MATERIAL FLOW ANALYSIS FOR PRODUCTION LINE AND WASTEWATER TREATMENT IN BREWERY INDUSTRY, AND RECOMMENDATIONS FOR CLEANER PRODUCTION SOLUTIONS

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Abstract. The novelty of this study is to apply Material Flow Analyses (MFAs) for both production line and wastewater treatment processes in a modern-technology beer company with an aim to assess cleaner production opportunities and potentials of the company through different scenarios for each cleaner production measure. As aspect of production line, two energy saving measures were proposed: (1) to reuse water-for-cooling for bottle and keg washing, and (2) to reuse thermal heat produced during rapid cooling to supply heat for the mashing process. Both solutions resulted in significant heat saving with 39 % and 16.3 %, respectively. Within the wastewater treatment plant (WWTP), the study proposed using biogas to generate energy through CHP (combine heat and power) system, of which electrical power is utilized for the WWTP operation and heat is used to maintain the temperature of sludge anaerobic digester (SAD) through a heat exchanger (HE). The results showed that the energy generated from biogas could compensate 16 % of the total energy consumption of the WWTP with 43 % (corresponding to 1,735 kWh) of electrical energy saving; 11 % of heat saving to maintain SAD system.

Keywords: brewery industry, MFA, cleaner production, energy saving.

Classification numbers: 3.3.3, 3.7.1, 3.4.2.

1. INTRODUCTION

Wastewater from brewery industry is featured by a high concentration of chemical oxygen demand (COD) (approx. 2200 - 2500 mg/l) [1 - 3], which should be treated properly before being discharged to the external source. Nowadays many modern technologies in wastewater treatment (WWT) are used in the beer industry not only with the purpose to treat the pollutants but also with the goal of material and energy saving [4]. This concept of cleaner production (CP) and energy efficiency (EE) is environment-friendly (reduction of methane emission, saving of
water and other natural resources, etc.), in return, to deliver to the beer companies lots of benefits namely electricity saving, thermal reuse in loop, etc. [5].

Many opportunities for CP and EE solutions can be applied in beer industry. Within the production process, water and heat consumption can be reduced by replacing dry malt milling by wet milling, reusing wort solution for brewing or reusing hot steam from brewing, etc [4-5]. Meanwhile, in WWT process, utilization of appropriate treatment technologies can also help reducing energy consumption as well as to reduce sludge generation [6-7].

Up-to-now, there have been several studies applying Material Flow Analyses (MFAs) method to quantify the material and concentration flows of pollutants within a WWTP such as [8-10], and the mass and energy balance of a WWTP i.e. in [11-12]. However, a full picture for the entire process from material inputs to output effluents plus energy consumption within the brewery industry have not been well discovered and limited. This study will bring new insights to different processes in brewery plant from production line to waste water treatment by applying MFAs for both production line and wastewater treatment processes in a modern-technology beer company with an aim to assess cleaner production opportunities and potentials of the company through different scenarios for each cleaner production measure.

2. MATERIALS AND METHODS

2.1. Case study

A beer industry in Viet Nam with a modern technology and the design capacity of 200 million liters of beer/year was selected as the study case (hereafter is called Company A). The facilities in the production line were imported from EU countries thus is modern and compliant with hygiene and food safety standards.

The production line in Company A consisted of 04 phases: (1) Preparation (dry milling and wet milling of rice and malt); (2) Brewing (saccharification, boiling, filtering, and cooling); (3) Fermentation; and (4) Packaging (keg and bottle washing, pasteurization, labelling). The calculation used in the research was applied for a production amount of beer of 166,341 ton/year. With this amount of beer production, the brewery plant needed an amount of 1,313,158 ton of water/year (Table 1).

