QUANTIFICATION OF POLLUTANTS MASS AND ENERGY CONSUMPTION AS A TOOL FOR INDUSTRIAL WASTEWATER POLLUTION CONTROL IN STEEL INDUSTRY

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Abstract. Quantification of mass flows in production lines and waste treatment lines, as well as quantification of energy consumption at a factory is always challenges in cleaner production and pollution control decision making. The case study has conducted at a representative steel making complex in Vietnam, simulating the material flows of water and waste streams, and energy balance (EB) for water production and wastewater treatment processes, by using STAN (subSTance flow ANalysis) and SANKEY software, respectively. Input data were taken from secondary data sources, and additional monitoring of wastewater flows at the complex. COD was a selected parameter for material flow analysis (MFA) for evaluation of performance of wastewater treatment plants. Further, two scenarios were given for comparison of water and energy consumptions at existing and upgraded wastewater treatment plants. The results have shown that scenario 2, using disc filter (DF) and ultrafiltration (UF) membrane in combination with ultraviolet (UV) for improving quality of treated wastewater, could allow factory to reuse wastewater for production purposes. At the saved amount of fresh water 10,000 m³/day by reuse of treated wastewater, the saved energy was 1,489.5 kWh/day. The quantitative flows of MFA and EB were clearly presented in STAN and SANKEY diagrams.

Keywords: steel industry, wastewater treatment and reuse, energy balance, material flow analysis, STAN.

Classification numbers: 3.3.1, 3.3.3, 3.8.1.

1. INTRODUCTION

Steel making has been considered as one of the most important industry which is dramatically developing year by year all over the world. According to the report of world steel association [1], 1,433 million tons of crude steel was produced in the world in 2010. After 8 years, the production reached 1,808 million tons which is nearly 2 times than that in 2010. It is also forecasted that the steel demand continues to grow in the future. Along with the strong development of steel production, the environmental issue is attracted special concerns of
international scientists and experts because of its huge greenhouse gases emission, highly contaminated wastewater generation into living environment in the steel making processes including coke production, blast furnace (BF) and basic oxygen furnace (BOF) [2,3]. The wastewater discharging from this industry contains a vast amount of contamination such as phenolic compounds, cyanide, ammonia and etc., resulting severe effects to surrounding environment [3]. Besides, in the coke quenching step, a huge amount of fresh water (4,000 m³) is consumed to produce 1,000 tons of coke. Therefore, the wastewater management and water resource recovery are challenge of any environmental experts nowadays. In order to monitor and control water resource and the generation of wastewater, it is required to have a highly qualified analysis tools to establish and observe clearly the mass flow of water consumption, the pollutants in wastewater. Over the decades, STAN (short for subSTance flow ANalysis) and Sankey are widely used in mass flow analysis to perform material flow analysis (MFA). Many applications of these software were published such as study of fate of nutrients and heavy metals in municipal organic waste [4], environmental issue in the printing industry [5], solid waste management [6,7], wastewater management in Qatar [8].

The study mainly aims to apply tools to quantify major pollutants in industrial wastewater, thereby proposing appropriate solution for industrial pollution and for energy saving in production and waste treatment. The project focuses on a number of typical industries causing significant pollution in Vietnam and the iron and steel industry is one of the three selected industries. Moreover, STAN and SANKEY software will be used to model mass balance and energy analysis of the case study.

2. MATERIALS AND METHODS

2.1. Case study description

Figure 1. Schematic diagram of Steel making by BF/BOF [9].
In this study, the production parameters of steel making plant were collected from actual data which is used to build production technology processes and water treatment lines. Input materials, products of production processes as well as water quality indicators are based on highly reliable environmental impact assessment reports.

The data are aggregated for use in analysis and evaluation of technological process such as annual input materials and annual output of steel production processes such as sintering, blast furnace, blast furnace, billet casting. From the technological process, wastes such as solid waste, gas, and wastewater are also calculated specifically.

