PROPOSAL OF A COMPUTATIONAL MODEL FOR A COAL FLUE GAS DESULFURIZER

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ABSTRACT

The present paper presents the modeling of a flue gas desulfurization system (FGD) with the aim of estimating its power demand and the impact on the overall efficiency of coal fired power plants. A limestone FGD is presented and modeled. The key simulation inputs are the flue gas mass flow rate, temperature, composition, and SO2 fraction, and the outputs are the amount of calcium sulfate dihydrate, or gypsum, and sulfur free flue gases. FGD power demand is the main information as it allows for estimating the energy penalty due to the operation of the system. Flue gases from bituminous and sub-bituminous coals are used to test the simulation routine and results show that the energy penalty ranges around 2% in average, witch is in accordance to data from literature. Model is designed to remove 100% of sulfur content and is sensitive to flue gas mass flow rate and SO2 content.

Key-Words: Energy Penalty, Flue gas filtration, Flue gas desulfurization, FGD

RESUMO

O presente trabalho apresenta uma estimativa da penalização energética imposta às plantas de potência devido à operação de sistemas de dessulfurização de gases da combustão (FGD), baseados em calcário como reagente. O estudo é numérico, realizado a partir de simulações de um modelo de FGD construído para esse fim. O modelo de simulação está centrado no tanque absorvedor, visto que é onde ocorrem as reações entre os gases de combustão e o calcário, e também são levados em consideração equipamentos auxiliares, como bombas, compressor, hidrociclone e trocador de calor. Os dados de entrada do sistema são vazão mássica dos gases de combustão e sua respectiva composição. Como saída têm-se as vazões mássicas dos gases de combustão sem a presença de enxofre e do gesso, que é um subproduto rentável. O consumo de energia do FGD modelado é estimado para uma faixa de valores de vazão mássica e composição dos gases de combustão, o que permite estimar a redução da eficiência líquida nas plantas de potência.

Palavras-chave: *Penalização energética, Filtragem de gases de combustão, Dessulfurizador de gases, FGD*

1 INTRODUCTION

Coal is the world most common source of energy for electricity generation, accounting for 41% of the total production. The Brazilian Association of Mineral Coal (ABCM) (2016) estimates that country’s known reserves could generate up to 17 GW, a significant value when compared to the actual 3.4 MW installed capacity. Coal represents 2.4% of the Brazilian electricity matrix (BEN, 2016), ahead of nuclear but behind wind power. The restriction on the use of coal in Brazil is associated to the socio-environmental impact caused by factors such as the degradation of mining areas and emissions of polluting gases, for example SO2. Therefore, the use of coal in a less impacting manner is directly related to the treatment of effluents on site.

The Flue Gas Desulfurization system, FGD, became mandatory after the Brazilian control policy for pollutant gases emission into the atmosphere. The CONAMA code 382/2006, which established emission standards for pollutant gases, set the maximum limit for the emission of sulfur dioxide from the combustion of mineral coal by 400 mg/Nm3, on dry basis and with 6% excess air.

Brazilian coal has high sulfur content, ranging from 1 to 4% with an average of 2%, thus reducing its quality. However, to comply with the pollutant control standards set by CONAMA, coal with a maximum sulfur content of 0.6% would be required to run power plants larger than 70 MW without the use of a gas cleaner. Therefore, the use of FGD systems in Brazil becomes essential for thermoelectric plants that use national coal as source (Tissot, 2010).

The purpose of this paper is to assess the energy penalty due to FGD system operation on a regular coal power plant unit. The addressed model is a wet limestone desulfurizer, whose main goal is to quantify the electric power demand from equipment as pumps, fans, mills, stirrers and hydrocyclones, according to flue gas content and mass flow rate.

2 THE FLUE GAS DESULFURIZATION SYSTEM - FGD

2.1 SYSTEM OVERVIEW

The Flue Gas Desulphurization system - FGD modeled and implemented in the present work is based on wet scrubbing (Perry, 1997), assuming that flue gases were already free of solid particulates.

The general wet scrubbing FGD system is depicted in the next figure, focusing three of its subsystems, dedicated to the reagent preparation, SO2 absorbing and gypsum dewatering.