Table 1. Breakdown of water use in beer production line.

| Item                | Quantity (ton/year) | References                                      |
|---------------------|---------------------|-------------------------------------------------|
| Beer                | 166,341             | Preliminary Audit Report (PAR) of the Company A |
| Water               | 1,313,158           | PAR of the Company A                            |
| Production          | 212,628             | Cleaner production Guidelines in Beer industry, p.15 [4] |
| Wort flushing       | 78,125              |                                                 |
| Wort cooling        | 173,374             | Tokos et al., p. 3 [13]                         |
| Keg & bottle washing| 124,755             | Tokos et al., p. 4 [13]                         |
| CIP water           | 623,204             |                                                 |

The main waste streams of the beer production procedure in the company comprised wastewater, solid waste (broken bottle glass, wort residues, label glue, propylene glycol, yeast, etc.) and air emissions (dust, odour gases, CO₂, CH₄, etc.).
The Company A had the Cleaning-in-place system (CIP) and WWTP which applied a combined anaerobic and aerobic WWT technology with the quality standards in compliance with A category in the issued standards on wastewater quality [2]. Domestic wastewater (DWW) was collected to the septic tank for decomposition then went further to the equalization tank. Sludge from this process was collected periodically. Production wastewater (PWW) after being filtered out of solid wastes and debris went to the equalization tank. The wastewater characteristics of the Company was taken from Table 2.

Company A used various treatment facilities and processes for treating wastewater including: equalization tank, pH adjustment and coagulation-flocculation, lamella clarifier, upflow anaerobic sludge blanket (UASB) and aerobic sequencing batch reactor (SBR), chlorine disinfection and excess sludge dewatering.

### Table 2. Wastewater characteristics of beer factory [2 - 3].

| Pollutant | Domestic wastewater (mg/l) | Production wastewater (mg/l) | QCVN 40:2011/BTNMT, Column A (Kq = 1.1; Kf = 1.0) |
|-----------|---------------------------|-------------------------------|---------------------------------------------------|
| SS        | 44 - 54                   | 500                           | 50                                                |
| COD       | 310 - 344                 | 2,200                         | 75                                                |
| BOD$_5$   | 129 - 147                 | 1,400                         | 30                                                |
| TotN      | 41 - 49                   | 30                            | 20                                                |
| TotP      | 12 - 14                   | 25                            | 4                                                 |

### 2.2. Methodology

**Material Flow Analyses (MFA)**

Research used MFA method to calculate water balance in the production line and to quantify pollutants through stages of wastewater treatment line. MFA is a quantitative method and assessment of materials and substances in the system for a specified period of time. The principle of MFA is based on the law of material conservation; The flow is expressed by the amount of substance per unit of time. This method allows to identify problems and quantify the impact of potential solutions to resource recovery and environmental pollution issues [14].

In brewery wastewater, most prominent pollutants are BOD and COD, and followed by Total Suspended Solids (TSS), Total Nitrogen (TotN) and Total Phosphorus (TotP) (Table 2). In order to assess the performance of the WWTP, the study focuses mainly on COD and TSS since these two sources are the main components of generated sludge, which also has to be treated before discharging to the environment. By quantifying those components in wastewater, the study therefrom calculated the energy balance within the WWT line and subsequently assessed the energy consumption status in each process of the WWT line based on efficiencies and operation time of the equipment [15 - 16]. The MFAs that were analyzed including production line, WWTP and energy balance were the basis for identifying the CP and EE solutions for the Company.

The system boundaries of the beer production MFA were set for only bottled beer products and using mass of water as quantitative measure. In the WWTP, the MFAs quantified the mass
of TSS and COD for DWW and PWW. Polymer/coagulant was neglected from the calculation due to the small amount compared to TSS and COD.

**Heat recovery**

The heat recovery was conducted in five steps from (1) calculating the heat \(Q_2\) and water volume \(W_{cool}\) required for rapid cooling of the wort; (2) calculating the heat \(Q_1\) for pre-heating of the mash; (3) calculating the heat \(Q_{tsac}\) for saccharification process; (4) calculating the heat for wort boiling \(Q_{wbl}\); and (5) calculating the heat for water boiling for wort flushing (Sparging) and clean the tuns (mashing, lauter, wort kettle) \(Q_{wa}\) (Table 3).