The calculation of energy consumption for the stages of wastewater treatment is based on previous studies with reliable data, assumptions about the equipment used, the time and operating capacity of the internal equipment wastewater treatment process [10].

In the steel making process, there are three main steps including sintering, blast furnace (BF) and basic oxygen furnace (BOF). The general process is illustrated in the Figure 1.

In the sintering process; iron, limestone, dolomite and coal are used as main raw materials to produce sintered ore. These materials are mixing thoroughly before sending to sintering machine. The sintered is used for the next process (blast furnace). In the sintering process, the exhaust gases consisting of COx, SOx, NOx… need to be treated before releasing to the air environment.

In the blast furnace process, the materials using for the process are: sintered ore, iron ore, limestone, coke, pulverized coal. Molten cast iron is produced in the process which will be used for basic oxygen furnace. After the process, granulated blast furnace slag and dust are filtered and storage.

In the basic oxygen furnace process, oxygen is blown on to molten cast iron to remove impurities and convert molten cast iron to steel. The exhaust gases consisting of COx, SOx, NOx; solid waste need to be treated before generating to the air environment.

Figure 2. Schematic diagram of water using control in Steelmaking plant.
Schematic diagram of water using control in steelmaking plant is shown in Figure 2. There are three WWTPs including: domestic wastewater treatment plant (DWWTP), coke wastewater treatment plant (CWWTP) and industrial wastewater treatment plant (IWWTP). Treated wastewater from DWWTP and CWWTP will be pumped to IWWTP in order to dilute other types of wastewater generated from plants such as thermal power plants wastewater, production workshops. After the dilution, the diluted wastewater is treated before discharging.

2.2. Instrumental analyses

This study used an analysis tool which is STAN software to quantify emission pollutants and use Sankey software to show research results.

STAN is a free software that supports performing material flow analysis (MFA) according to the Austrian standard ÖNORM S 2096 (Material flow analysis - Application in waste management). After building a graphical model with predefined components (processes, flows, system boundary, text fields) it can be entered or imported known data (mass flows, stocks, concentrations, transfer coefficients) for different layers (good, substance, energy) and periods to calculate unknown quantities. All flows can be displayed in Sankey-style.

Sankey software tool is commonly used for creating charts. Sankey Diagram describes a physical flow chart with the width of the arrow proportional to the amount of matter. Sankey diagram is an effective way to express the flow of materials and energy.

STAN is often used simply for displaying mass flows of goods and substances as Sankey arrows. The calculation algorithm uses mathematical statistical tools such as data reconciliation, error propagation and gross error detection. In order to describe the model in a mathematical way, the balance equation is used as below:

Mass conservation: sum of inputs = sum of outputs + change in stock and concentration equation:

\[ \text{mass} \ \text{substance} = \text{mass} \ \text{good} \times \text{concentration} \ \text{substance in good} \]

A wide spread use of STAN offers the opportunity to describe and analyse arbitrary systems with a standardized method. Compare with the calculation of mass balance and energy balance by Microsoft excel, STAN and SANKEY can be instrumental as a base for modelling material flows with the advantages can be offered that the largest flows of materials can be recognized immediately and the data uncertainties can be considered. This software performs a statistical test to check if the necessary adjustments can be explained by random errors. If reconciled values are detected that lie outside of the 95% confidence interval, the model is likely to contain gross errors.

- Specific stages in this study consist of four stages: The first step is database establishment which consists of data collection and analysis. The second step is mass balance calculation based on the data input and output data. The third step is environment assessment identifying causes for waste pollution, especially wastewater. The final step is recommendation for the improvement of steel making process and wastewater treatment plant with the aim of cleaner production and environmental protection.
- Estimation of electrical energy input.

The electrical energy input is estimated by considering the electrical load of the pump/motor (kW), time in hours (h) for which the motor is operated and total amount of wastewater treated (Eq. 1).
where: $E_p$ is the electrical energy kWh/m$^3$, $Q$ the total flow of wastewater in m$^3$/day, $P$ the rated power of the electrical motor in kilo Watt (kW), and $T$ is the operation hours in a day (h/day). The motor efficiency is assumed as 80 % [11].