2.2 ABSORBER

At the heart of the process, a counter flow absorber tank based on a vertical tower gathers the acid sulfuric flue gas stream from flue gases (stream 4) with the alkaline limestone slurry (stream 10) and some extra atmospheric air (stream 12) to produce raw calcium sulfate dihydrate (stream 19). The scrubbing process is described as follows:

$$\mathrm{CaCO_3} + \mathrm{SO_2} + 2\mathrm{H_2O} + \frac{1}{2}\mathrm{O_2} \rightarrow \mathrm{CaSO_4} \cdot 2\mathrm{H_2O} + \mathrm{CO_2}$$

[Eq. 01]

based on the unitary molar inputs of calcium carbonate CaCO3 and sulfur dioxide SO2, water H2O and extra atmospheric air O2. The irreversible reaction produces gypsum CaSO4.2H2O and carbon dioxide CO2. Besides that reaction, the inert gases from all streams are taken into account to perform the mass and energy balances.

The absorber tank was modeled to operate under steady state conditions. Its mass balance is given below, where each parameter is labeled and numbered according to Fig.1:

$$\sum_{i=in} \dot{m} = \sum_{j=out} \dot{m}$$

$$\sum_{i=in} \dot{m} = \dot{m}_{flue\ gas-in(4)} + \dot{m}_{limestone\ slurry\ (10)} + \dot{m}_{air(12)} + \dot{m}_{water(14)} + \dot{m}_{gypsum\ slurry(12)}$$

$$\sum_{j=out} \dot{m} = \dot{m}_{flue\ gas-out(17)} + \dot{m}_{gypsum(19)}$$

[Eq. 02]

Power plant flue gases (stream 3) are cooled down before admission in the absorber (stream 4), where they react with limestone slurry (stream 10), added by an air injection (stream 12). In addition, cooling water (stream 14) aids to control the inside tank temperature and some residual calcium sulfate dihydrate is recovered from the gypsum slurry tank to enhance its concentration (stream 28). The absorber outputs are calcium sulfate dihydrate, or gypsum, and sulfur free flue gases. The proposed model considered a 100% efficiency removal. Eq. 3 expresses the absorber tank energy balance, following the same assumptions taken for Eq. 2.

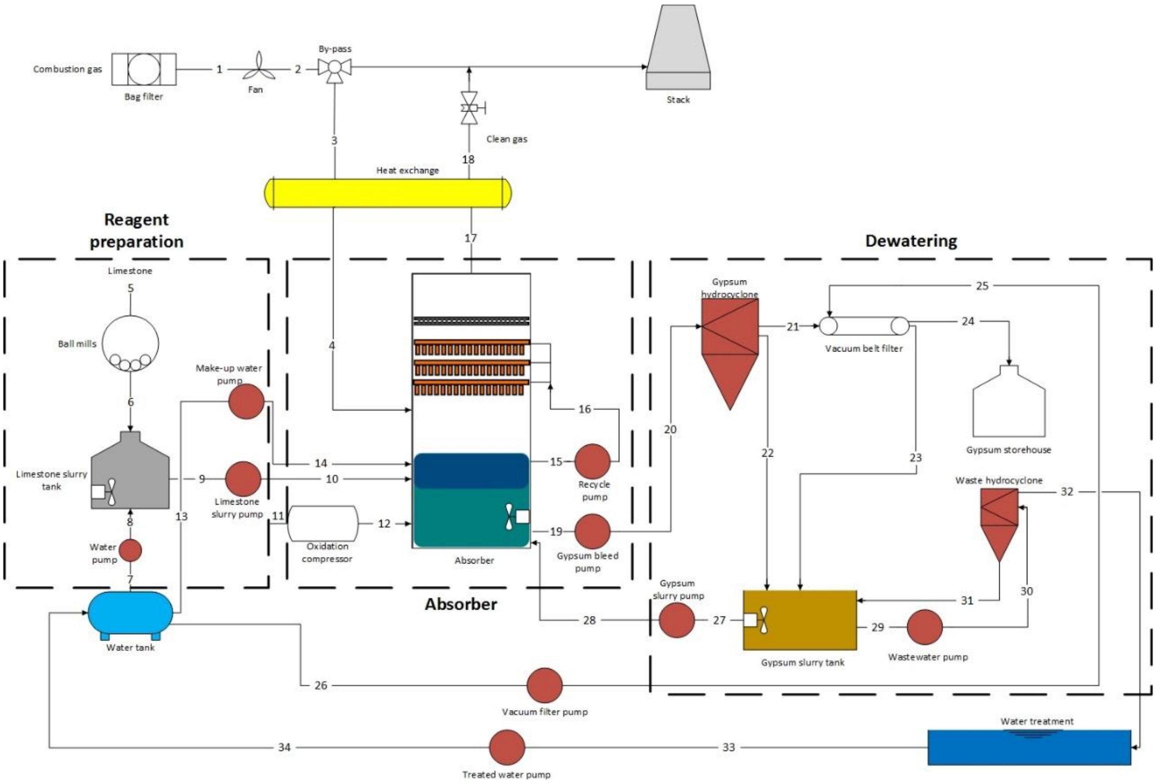
$$Q = 0 = \xi \Delta H°_{reaction}(T_0) + \sum_{i=in} \int_{T_i}^{T_0} \dot{m}_i\, c_{pi}\, dT_i + \sum_{j=out} \int_{T_0}^{T_j} \dot{m}_j\, c_{pj}\, dT_j \qquad \text{[Eq. 03]}$$