The heat supply and recovery were calculated using heat transfer formula [17], where \(m\) is the mass of the solution, \(C\) is the specific heat capacity, \(t\) is duration, \(\Delta T\) is the heat change from time \(T_1\) to \(T_2\):

\[
Q = m \times C \times t \times \Delta T.
\]

**2.3. Data sources**

Data on design capacity, wastewater treatment line and wastewater characteristics were taken from pre-feasibility reports, environmental impact assessment reports and the construction completion report of the brewery plant. Data on the total annual volume of beer products, total annual electricity consumption of the plant were collected from the annual energy audit report of the plant [18]. Data on equipment capacity, parameters of each stage in the production line and the efficiency of each treatment step was taken from the Cleaner Production Guideline in the beer industry by the Cleaner Production Component in Industry Sector under the Environment Program of Vietnam - Denmark Development Cooperation, and the Vietnam Cleaner Production Center under the Institute of Environmental Science and Technology, Hanoi University of Science and Technology [4]; and other international and national publications [13, 19 - 24].

All quantitative data of waste and wastewater, water in the production line were converted uniformly to ton/year.

**2.4. Software**

STAN flow analysis software (subSTance flow ANalysis) was used in the research to calculate material balance for beer production line and waste water treatment. This is a free software developed by the Technical University of Vienna, Austria (Technische Universität Wien), helping to calculate the MFA according to Austria’s ÖNorm S 2096 standard. The software allows users to design an outline model of the component in the waste water production/treatment line (including input, output, physical flow, system stages, margins, and annotation, etc.) will enter known values (mass, concentration, exchange coefficient, etc.) for different classes of properties (material, substance, energy) as well as the calculation period to calculate the remaining unknown values of the entire chain [25].

iSankey software was chosen to demonstrate energy balance. The software provides many features to support the presentation of energy flow and physical lines shown on the Sankey diagram with arrows proportional to the amount of material/energy transferred through processes with a user-friendly interface [26].
Table 3. Heat components in each brewery process and formula.

| Items | Formula | Description | References |
|-------|---------|-------------|------------|
| Heat for wort rapid cooling | $Q_2 = G_{\text{wort}} \cdot C_{\text{wort}} \cdot \Delta t \cdot 1000$ | $G_{\text{wort}}$: Mass of the filtered wort (tons); $C_{\text{wort}}$: Specific heat of wort (kcal/kg°C); $\Delta t$: temperature differences | Obtained from MFA |
| Water volume for wort rapid cooling | $W_{\text{cool}} = Q_2 / (C_{\text{water}} \cdot \Delta t \cdot 1000)$ | $C_{\text{water}}$: Specific heat of water (kcal/kg°C) | |
| Heat for pre-heating of the mash | $Q_{\text{mash}} = Q_1 + Q_i + Q_f$ | $Q_1$: Heat for increasing temperature from 72 to 85°C; $G_{\text{mash}}$: Mass of the rice paste in tons/year; $C_{\text{mash}}$: Specific heat of rice paste in kcal/kg°C; $Q_i$: Total heat for maintaining temp at 85°C for 30 mins; $i'_{85}$: Specific enthalpy of vaporization of the steam at 85°C in kcal/kg; $W_2$: Mass of the steam vaporized at 85°C in tons; $Q_f$: Heat loss, $f$: loss coefficient in mashing | [21], [27-29] Table 1.250, p.312[30] |
| Heat for saccharification process | $Q_{\text{Sac}} = Q_{\text{Sac}} + Q_{\text{Sac}} + Q_{\text{Sac}}$ | $Q_{\text{Sac}}$: Ratio of the water mass vapourized at 75°C; $W_2$: Mass of the steam vaporized at 85°C in tons; $Q_{\text{Sac}}$: Heat loss, $f_{\text{Sac}}$: loss coefficient in saccharification | [21], [27-29] Table 1.250, p.312[30] |
| Heat for wort boiling | $Q_{\text{wb}} = Q_{\text{wb}} + Q_{\text{wb}} + Q_{\text{wb}}$ | $Q_{\text{wb}}$: Heat supply for wort boiling; $Q_{\text{wb}}$: Total heat for maintaining temp at 105°C in kcal; $r_{75}$: Ratio of the water mass vapourized at 75°C; $W_{105}$: Mass of the steam vaporized at 105°C in tons; $Q_{\text{wb}}$: Heat loss, $f_{\text{wb}}$: loss coefficient in wort boiling | [21], [27-29] Table 1.250, p.312[30] 1.250, 1.350 |
| Heat for water boiling for wort flushing and clean the tuns | $Q_{\text{nA}} = Q_{\text{wa}} + Q_{\text{wb}} + Q_{\text{wb}}$ | $Q_{\text{wa}}$: Water for tun CIP in ton/year; $Q_{\text{wb}}$: Water for brewhouse ton/year; $Q_{\text{wb}}$: Water for brewhouse ton/year; $Q_{\text{wb}}$: Heat transfer loss, $f_{\text{wa}}$: Heat transfer loss ratio | [21], [27, 28, 29] Table 1.250, p.312[30] 1.250, 1.350 |
| Total heat for brewhouse processes | $Q_{\text{brew}} = Q_{\text{mash}} + Q_{\text{Sac}} + Q_{\text{wb}} + Q_{\text{wb}}$ | |
3. RESULTS AND DISCUSSION