3. RESULTS AND DISCUSSION

3.1. Material flow analysis (MFA) of production line by STAN software

*Figure 4. Schematic MFA diagram of Steel making by STAN (all numbers are in ton material year$^{-1}$).*
In this study, Company A with BF/BOF and coke wet quenching technology which is representative for a current modern technology steelmaking plant in Viet Nam. The total design capacity of the Company A is 4 million tons of steel per year including 3 million tons of rebar steel and 1 million ton rolled steel product.

Figure 4 shows the results of material balance calculation according to the production line diagram of the steel making plant which was quantified by STAN software. Consequently, the product volume of each stage is calculated in detail. The amount of waste of each technology process is also given in detail. During sintering, gases emission is 1,666,000 tons/year. For the blast furnace process, the amount of solid waste such as slag is 2,310,000 tons/year, the amount of dust reaches 3,631,800 tons/year. Although the amount of solid waste in the blast furnace process is less, the content is relatively large, reaching 400,000 and 200,000 tons/year for slag and dust. The above two processes also generate very large amounts of wastewater with pollutant content in wastewater of 156.7 and 43.14 tons/year, respectively. The final stage (heating, rolling steel, stamping) also releases water with a small amount of pollutants, 6,000 tons/year. Since then, it shows that the content of solid, liquid and gas wastes discharged into the environment is very large every year which needs to be thoroughly treated to ensure the safety of the surrounding living environment.

Table 1. The wastewater in steel making processes in industry benchmark and in the case study.

| Waste<sup>(1)</sup> | Unit | Sinter | Coke oven | BF | BOF | Reference |
|---------------------|------|--------|-----------|----|-----|-----------|
| Wastewater          | m<sup>3</sup>/T product | -      | 0.3       | 0.2| 0.1 | (i)       |
|                     |      | 0.06   | 0.3-0.4   | 0.1-3| -  | (ii)      |

(i) Calculated from the mass balance of steel making in the case study for all of the stages.
(ii) European Commission, IPPC, “BREF Document on the Production of Iron and Steel” and “Reference Document in BAT in the Ferricus Metals Processing Industry” December 2001 [12].

Table 1 shows amount of wastewater released in each stage during steel making process. According to the environmental impact assessment report of the case study, the amount of water supplied for the sintering process is very small with only 30 L for a ton of product. After the sintering process, the amount of water is evaporated significantly. Therefore, the wastewater from this process is negligible in this stage for the case study. Regarding to other processes such as coke, BF and BOF, the amount of wastewater is in agreement with the industry bench mark as shown in Table 1.

3.2. MFA of wastewater treatment line

3.2.1. MFA of COD of domestic wastewater

*(elaborated with the STAN software and all flows are in milligram per litter)*

The domestic wastewater treatment plant is shown in Figure 5 with capacity 2,400 m<sup>3</sup>/day operated with treatment line such as: Detention tank – Sequencing batch reactor SBR – Disinfection – pump to IWWTP.
3.2.2. MFA of COD of coke wastewater (elaborated with the STAN software and all flows are in milligram per litter)

Figure 6 illustrates the coke wastewater treatment plant CWWTP with capacity 4,500 m³/day operated with treatment line such as: Oil water separator – Detention tank – Dissolve air flotation – Fast mixing tank – Coagulation/Flocculation – Primary sedimentation tank – AAO system – High load sediment tank – pH detention tank and Fenton system – Reservoir– pump to IWWTP.

3.2.3. MFA of COD in industrial wastewater treatment line (elaborated with the STAN software and all flows are in milligram per litter)

The MFA of COD is established by the software named “short for substance flow analysis” (STAN). The flow unit in MFA are in milligram per litter.