Model considered the absorber tank surfaces to be adiabatic (Q = 0), and the balance was written to find $\dot{m}_{water(14)}$, the cooling water mass flow rate. The adopted strategy was to force the process to operate at controlled tank bulk temperature T_0 and fixed cleaned flue gas flow output temperature$T_{flue\ gas-out(17)}$. The scrubbing process (Eq. 1) is exothermic, and though its enthalpy of reaction $\xi \Delta H°_{reaction}$ is positive, with ξ the extent of reaction (ξ = 1 for full sulfur conversion).

2.3 REAGENT PREPARATION

Calcium carbonate CaCO3 (limestone) is admitted (stream 5) at the ball mill to be crunched and then send to the limestone slurry tank to become the scrubbing agent, injected in the absorber tank (stream 10). Water to that process is recovered from the gypsum dewatering treatment (streams 26 and 34).

Fig. 1- Flue gas desulfurization FGD plant flow diagram with three subsystems: reagent preparation, SO2 absorbing and gypsum dewatering.



2.4 DEWATERING

Calcium sulfate dihydrate (stream 19) is pumped from the absorber tank to the hydrocyclone (stream 20) to start the 1st step towards the gypsum drying, which ends at stream 24. Hydrocyclone underflow stream (21) is processed at a vacuum filter to be then (stream 24) send to its final destination, the gypsum storehouse storage. The rejected product from the vacuum filter (stream 23) joins the same class of waste rejected from the hydrocyclone overflow stream (22).

3 FGD ENERGY PENALTIES AND MODEL PARAMETERS

FGD contribution to energy expenditure on a power plant comes from mechanical work, as fluid transport and movement, performed by pumps and fans, mineral treatment on mills, and other auxiliary equipment. Most relevant auxiliary devices are listed in the next table.

Table 1. FGD mechanical drivers and their position on the plant

#	equipment	Up stream	downstream
1	Flue gas fan	1	2
2	Ball mill	5	6
3	Water pump	7	8
4	Make-up water pump	13	14
5	Limestone slurry pump	9	10
6	Oxidation compressor	11	12
7	Recycle pump	15	16
8	Gypsum bleed pump	19	20
9	Gypsum hydrocyclone	20	22
10	Vacuum filter pump	25	26
11	Waste hydrocyclone	30	31-32
12	Waste water pump	29	30
13	Gypsum slurry pump	27	28
14	Treated water pump	33	34

15	Limestone slurry stirrer	Limestone slurry tank
16	Slurry stirrer	Absorber
17	Recovered slurry tank stirrer	Gypsum slurry tank

Electrical power demand from pumps and fans depend on the fluid mass flow rate of the streams mentioned on the last table. Eq. 1 describes the reaction that takes place in the absorber, in molar basis. Its driving input is the amount of SO2 produced by combustion process that takes place at the power plant steam generator. That information comes from a prior power plant simulation, whose outputs are the species fractions of the flue gases, developed in the same framework of this project. According to the reaction in Eq. 1, all species quantities related to react with one mole of SO2 are then calculated, as well as the process energy requirements, by equations 2 and 3. As a general relation, electrical power demand W˙ (kW) for fluid machines was calculated from:

$$\dot{W} = \frac{\dot{m}\, v\, \Delta P}{\eta} \qquad \text{[Eq. 04]}$$

where $\dot{m}$ is the fluid mass flow rate (kg/s), v is the fluid specific volume (m³/kg), ΔP is the flow pressure difference (kPa), and η is the conceptual or average equipment conversion efficiency.