3.1. Mass balance of the beer production line

Total material import was 564,679 ton/year which produced a final product (bottled beer) of 166,152 ton/year (Figure 1) and the material inputs are shown in Table 4. Compared to the amount of bottled beer produced in 2012 (163,559,962 liter/year eq. 166,341 ton/year) according to the Preliminary Audit Report (PAR) of the Company [19], the beer production in the plant was underestimated with an error of 1%. This can be explained due to the time-scale difference. The PAR was based on absolute data of a specific year whereas the calculations in this study was based on stocking data.

Table 4. Material inputs for beer production [20].

| Ingredients | Quantity (ton/year) | Ingredients | Quantity (ton/year) |
|-------------|---------------------|-------------|---------------------|
| Rice        | 6,384               | Collupuline | 3.2                 |
| Malt        | 19,700              | Houblon     | 78.8                |
| Sugar       | 2,640               |             |                     |

The MFA in Figure 1 scheme shows clearly that the areas consuming the highest amount of water were rapid cooling, keg washing and saccharification. Some solutions could be considered to reuse this water or to recycle water within the production line for consumption in these processes as well as to recover the heat from water cooling process.

Circulation of the water from rapid cooling of the wort for other purposes

Table 5. Solution 1: reuse heat from rapid cooling for heating water for bottle cleaning.

| Water for bottle cleaning (tons) | Heat for bottle washing (kcal) | Heat from Rapid cooling (kcal) | Saving (%) |
|----------------------------------|--------------------------------|-------------------------------|-------------|
| 124,755                          | 4,990,214,440                  | 1,946,560,324                | 39          |

Table 6. Solution 2: reuse hot water from flash cooling for mashing process.

| Items                                                      | Denotation | Unit  | Value         |
|------------------------------------------------------------|------------|-------|---------------|
| Heat for increasing temperature from 72 to 85 °C            | Q1         | kcal  | 501,697,899   |
| Mass of the steam vaporized at 85 °C for 30'               | W2         | Tons  | 37            |
| Total heat for maintaining temp at 85 °C for 30 mins       | Q2         | kcal  | 23,233,140    |
| Heat transfer loss                                         | Q3         | kcal  | 20,997,242    |
| Total thermal energy consumption                           | Q           | kcal  | 545,928,281   |
| Heat for wort rapid cooling from 90 to 12 °C in 10 minutes | Q2         | kcal  | 70,076,171,647|
| Water volume for rapid cooling (temperature rise from 2 to 80 °C) | W_\text{cool} | m³    | 898,412       |
| Heat supply after rapid cooling                            |            | kcal  | 545,928,280   |
| Steam supply                                               |            | kg of steam/h | 2,068 |
| Saving                                                     |            |       | 16.3          |

A significant amount of heat was recovered by reusing water from rapid cooling for
Material flow analysis for production line and wastewater treatment in brewery industry, and processes within the brewhouse. This heat can be reused for heating water for bottle cleaning (Solution 1 in Table 5) and for mashing process (Solution 2 in Table 6). The results show that in Solution 1, the heat recovery can be achieved at 39 %, meanwhile, Solution 2 could bring a saving benefit of 16.3 %.