The general industrial wastewater of the plant (including wastewater from thermal power
plants, wastewater from production workshops etc.) containing high content of pollutants will be diluted by treated domestic wastewater and treated coking wastewater to reduce the concentration of pollutants in the industrial wastewater. Total industrial wastewater with capacity 36,900 m³/d will be transferred to coagulant tank, after settling, treated water is taken to post-treatment water tank. Then, the treated water will be discharged to receiving source after monitoring. Base on the efficiency of removal COD by proposed technology in wastewater treatment lines, MFA of COD in industrial wastewater treatment line was calculated and shown in Figure 7. More specifically, in this treatment process, COD is significantly removed in sedimentation tank with about 30% removal in efficiency [13] while COD removal in the other steps is negligible.

![Figure 7. MFA of COD in industrial wastewater treatment line.](image)

### 3.3. Reuse wastewater in plant

Discharge of large quantities of pollutants in wastewater to surface waters is a contributing factor to lack of water suitable for drinking water. Moreover, Steel making plant consume a large amount of clean water while many applications for used water in the plant do not require water of such high quality. Therefore, the reuse of treated wastewater which is a promising solution in this study, has been identified as one of the most significant approaches to meet current and future water demands [14 - 17]. While access to fresh water is getting costlier due to environmental pollution, climate change and increased demand on water resources, the use of water for non-potable purposes can be based on reclaimed wastewater.

![Figure 8. Water balance in scenario 1 by STAN software.](image)

The reuse of treated wastewater has advantage in saving the amount of water that must be extracted from the source as well as treatment and distribution for plant. In addition, reusing wastewater also allows to reduce the amount of wastewater discharged into the environment.
This means reducing the risk of pollution and environmental incidents. Furthermore, this solution is especially more effective in areas where has a severe shortage of fresh water.

More specifically, in this study, the solution for treatment wastewater to be reused for different purposes in steel making plant (e.g., production stages, irrigation, street cleaning, toilet flushing, car washing, firefighting) is proposed as a scenario 2 with capacity 10,000 m$^3$/d in Figure 8 and compare to the current scheme (scenario 1) in Figure 9.

Scenario 1: without reuse (Figure 1).
Scenario 2: with reuse

For scenario 1 (Figure 8), all wastewater was treated and discharged into the resource with large daily flow rate; 36,900 m$^3$/d, and water supply for the plant up to 60,000 m$^3$/d. Whereas, in the scenario 2 (Figure 9), the total amount of treated wastewater did not discharge into the resource. Wastewater with capacity 10,000 m$^3$/d will be treated continuous and reused in plant. This means also reduces the load of 10,000 m$^3$/d for water supply treatment plant. Thus, it can be seen that the reuse of treated wastewater in industrial zones for different purposes can reduce the exploitation of water from natural resources as well as the amount of wastewater discharged into the environment.

In order to reuse water safely for different purpose in plant, not only solids and pathogens, but also micro pollutants and emerging contaminants need to be removed. Since this cannot be achieved with traditional secondary treatment alone, additional tertiary and disinfection steps are required. Hence, a system coupling disc filter and Ultrafiltration UF membrane combination with Ultraviolet UV for the treatment of wastewater for reusing was studied in this case.

**Calculation energy consumption**

The calculation of the energy demand (Table 2) makes clear that by the application of system coupling Ultrafiltration UF and UV disinfection for treatment reused wastewater in plant as in scenario 2 allows a reduction of 1,489.5 kWh/day compared to scenario 1. Energy saving is mainly due to saving energy for producing clean water and pump wastewater discharge to the resource. This means that wastewater presents an attractive raw water source, which, in this case, is even more energy efficient than the production of water from sources outside the plant. These findings are in line with the general experience that wastewater often presents a cost- and energy-efficient source for raw water, this especially in case of natural raw water sources of poor quality resp. in case of long transport routes [18]. Depending on the purpose of reuse treated wastewater, tailoring water quality to a specific water use also reduces the energy needed to treat
Quantification of pollutants mass and energy consumption as a tool for industrial …

water. For example, the water quality required for irrigation is less stringent than the water quality needed for drinking water and requires less energy to achieve.

