}]	0.16-0.24
Heat duty for solvent regeneration, [MJ/h]	1400-4000
Specific heat duty for solvent regeneration, [GJ/t _{CO₂}]	2-6
Power, [kW]	750-910
CO ₂ emission factor, [kg _{CO₂} /MWh]	70-85
Thermodynamic efficiency, [%]	22-27
Efficiency penalty, [%]	11-26

The ratio between the chemical solvent flow and the waste gases flow was calculated for the three cases studied. The lowest value of the L/G ratio was obtained for the 30 % wt. MEA (Figure 3) of 1.23. With the decreasing of the weight concentration of MEA in the chemical solvent, the L/G ratio increased. However, the weight concentration of MEA is limited, since in higher concentration of 30 % the monoethanolamine is corrosive [18]. In Figures 3 and 4 there are represented the heat duty and the specific heat duty according to the CO₂ lean loading solvent. The heat duty for solvent regeneration increases with the CO₂ lean loading solvent decreases due to the amount of chemical solvent used for to maintain the CO₂ capture efficiency of 90 %. The lowest value for the heat duty was obtained for a MEA 30 wt. % and

for a CO₂ lean loading solvent of 0.24 kmol_{CO₂}/kmol_{MEA}. The specific heat duty represents the thermal energy required for capturing one ton of CO₂. The results obtained of the specific heat duty for the cases studied are between 2-6 GJ/t_{CO₂}. The value of the specific heat duty for the case MEA wt. 30 % and CO₂ lean loading solvent of 0.22 mol_{CO₂}/mol_{MEA} is of 2.21 GJ/t_{CO₂}.

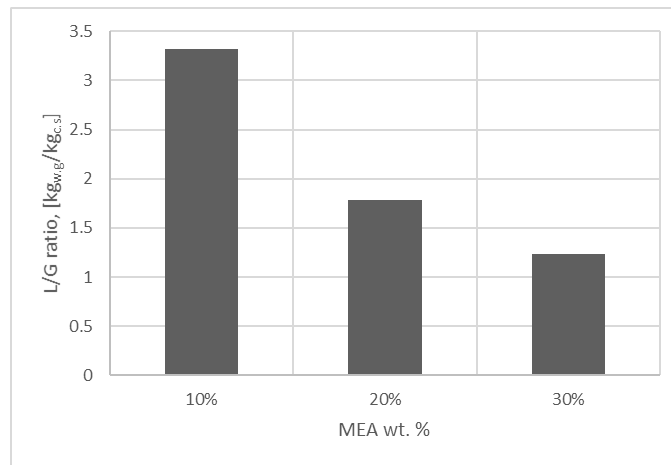


Figure 3: The L/G ratio according to the weight concentration of MEA

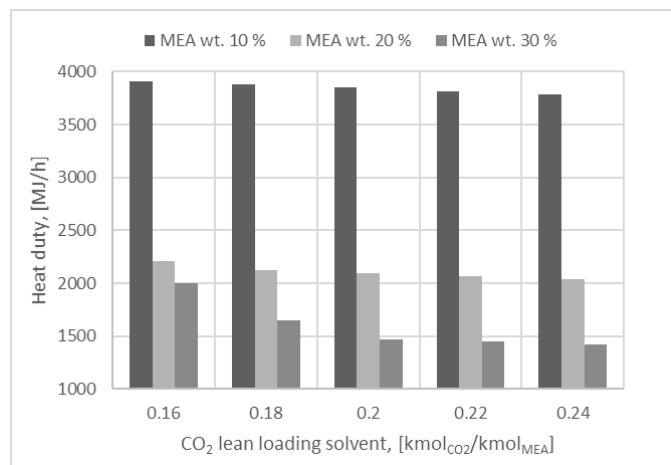


Figure 4: The heat duty according to the CO₂ lean loading solvent and the weight concentration of MEA

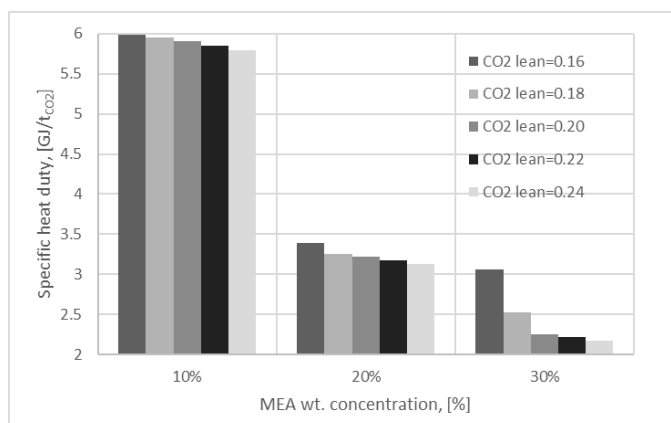


Figure 5: The specific heat duty according to the weight concentration of MEA and the CO₂ lean loading solvent