Figure 1. Mass balance of Beer Production at Company A. I: import, E: export. VOC: volatile organic compounds. Unit: t/a (ton per annual).
3.2. Mass balance of the WWT line

As can be seen on the Figure 2, the TSS was removed in lamellar clarifier and SBR processes, meanwhile, COD could be partly removed in clarifier, UASB, and finally in SBR. The removal rate of COD through WWTP was calculated to be 97%. Since the WWTP did not have the sludge anaerobic digestion (SAD), the sludge treatment included thickening and dewatering, which are considered high costs and electricity consumption processes. The calculation of sludge amount is described in the following section.

3.4. Energy balance of the WWTP

Scenario 01 (KB01) - Current technology at the WWTP

Sludge generation

Two types of sludge going to sludge thickening and dewatering were primary sludge from the lamella clarifier and waste activated sludge from UASB and SBR. Sludge generation was calculated based on the COD load to the WWTP. The amount of TSS and COD in the polymer used for sludge dewatering was too little compared to the sludge amount thus it was neglected from the calculation. Each kilogram of incoming COD to the WWTP was assumed to generate
0.5 kg of sludge [23]. The analysis of energy balance was based on the amount of COD, so the removal rate of COD was used as the efficiency of the system (97%).

Total sludge generated from WWTP in KB01 was approx. 3,770 kg/day. It could be reduced if the Company applies SAD. This solution will be assessed to see its feasibility in energy saving and sludge reduction in the KB02. Details of sludge contents are described in Table 7.

Table 7. Calculation of sludge contents generated from WWTP in KB01.

| Sludge contents (dry substances)                  | Quantity |
|--------------------------------------------------|----------|
| Dry solids (TSS) (kg/day) (1)                     | 417      |
| Excess activated sludge (kg/day) (2)             | 3,354    |
| Total ((1)+(2)) (kg/day)                         | 3,770    |
| Sludge discharge (m³/day)                        | 3.9      |

Energy balance

The MFA scheme in Figure 3 shows that the process consumes the most energy is SBR especially for the operation of the air blowers. Meanwhile, the two other areas consuming relatively much energy are equalization tank and sludge treatment (thickening & dewatering). Specifically, in the sludge thickening, the electricity consumption of the disc sludge thickener is considerably high (300 kWh). Thus, if the sludge amount going to the sludge thickening can be reduced, it can save some energy.

Scenario 02 (KB02) – anaerobic digestion of sludge and biogas utilization for energy

Sludge generation
In KB02, exceeded sludge generated from WWT processes went to SAD and was converted partially to biogas. The post-treated sludge then went to sludge thickening and dewatering processes. Since part of the sludge was converted to biogas, the amount of sludge going to sludge thickening and dewatering processes was reduced remarkably.

To estimate the post-treated sludge by SAD process, the study used the ratio of biogas yielded from SAD over sludge (dry solids) entering the SAD system and the ratio of removed dry solids over influent ratio. The post-treated sludge (which cannot be converted to biogas) of 711 kg/day then went to sludge thickening and dewatering process (Table 8). With this technology upgrade, the amount of sludge was reduced by 3,359 kg/day.

Table 8. Sludge going to sludge thickening & dewatering.

| Item                                                   | Value | Unit    |
|--------------------------------------------------------|-------|---------|
| Biogas yielded/sludge (dry solids) input               | 0.153 | m³/kg   |
| Removed dry solids/Influent ratio                       | 0.189 | -       |
| Sludge going to sludge thickening & dewatering in KB01 | 3,770 | kg/day  |
| Sludge going to sludge thickening & dewatering in KB02 | 711   | kg/day  |

Energy balance

Figure 4. Energy balance in KB02.