Operational data for limestone milling was quite hard to find, and a first approximation was done by combining to separate information. Limestone consumption was based in actual data from the Pego power plant in Portugal (Alves, 2013), reported as 75.335 ton/year. The HJ Crusher catalog (2016) indicated that their product power demand was 155 kW for a range of 4.5 to 12.0 ton/year. A specific energy consumption eL was then estimated as 64.8535 kJ/kg, and milling power W˙_milling (kW) was then estimated by

$$\dot{W}_{milling} = \dot{m}_L\, e_L \qquad \text{[Eq. 05]}$$

with $\dot{m}_L$ the limestone mass flow input at stream 5.

Stirrer power demand $\dot{W}_{stirrer}$ (kW) was taken from Perry as

$$\dot{W}_{stirrer} = N_{Po} \rho N^3 D^5 / 1000 \qquad \text{[Eq. 06]}$$

where *Npo* is the power number (dimensionless), ρ the fluid density (kg/m³), *N* the propeller angular velocity (rps) and D its diameter (m).

Hydrocyclone power demand $\dot{W}_{hydro}$ was estimated on private communication with the operational staff from a Brazilian power plant owner, the TRACTEBEL group, which operates these devices with an average stream balance of 23% downstream mass flow and 77% upstream mass flow. Energy requirement was calculated by the aid of Eq. 4 to both streams.

Total power requirement $\dot{W}_{FGD}$ to run the FGD plant could be expressed by the summation of all individual demands described in Table 1, given as:

$$\dot{W}_{FGD} = \sum \dot{W}_{pump} + \dot{W}_{fan} + \dot{W}_{mill} + W_{stirrer} + \dot{W}_{hydro} \qquad \text{[Eq. 07]}$$

The FGD model inputs and operational parameters are the flue gas mass flow rate, temperature and composition, with SO2 fraction as key information. The operational bulk temperature in the absorber tank T_0 and the flue gas temperature at the heat exchanger discharge (stream 18) are also prescribed. These values are presented on the next table.

Table 2. Input parameters for the FGD model

Parameter description	Stream	reference values
Flue gas temperature	4	140 ºC
Flue gas mass flow rate	1 or 4	250 kg/s
Flue gas pressure	1	1050 kPa
Absorber exit temperature	17	60 ºC
Stack exit temperature	18	90 ºC
Make-up water temperature	14	20 ºC

Equipment and system parameters are presented on the next table.

Table 3. System and equipment parameters for the FGD model

Device parameter	Value
Pump efficiency	60%
Compressor efficiency	65%
Impeller power number	1,5
SO2 removal efficiency	100%

It is worth noticing that the SO2 removal process was assumed to be 100% efficient, as a first research approach. Equipment efficiencies were taken from a conceptual point of view, and can range in an actual case. Simulation routine was built with Engineering Equation Solver – EES.

4 CASE STUDY

FGD energy demand depends on coal composition, mainly on its SO2 fraction. Two types of coal were chosen to perform the model performance, and presented in the next table.

Table 4. Bituminous and sub-bituminous coal chemical composition (%) (Pershing, 1977)

Chemical Composition	*Bituminous*	*Sub-bituminous*
Carbon (C)	69.57	32.7
Hydrogen (H)	3.93	2.2
Nitrogen (N)	1.17	0.7
Sulfur (S)	0.17	1.6
Oxygen (O)	5.86	8.8
Ash	16.8	54

Bituminous coal is a low sulfur, low ash content fuel, common in the US. Sub-bituminous coal goes in the opposite sense, with higher amount of sulfur, and a great deal of ashes. Electrical power production from this south Brazil fuel is only viable whenever the power plant is placed virtually on the top of the mine, due to its lower energy content, in comparison to the bituminous coal.

A combustion routine was developed to simulate flue gas composition for these two coals, based on a stoichiometric balance of reagents and products. A prior simulation performed by a Rankine cycle routine, also developed along the present project, indicated a flue gas mass flow rate of 250 kg/s to produce 600 MW of electrical energy (e.g. an specific energy of about 2400 kJ/kg). Next table presents the energy penalty imposed to electricity production due to sulfur removal of a 600 MW electric power plant, for two types of coals.

