Flue Gas Desulfurizer mass and energy balance in 300 MW class subcritical Coal-Fired Power Plant for retrofit application

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Abstract. Based on the recent implementation of the Ministry of Life and Environment (MOLE) Regulation No. P.15/MENLHK/SETJEN/KUM.1/4/2019 regarding Power Plant Flue Gas Emission, which supersedes MOLE Regulation No. 21 year 2008, there is a reduction of maximum Sulfur Dioxide (SO₂) concentration in flue gas emission of Coal-Fired Power Plant (CFPP), from 750 mg/Nm³ @7% O₂ content (dry basis), to 550 mg/Nm³ in existing CFPP, and 200 mg/Nm³ in CFPP constructed after the implementation of the regulation. Thus, arises the necessity for the consumption of Coal with lower Sulfur (S) content and/or retrofitting of Flue Gas Desulfurizer System (FGD) system in CFPP, not yet equipped with the FGD system. One of the applicable systems for retrofit is Sea Water FGD (SWFGD). This paper explores the energy and mass balance aspect of the SWFGD system for application in 300 MW subcritical reheated steam CFPP. Operational aspect is the increase of allowable sulfur content in consumed coal up to 1,162%, when the plant is retrofitted with SWFGD, and an increase in condenser cooling water of 0.6 °C due to SWFGD Absorber interface.

1. Introduction: Coal-Fired Power Plant (CFPP) and latest Indonesian flue gas emission regulation

Electricity energy production employing Coal-Fired Power Plant (CFPP) creates a byproduct of flue gas emission that is ejected into the environment, with a composition of Carbon Dioxide (CO₂), Nitrous Oxides (NOx), Particulates, Oxygen (O₂), and Sulfur Dioxide (SO₂). Sulfur Dioxide emission in flue gas that is the main subject of this academic paper, originates from the combustion of Sulfur content in coal, with the following exothermic chemical reaction:

\[ S + O_2 \rightarrow SO_2 \]  

(1)

Excessive SO₂ concentration in flue gas can cause acid rain phenomenon in the local surrounding area of CFPP [1]. Thus, the concentration limit of SO₂ in flue gas is regulated by the Indonesian Government in the newly adopted Ministry of Life and Environment (MOLE) Regulation No. P.15/MENLHK/SETJEN/KUM.1/4/2019 regarding Power Plant Flue Gas Emission that supersedes Regulation No. 21 year 2008 with the following regulated SO₂ concentration:
Table 1. Indonesian CFPP SO$_2$ Flue gas emission limit [2].

| CFPP Operation Period | Maximum SO$_2$ Concentration | Unit | Flue gas Oxygen content equivalency |
|-----------------------|------------------------------|------|-----------------------------------|
| Operation before 2019 | 550 mg/Nm$^3$ | 7% O$_2$ Dry Basis |
| Operation after 2019  | 200 mg/Nm$^3$ | |

SO$_2$ concentration in flue gas is a function of coal calorific value, Sulfur content, and excess combustion air. The more excess combustion air introduced, the more diluted the SO$_2$ and the other regulated emission become. Consequently, the measured flue gas is normalized into 7% O$_2$ content dry basis (DB) which translates into approximately 48-50% more air than the amount of air needed to combust the fuel completely (Combustion stoichiometric air).

Due to the linear correlation between combustion stoichiometric air with coal calorific value, an increase in coal calorific value will increase the allowable Sulfur content in relation to coal calorific value, the regulated SO$_2$ value of 550 mg/Nm$^3$ @7% O$_2$ DB is exceeded. This correlation of environmentally compliant coal is explained in figure 1, as result of common knowledge stoichiometric combustion calculation. Combustion of Coal in any type of CFPP with Sulfur content above the calorific value specific figure will produce flue gas emission above the regulatory allowed concentration.

![Environmentally Compliant Coal Specification](image)

Environmental Compliant Coal Specification  
(Calorific Value & %Sulfur Correlation)

Figure 1. SO$_2$ environmentally compliant coal as function of calorific value.