Table 9. Energy parameters and calculation.

| Parameter                        | Unit | Value          |
|----------------------------------|------|----------------|
| Volumetric potential            | 6.5  | kWh/m³ of biogas |
| Electrical energy generation efficiency | 35   | per cent (%)   |
| Thermal energy generation efficiency | 55   | per cent (%)   |
| CHP efficiency                   | 90   | per cent (%)   |
| Electricity generated from biogas | 1,735 | kWhel/day    |
| Thermal energy generated from biogas | 2,726 | kWhht/day    |
| Total energy generation         | 4,461 | kWh/day       |
As shown in Figure 4, the Company, thanks to the energy generated from CHP system, could compensate some of the thermal and electrical energy consumption in the WWTP. Specifically, the CHP generated 1,735 kWhel/day of electrical energy and 2,726 kWhht/day of heat. The heat was utilized in supplying hot water for the heat exchanger to maintain the temperature of SAD at 37 °C. Meanwhile, the electricity generated from biogas returned to supply for the operation of the WWTP (Table 9).

**Comparison between KB01 and KB02**

By installing the sludge anaerobic digester with biogas recovery, the Company could generate 1,735 kWh of electrical energy daily from biogas, which could serve 43 % of the electricity demand of the WWTP (4,066 kWh/day in Scenario 2) (Table 10).

Besides, the heat yielded from biogas (2,726 kWh/day) would be used to contribute heat to the SAD system to maintain mesophylic condition (37 °C) in the reactor. The result showed that thermal energy from biogas could also save 11 % of the energy demand for this process (Table 10). Several previous research mentioned some examples for the installation of CHP system in other brewery companies, where the electrical demand could be reduced ranging from 20 - 40 %, and some where total primary energy reduction could reach over 30 % [31, 32]. The value of electrical demand in this research falls within the range of previous research which prove the validity of the calculation.

**Table 10. Comparison of KB01 and KB02.**

| Compared item                                      | Scenario 1 | Scenario 2 |
|---------------------------------------------------|------------|------------|
| Electricity consumption of WWTP (kWh)             | 2,911      | 4,066      |
| Heat for maintaining temperature for SAD (kWh/day)| 0          | 24,590     |
| Specific energy per volume (kWh/m³)               | 0.65       | 0.92       |
| Specific energy per kgCOD (kWh/kgCOD)            | 0.001      | 0.0014     |
| Biogas yield (m³/d)                               | 185        | 763        |
| Electrical energy generated from biogas (kWhel)   | 0          | 1,735      |
| Volumetric electrical energy generated from biogas (kWhel/m³) | 0          | 0.386     |
| Electricity saving (%)                            | 0          | 43         |
| Heat generated from biogas (kWhht)                | 0          | 2,726      |
| Volumetric heat generated from biogas (kWh/m³)    | 0          | 0.606      |
| Heat saving in in SAD process (%)                 | 0          | 11         |
| Total energy consumption at the WWTP (kWh/day)    | 0          | 28,656     |
| Total energy generated from CHP (kWh/day)         | 0          | 4,461      |
| **Total energy saving (%)**                       | 0          | 16         |

**4. CONCLUSIONS**

From the research findings, the Company A are recommended to apply the mentioned solutions in production line (returning heat from rapid cooling to supply for mashing process and/or reusing water from rapid cooling in keg washing) with promising heat saving. Regarding the upgrading of WWTP, with the installation of SAD and CHP system, the Company could
reduce the amount of excess sludge and simultaneously gain energy through CHP which helped saving up to 43% of electrical energy and 11% of heat in SAD process, simultaneously, the excessive sludge was also reduced significantly. These solutions are well representative for the combination of CP and EE approaches. Cost-benefit analysis will be the next step of the study to assess the economic efficiency of these solutions.

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