The thermal heat required for chemical solvent regeneration is provided by the low pressure steam turbine. The steam is extracted at pressure of 5 bar and at temperature of 151 °C. In all cases studied the heat produce of turbines covers the demand of heat for desorption process. In Figure 6 is represented the thermodynamic efficiency after the chemical absorption process was integrated. Without the CO₂ capture technology the power produced is of 1 MW after the integration of chemical absorption process the thermodynamic efficiency of cycle decreases with 11-26 percentage points

according to the amount of steam extracted for chemical solvent regeneration. The total CO₂ emissions factor without carbon dioxide capture for glass process is of 700 kgCO₂/MWh of which 80 % is from fuel combustion. For a high concentration of MEA in the chemical solvent the CO₂ emission factor is lower (Figure 7) because the amount of the CO₂ released in atmosphere is reported of the total power produced.

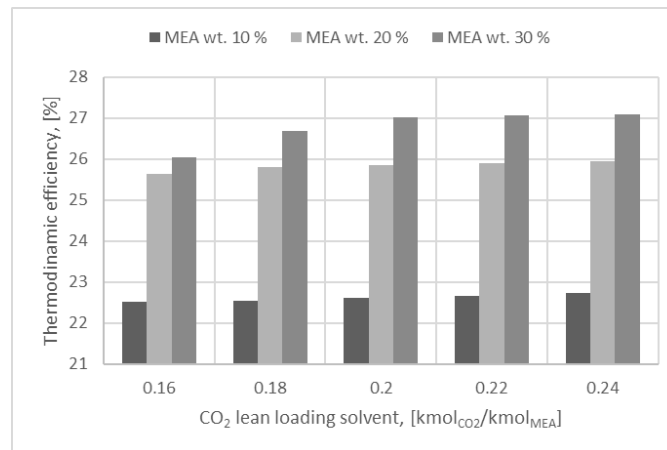


Figure 6: The thermodynamic efficiency according to the concentration of MEA and the CO₂ lean loading solvent

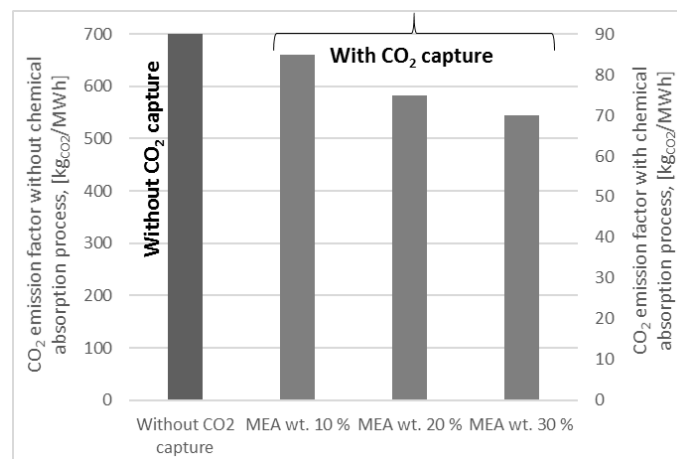


Figure 7: The CO₂ emission factor according to the weight concentration of MEA

4 CONCLUSIONS

In this study, we analyzed from a technical point of view the integration of chemical absorption process in glass production for reducing the carbon dioxide emissions. The glass manufacturing is a consuming energy process. For produced the glass in the melting furnace is required a high temperature that is provided by fossil fuel combustion. The carbon dioxide emissions are generated of fuel combustion and raw materials decomposition in the melting phase. The chemical absorption process was analyzed according to the weight concentration of monoethanolamine in the solvent and the CO₂ lean loading solvent. The L/G ratio is higher for a smaller concentration of MEA in the solvent. For a 30 % weight concentration of MEA the L/G ratio obtained was 1.23 kg_{w.g}/kg_{c.s}. The heat duty was lower for a higher concentration of MEA due to the amount of the chemical solvent. The heat of waste gases was used to provide the heat duty for solvent regeneration thus reducing the integration impact of capture technology. The optimal case in terms of the thermal energy consumption was obtained for a wt. 30 % MEA and for a CO₂ lean loading solvent of 0.24 mol_{CO2}/mol_{MEA}.

The CO₂ capture technology by chemical absorption process is a promising method for separating the CO₂ emissions from glass production if the heat of waste gases is recovered and used in a steam turbine cycle. The thermal heat produced of the steam turbine cycle covers the necessary heat in desorption unit. In addition, the remaining energy surplus after the solvent regeneration can be sold to cover a part of the costs with integration of the CO₂ capture technology and the steam turbines. From this point of view, an economic analysis is needed that we propose to do in future works.