2. Methodology: Sea Water Flue Gas Desulfurizer (SWFGD) and mass and energy balance interaction in 300 MW CFPP retrofit application

Consumption of Environmentally Compliant (EC) coal is a surefire way to ensure SO$_2$ emission compliance. However, EC coal comes at a premium price point relative to non EC Coal, and its availability is limited. Thus, in order for CFPP to ensure long term operation feasibility and emission compliance, a retrofit of the Flue Gas Desulfurizer (FGD) system might be needed. Among the various FGD system available, this paper reviews the Sea Water (SW) FGD system, especially for retrofit application. SWFGD utilizes the reaction between flue gas and seawater, to extract SO$_2$ and turn it into Sulfur Trioxide (SO$_3$) in the reaction absorber, then into Sulfate (SO$_4$) after oxidation reaction in the Aeration Basin [3,4]. The seawater is extracted from the Turbine Rankine cycle condenser discharge, in which a portion of it is reacted in the Flue Gas Absorber, as described in figure 2. The flue gas is then reheated by means of Gas-Gas Heater (GGH), and the seawater is discharged back into the marine environment via outfall. Seawater has a SO$_4$ concentration of 2,71g/kg seawater [5], and MOLE Regulation No 8 year 2009 that limits the increase of SO$_4$ in seawater discharged back to the environment by 4%, and maximum temperature of 40°C [6].
2.1. **Energy balance of 300 MW subcritical single reheated steam CFPP and maximum coal sulfur content in SWFGD Retrofit application**

The basis of SWFGD retrofitted Power Plant is a typical 300 MW Subcritical Single Reheated Steam CFPP in 100% and 60% unit load as described in table 2. The CFPP consumes Low Rank Coal typically consumed by Indonesian Power Plant with calorific value of 4200 kcal/kg coal [7], with separate calculation yielding stoichiometric combustion air of 5.69 kg air/kg coal, with the boiler efficiency determined after the last stage of flue gas heat exchange in the Regenerative Air Pre Heater (RAPH).

**Table 2.** Typical 300 MW SC CFPP as case study.

| Parameter                              | Unit | 100% Load | 60% Load |
|----------------------------------------|------|-----------|----------|
| Nett Electric Power                    | MW   | 300       | 180      |
| Gross Electric Power                   | MW   | 325       | 200      |
| Boiler Efficiency (HHV)                | %    | 88        |          |
| Boiler Efficiency (LHV)                | %    | 93        |          |
| Turbine Cycle Efficiency               | %    | 41.85     | 39.62    |
| Coal Calorific Value (HHV)            | kcal/kg | 4200     |          |
| Coal Stoichiometric Combustion Air    | kg air/kg coal | 5.69 |          |
| Unit Nett Efficiency (HHV)             | %    | 34        | 31.3     |
| Fuel Energy Flow Rate (HHV)           | MW   | 882.35    | 573.52   |
| Fuel Mass Flow Rate (AR Basis)        | ton/h| 180.88    | 117.57   |
| Flue Gas Energy Flow (HHV) RAPH Discharge | MW   | 105.88    | 68.82    |
| Flue Gas Energy Flow (LHV) RAPH Discharge | MW   | 61.76     | 35.32    |
| Flue Gas RAPH Outlet Mass Flow Rate   | kg/h | 1.441.270 | 936.825  |
| Steam Energy Flow (100% Load)         | MW   | 776.40    | 504.70   |
| Condenser Cooling Energy Flow         | MW   | 451.50    | 318.36   |
| Cooling Water inlet temperature       | °C   | 31        |          |
| Cooling Water temperature Increase    | °C   | 7         | 4.94     |
| Cooling water volumetric flowrate     | m³/h | 56.743    |          |
| SO₂ cooling water flowrate (initial)  | kg SO₂/h | 157.579  |          |
| 4% SO₂ Increase allowance             | kg SO₂/h | 6303.16  |          |

Based on the parameter in table 2, and an assumption of 100% flue gas desulfurization effectiveness, the maximum amount of coal sulfur content in 100% Unit load that yields an addition of +4% \( \text{SO}_4 \) in condenser cooling water can be obtained from the following calculation:
Condenser cooling water is pumped by the Cooling Water Pump (CWP) as a constant flow rate independent of the CFPP unit load [8]. Thus, the lower the CFPP Unit load, the lower the coal fuel flow rate needed, but the same amount of cooling water is supplied, resulting in an increased ratio of cooling water relative to coal consumption. Furthermore, the boiler fans supply a proportional amount of air relative to coal consumption, but consume a constant amount of Auxiliary power in lower Plant load. Consequently, the relation of coal mass flow rate to unit load is not entirely proportional. The writer assumes coal consumption in 60% unit Load is approximately 65% of the mass flow rate of 100% load. Thus, the maximum amount of coal sulfur content in 60% Unit load that yields an addition of +4% SO\(_4\) in condenser cooling water can be obtained from the following calculation:

\[
Max S(\% AR) = \frac{m_{SO_4} x m_S}{\%Flow x m_{coal}} \times 100% = \frac{6306.14 \ kg \ SO_4}{h} x \frac{34 \ g/mol \ S}{96 \ g/mol \ S} \times \frac{kg \ SO_4}{mol \ S} \times 100% = 1.162% 
\]