Table 2. Calculation of the energy demand*.

| Water flows                  | Units | Without reuse | With reuse |
|------------------------------|-------|---------------|------------|
| Wastewater flow              | m3/d  | 36,900        | 26,900     |
| Reuse-water flow             | m3/d  | 10,000        |            |
| Treated raw water flow       | m3/d  | 60,000        | 50,000     |

| Energy requirement           | Units | Total requirement | Total requirement |
|------------------------------|-------|-------------------|-------------------|
| Water supply treatment plant |       |                   |                   |
| Raw water conveyance         | kWh/d | 8,101.85          | 6,751.54          |
| Raw water treatment         | kWh/d | 7,32.00           | 452.00            |
| Treated raw water distribution | kWh/d | 4,629.63          | 3,858.02          |
| Wastewater treatment plant and reuse water treatment plant |       |                   |                   |
| Wastewater treatment         | kWh/d | 6,002.815        | 4,962.01          |
| Reuse water treatment       | kWh/d | 1,181.60         | 1,181.60          |
| Reuse water distribution    | kWh/d | 771.60           |                   |
| **Total energy requirement** | kWh/d | **19,466.296**   | **17,976.786**    |

* The calculation does not consist of the energy consumed by other equipment such as controls, lighting…;

Figure 10. Schematic of energy balance in WWTP for scenario 2 with reuse wastewater.
Energy balance elaborated with the Sankey diagram

The energy providing for all stages of the wastewater treatment process depends on each technological process. At the different levels of treatment (treatment of level I, level II or level III), the energy consumption is different. Electric energy consumed at wastewater treatment plants is mainly used for pumps, air blowers, control equipment, etc., and in this case, ultraviolet germicidal irradiation is added for the wastewater treatment line. In addition, the wastewater treatment plant also requires a sludge treatment system, which also consumes a large amount of energy. The study has applied Sankey software to show the energy balance diagram for the wastewater treatment plant for scenario 2 with reuse of treated wastewater as shown in Figure 10 below.

The Sankey energy balance diagram shows the energy flow for each stage of water treatment with the width of the arrow proportional to the energy consumed. The above diagrams show that the electric energy consumed at the wastewater treatment plant is mainly supplied to the pump for water transportation.

4. CONCLUSIONS AND RECOMMENDATION

Waste from steel making manufacturing industry is a serious source of pollution. It is therefore necessary to control this source of industrial pollution. Based on the actual data collected in the environmental impact assessment reports for steel making plant, combined with STAN software, the study has quantified the amount of waste generated from each process in steel making plant such as blast furnaces, basic oxygen furnace, iron strip mill. Annually, the waste is extremely large. In detail, the amount of solid waste, slag and dust is over 5 million tons/year and the amount of waste in wastewater is over 200 tons/year. The study focused on analysing wastewater treatment lines to assess its effectiveness of contaminant removal and propose some solution to increase processing efficiency as well as save fresh water and energy consumption for wastewater treatment stages.

Proposing the treatment and reuse of wastewater with the solution of applying UF membrane filtration technology in wastewater treatment which indicates that energy use saves 1,489.5 kWh/day compared to the scenario which does not handle wastewater reuse. In addition, about 16.67% of the water supply needed to operate the plant daily is reduced, 10,000 m³/d.

Currently, the studied plant has been using wet coke quenching process for coke production, emitting a large amount of wastewater with many toxic pollutants such as phenol, cyanide, hydrogen sulphide etc. Therefore, it is proposed to replace coke wet quenching process by coke dry quenching process minimize toxic waste to the environment and save the cost of water supply and energy consumption of wastewater treatment. Besides, it is recommended to replace blast furnaces, basic oxygen furnace (BF/BOF) by electric arc furnace technology (EAF). Electric arc furnace (EAF) is an advanced method for the production of cast iron and steel. In the technology of blast furnaces, blast furnaces, input materials are iron ore, coal, while electric arc furnaces can utilize scrap steel to recycle as raw materials for the process of producing iron and steel with much more simple process.

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158
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159
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