Table 5. FGD energetic demand (kW) and its penalty for a 600 MW electric power plant running with two types of coal

Flue gas compositions (mole)		
	Bituminous	Sub-Bituminous
CO2	50.650	22.870
H20	24.010	18.550
N2	217.000	96.320
SO2	0.00464	0.41910
FGD eletric power (kW)	11,818.0	13,054.0
Energy penalty	1.97%	2.18%

The energy penalty was calculated as the relative ratio of the FGD electric power demand to clean the flue gases to the electric power plant output, according to the type of coal. The FGD model was sensitive to the sulfur content, as the required power was directly proportional to the amount of SO2 from flue gases. Results were also compared to released data from a 600 MW ALSTOM power plant, given as follows:

Table 6. FGD energetic demand (kW) and its penalty for an ALSTOM 600 MW electric power plant running with two types of coal (Gansley, 2008)

	Low sulfur	High sulfur
SO2 mass flow rate (kg/s)	1.512	5.670
Energy Consumption (kW)	6,128.0	11,464.0
FGD penalty (%)	1,021	1,911

Results from the present simulation were in accordance to the ones from ALSTOM as the model captured the same tendency. Required power was different, but there was no information on the coal composition from ALSTOM data.

5 CONCLUSION

The FGD model was able to calculate the required electric power to perform flue gas desulfurization, based on the ideal assumption of 100% removal efficiency and with equipment operating on their best situation, around the conceptual design point.

Two types of coal were chosen to perform simulations, the US bituminous and the Brazilian sub-bituminous ones. Coal flue gases displayed similar elementary composition, but with an important difference on their contents, with 0.17% and 1.60% of sulfur on these two types, respectively.

Energy penalty was calculated after the summation of the required electrical power demanded by pumps, fans, limestone mill, slurry stirrer and hydrocyclones. The key model input was the SO_2 amount in flue gases, witch demanded a calculated quantity of limestone, water and air. The model showed to be sensitive to sulfur content, predicting an energy penalty of 1.19% and 2.18% for the bituminous and sub-bituminous coals, respectively.

Results from the present FGD model were compared to similar ones from a 600 MW ALSTOM power plant, and deviation can be considered as of low significance, with 1.19% to 1.021% for the bituminous coal and 2.18% to 1.911% to the sub-bituminous coal. The accuracy of these deviations cannot be assessed due to the lack of details on ALSTOM data

Further efforts should be done on the model to take into account the sulfur removal efficiency, and the routine integration to the already developed cofiring Rankine power plant

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7 REFERENCES

ALVES, M.S. Quality Control of Gypsum - Product of the Desulfurization Process of the Flue Gases at the Pego Thermoelectric Power Plant (Controlo de Qualidade do Gesso – **Produto do Processo de Dessulfuração dos Gases de Combustão na Central Termoelétrica do Pego**), (dissertation), Escola Superior de Tecnologia de Tomar, Portugal, 2013 (in Portuguese).

BRAZILIAN ASSOCIATION OF MINERAL COAL (ABCM), Available at: < www.carvaomineral.com.br/ > [accessed 10.15.2016]

BRAZILIAN NATIONAL ENERGY BALANCE (Balanço Energético Nacional). **BEN** – Available at: <https://ben.epe.gov.br/downloads/Relatorio_Final_BEN_2016.pdf> [accessed 1.17.2017] (in Portuguese).

CONAMA - National Council for the Environment (Conselho Nacional do Meio Ambiente) code 382/2006. Available at: <http://www.mma.gov.br/port/conama/legiabre.cfm?codlegi=520> [accessed 08.14.2016]

GANSLEY R. **Wet FGD System Overview and Operation**. In: WPCA Wet FGD Seminar Power Gen International; 2008.

HJCRUSHER, **Ball Mill**, Available at: <http://www.hjcrusher.com.pt/1-ball-mill-1.html> [accessed 05.17.2016]

PERRY, R.H.; GREEN, D.W. **Perry's Chemical Engineers' Handbook**. 7th ed., The McGraw-Hill Companies; 1997

Pershing, D.W., Wendt, J.O.L. **Pulverized Coal Combustion: The Influence of Flame Temperature and Coal Composition on Thermal and Fuel NOx**. Symposium (International) on Combustion 16, (1), 1977: 389–399

TISSOT R.C.M., Study of the Dispersion of Particulate Matter Emitted by the Charqueadas Thermoelectric Power Plant (**Estudo da dispersão de material particulado (pts), emitido pela usina termelétrica de Charqueadas**). (dissertation), Universidade Federal do Rio Grande do Sul, Brazil, 2010. (http://hdl.handle.net/10183/61680) (in Portuguese).