Thus, a relation of maximum coal sulfur in relation to cooling water SO\(_4\) addition and CFPP unit load can be described in figure 3, with increasing sulfur content in coal relation to decreasing of CFPP unit Load. The graph is based on a specific coal calorific value of 4200 kcal/kg, and 100% flue gas desulfurization. Actual desulfurization is slightly below 100%, and actually allowable coal can increase by a small fraction. Furthermore, the actual graph might not be entirely linear, due to the nonlinear relation between coal consumption and unit part load operation between 100% and 60% load, but such graphical illustration provides an important understanding of the practical operational approach to sulfur coal mixing in part load operation.

\[
y = -1.8425x + 3.0045 
\]

\begin{figure}
\centering
\includegraphics[width=\textwidth]{sulfur_coal_max_value_relative_to_SO4_addition_allowance_and_300_MW_CFPP_Unit_Load.png}
\caption{Sulfur coal maximum value relative to SO\(_4\) addition allowance and 300 MW CFPP Unit Load.}
\end{figure}

2.2. Heat and mass balance interface of SWFGD and CFPP

The addition of SWFGD in the CFPP system, creates an interface in the heat and mass balance that increases SO\(_4\) and temperature in the seawater discharged to the outfall. SO\(_4\) addition calculation is calculated in subchapter 2.1, and further calculation is made to find the increase in cooling water temperature, based on heat and mass balance interaction in a 300 MW subcritical reheated Steam CFPP,
but the calculation principle and methodology can be scaled into different capacity and configuration of CFPP. Addition of SWFGD absorber and GGH in the discharge side of CFPP Flue gas will also introduce additional pressure drop that will have to be resolve by the addition of booster fan, or increasing the capacity of Induced Draft Fan [9]. However, such aspect will not be discussed in this paper.

The corresponding mass balance equations based on figure 2 is as follow:

$$m_B = m_A + m_C$$
$$m_D = m_B + m_E - m_{10}$$
$$m_{11} = m_{10} + m_2$$
$$m_4 = m_{10} + m_3$$
$$m_{11} = m_2 = m_B = m_{CW}$$
$$m_{12} = m_{fuel} \times % Ash$$
$$m_{10} = m_1 \times % GGH Leakage$$

The corresponding heat balance equations based on figure 2 is as follow:

$$P_{Boiler\ Exhaust} = P_{Fuel} \times (100\% - \eta_{Boiler}) = P_B = P_D$$
$$P_B = m_B \times [(C_{Boiler\ Exhaust} \times T_B) - (C_{Ambient} \times T_{Ambient})]$$
$$P_D = (m_B + m_E) \times (C_{D} \times T_{D})$$
$$P_{Condenser} = m_{CW} \times [(C_{P} \times T_6) - (C_{P} \times T_7)]$$
$$P_{Absorber} = m_{CW} \times [(C_{P} \times T_6) - (C_{P} \times T_7)] = m_2 \times [(C_{P} \times T_3) - (C_{P} \times T_2)]$$

3. Result and discussion: SWFGD parameter in retrofitted CFPP

3.1. Flue gas and cooling water discharge parameter after SWFGD retrofit in 300 MW CFPP

Operation parameter of SWFGD system in Reference of “Paiton” CFPP in East Java, Indonesia, that has an absorber desulfurization effectiveness parameter of 96% [3]. The discharged SO₂ concentration to the environment, however, is also a function of the flow percentage of GGH leakage that is manufacturer specific. One manufacturer state that leakage can go as low as 0.25% of the GGH hot inlet [10], but a conservative figure of 0.5% leakage is to be used for calculation [11]. GGH cold side out is the measured gas discharged into the environment, and is subject to regulation as stated in table 1.