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REFERENCES

- [1] Schmitz, A. et al.: Energy consumption and CO₂ emissions of the European glass industry, *Energy Policy*, Vol. 39 (2011), Iss. 1, pp. 142-155, ISSN: 0301-4215.
- [2] European Environment Agency: *EMEP/EEA air pollutant emission inventory guidebook 2013. Technical guidance to prepare national emission inventories*, Publications Office of the European Union, ISBN 978-92-9213-403-7, Luxembourg, 2013.
- [3] European Environment Agency: *EMEP/EEA air pollutant emission inventory guidebook 2016. Technical guidance to prepare national emission inventories*, Publications Office of the European Union, ISBN ISBN 978-92-9213-806-6, Luxembourg, 2016.
- [4] Scalet, B.M. et al.: *Available Techniques (BAT) Reference Document for the Manufacture of Glass*, Publications Office of the European Union, Scientific and Technical Research series, ISBN 978-92-79-28284-3, Luxembourg, 2013.
- [5] Dumitrescu, O. et al.: *Materiale si tehnologii-sticla, ceramica, lianti, metale*, Ministerul Educatiei si Cercetarii, Bucuresti, 2005.
- [6] Li, Y. et al.: Energy auditing and energy conservation potential for glass works, *Applied Energy*, Vol. 87 (2010), Iss. 8, pp. 2438-2446, ISSN: 0306-2619.
- [7] Carbon Trust: A Study of the Balance between Furnace Operating Parameters and Recycled Glass in Glass Melting Furnaces, 2004, *Available from* <https://studylib.net/doc/18659741/a-study-of-the-balance-between-furnace-operating-paramete...> *Accessed:* 2017-05-29.
- [8] Dinca, C.; Slavu, N. & Badea, A.: Benchmarking of the pre/post-combustion chemical absorption for the CO₂ capture, *Journal of the Energy Institute* (2017), *Available from* <http://dx.doi.org/10.1016/j.joei.2017.01.008>, *Accessed:* 2017-06-2.
- [9]. Leung, D. Y.; Caramanna, G. & Maroto-Valer, M. M.: An overview of current status of carbon dioxide capture and storage technologies, *Renewable and Sustainable Energy Reviews*, Vol. 39 (2014), pp. 426-443, ISSN: 1364-0321.
- [10] Dinca, C.: Critical parametric study of circulating fluidized bed combustion with CO₂ chemical absorption process using different aqueous alkanolamines, *Journal of Cleaner Production*, Vol. 112 (2016), Part 1, pp. 1136-1149, ISSN: 0959-6526.
- [11] Pascu, A. et al.: The package type influence on the performance of the CO₂ capture process by chemical absorption, *U.P.B. Sci. Bull., series C*, Vol 78 (2016), Iss. 1, pp. 259-270, 2016, ISSN 2286-3540.
- [12] Wang, M. et al.: Process intensification for post-combustion CO₂ capture with chemical absorption: a critical review, *Applied Energy*, Vol. 158 (2015), pp. 275-291, ISSN: 0306-2619.
- [13] European Commission: CO₂ reduction in the ETS glass industry by means of waste heat utilization, CO₂-Glass, 2014, *Available from* <http://www.lignite.gr/events/webd1.1.pdf>, *Accessed:* 2017-06-4.
- [14] Guo-Malloy, S.; McMillan, F. P. & Petuskey W.T.: Glass formation and characterization in the 3Al₂O₃·2SiO₂-LaPO₄ system, *Journal of Non-Crystalline Solids*, Vol. 451 (2016), Iss. 1, pp 77-83, ISSN: 0022-3093.
- [15] Badea, A. & Dinca, C.: CO₂ capture from post-combustion gas by employing MEA absorption process-experimental investigations for pilot studies, *U.P.B. Sci. Bull., series D*, Vol. 74 (2012), Iss.1, pp. 21-32, ISSN 1454-2358.
- [16] Dinca, C. et al: Absorber design for the improvement of the efficiency of post-combustion CO₂ capture, *Journal of the Energy Institute*, Vol. 88 (2015), Iss. 3, pp. 304-313, ISSN: 1743-9671.
- [17] CHEMCAD simulation process software, Version 6.0.1. <http://www.chemstations.com/>.
- [18] Fytianos, G. et al.: Corrosion and degradation in MEA based post-combustion CO₂ capture, *International Journal of Greenhouse Gas Control*, Vol. 46 (2016), pp. 48-56, ISSN: 1750-5836.

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