### Table 3. Flue gas parameter of SWFGD retrofitted 300 MW CFPP in 100% and 60% load.

| No | Name             | Temperature | % Dry Basis | O₂ Content | Mass Flowrate @ 100% Load kg/s | 1,162% S kg/s | Mass Flowrate @ 100% Load | SO₂ Concentration @ 100% Load & 1,162% S % | Exergy @ T ambient 31°C kg/s | Energy @ T ambient 31°C Energy @ T ambient 31°C MW | Energy @ T ambient 31°C Energy @ T ambient 31°C MW |
|----|------------------|-------------|-------------|------------|--------------------------------|---------------|--------------------------|---------------------------------------------|------------------------------------------|------------------------------------------------|------------------------------------------------|
| A  | Economizer Outlet| 130         | 3           | 377.09     | 4090                           | 245.50        | 6646                     | -                                           | -                                         | -                                              | -                                              |
| B  | RAPH Outlet      | 175         | 4.18        | 400.15     | 3821                           | 61.76         | 260.23                   | 303.08                                      | 6209                                      | 40.144                                      | 40.144                                       |
| C  | RAPH Leakage     | 31          | 21          | 22.66      | 0                               | 14.73         | 0                        | 0                                           | 0                                         | 0                                              | 0                                              |
| D  | ESP Outlet       | 155         | 7           | 466.27     | 3180                           | 61.76         | 303.08                   | 5168                                        | 29.721                                    | 40.144                                      | 40.144                                       |
| E  | ESP Leakage      | 31          | 21          | 65.92      | 0                               | 42.85         | 0                        | 0                                           | 0                                         | 0                                              | 0                                              |
| F  | GGH Hot Inlet    | 155         | 7           | 466.27     | 3180                           | 61.76         | 303.08                   | 5168                                        | 206.72                                    | 13.3445                                     | 13.3445                                      |
| G  | GGH Cold Inlet   | 70          | 7           | 463.94     | 272.70                         | 50.53         | 301.56                   | 206.72                                      | 13.3445                                   | 206.72                                      | 13.3445                                      |
| H  | GGH cold side outlet (Emission Regulated) | 105 | 7 | 466.27 | 136.47 | 37.576 | 303.08 | 231.52 | 24.2244 |
| I  | GGH Leakage      | 155         | 7           | 2.331      | 1981                           | 0.312         | 1.52                     | 5168                                        | 0.2028                                    | 5168                                          | 0.2028                                       |
Cooling water discharge temperature addition due to interface of SWFGD CFPP is described in table 4. Calculation is based on Lower Heating Value (LHV) Basis with actual absorber discharge calculation. Further conservative calculation of High Heating Value (HHV) basis with 100% of the flue gas energy also yield Aeration basin outlet lower than the regulated limiting factor of 40°C as per regulation [3]. Such calculation of temperature addition to cooling water is a plant specific limiting factor to the retrofit aspect of SWFGD, and should be calculated based on the actual values of the CFPP in 100% load condition.

Table 4. Flue gas parameter SWFGD retrofitted CFPP in 100% load.

| No | Name                          | Temperature | Mass Flowrate |
|----|-------------------------------|-------------|---------------|
| 11 | Condenser Inlet               | 31          | 16.152        |
| 7  | Condenser Outlet              | 38          | 16.152        |
| 8  | Aeration Basin Outlet (Emission Regulated ) | 39.64 (LHV calculation) | 16.152 |
| 5  | Absorber Inlet                | 38          | 3.230         |
| 6  | Absorber Outlet               | 39.96 (LHV calculation) | 3.230 |

4. Conclusion and suggestion: Detailed design aspect in SWFGD retrofit in existing CFPP
Based on the calculation result of retrofitting SWFGD in 300 MW Subcritical Single Reheated Steam CFPP, the following can be concluded:

- The limiting factor of as Received Sulfur content relative to specific coal calorific value of 4200 kcal/kg in relation to the regulated addition of SO₄ in condenser cooling water discharge, yields a figure of 1,162% S in 100% load, and 1,899% S in 60%.
- The variable Sulfur content as described in figure 3, can be applied practically in operation aspect, by means of Coal mixing for fuel cost optimization in CFPP part Load operation.
- Additional heat given to the cooling water due to retrofit of SWFGD in existing CFPP with cooling water intake temperature of 31°C and condenser temperature increase of 7°C as described in table 2, will yield final temperature lower than the regulated limit value of 40°C.

Suggestion:

- Further detailed system design effort in retrofitting SWFGD in existing CFPP should consider the following plant parameter: Nett/Gross Efficiency, Boiler efficiency, Turbine cycle efficiency, cooling water temperature increase, cooling water flow, and coal calorific value,
- Based on the existing plant parameter, the SWFGD detailed design effort should specify the following parameter: SWFGD Absorber desulfurization effectiveness, desulfurization capacity, sea water flowrate and pressure drop, GGH leakage rate, and aeration basin effectiveness.
- To fully consider the 3 main regulated limiting factor in SWFGD operation: SO₄ increase in cooling water, Cooling water discharge temperature, and the regulated SO₂ emission itself.

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