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Exergoeconomic Performance Assessment of a Sulfuric Acid Production Unit Using the Specific Exergy Costing Method

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In this work, an industrial sulfuric acid production unit was evaluated using exergetic and exergoeconomic analysis to determine possible improvements in its efficiency and cost effectiveness. The exergoeconomic evaluation was performed by Specific exergy costing method (SPECO). The case study process is the production of sulfuric acid from liquid sulfur by a double absorption contact. The exergy efficiency, exergy losses and exergoeconomic performance of each component in the overall plant were calculated and analyzed. The exergetic analysis, on the studied process, identifies the location, magnitude, and sources of thermodynamic inefficiencies. The obtained results indicated that the largest exergy destruction took place in the combustion stage, representing a 67 % of the total exergy losses. The exergy efficiency of the unit was around 44.7 %. Through the exergoeconomic analysis, the selling price of the produced H_2SO_4 as well as the total investment cost were estimated and the exergoeconomic factor of each component was quantified. The highest exergoeconomic factor, of 86 %, was observed in the recovery boiler, meaning that reducing the equipment cost of the studied process is of high importance to reduce the final product of the overall system. On the other hand, the combustion oven showed the lowest exergoeconomic factor, of 1.22 %, implying that improving its thermodynamic efficiency would be compulsory for that component.

1. Introduction

Currently, the rapid increase of global energy demand and limited energy resources have promoted the efficient utilization of available energy resources as well as the development of renewable forms of energy (Kerdan et al., 2017). Recent research works combine energetic, exergetic and economic criteria for the evaluation of the energy consumption efficiency and the cost minimization potential in thermal process systems. Hence, developing some approaches to improve the design of energy conversion systems and to reduce environmental impacts is of high significance (Mergenthaler et al., 2017). The exergoeconomic approach is a robust method that combines exergy analysis with economic studies (Diaz et al., 2018). In exergoeconomics field, exergy analysis is a powerful tool to study interdependencies and, quite often, exergy destructions within components do not only depend on the component itself but on the efficiency of the other system components (Erbay and Hepbasli, 2017). Different publications about the application of exergoeconomic analysis to different types of energy conversion systems can be found in the literature. A solid oxide fuel cell based on the combination of the heat and the power generation system (Lee et al, 2014), thermal processes in an existing industrial plant (Vuckovic et al.,2014), a gas engine heat pump for food drying processes (Gungor et al., 2015) and a multi-effect evaporation–absorption heat pump desalination were studied (Esfaani et al., 2009). There are different exergoeconomic approaches in the literature; specific exergy costing (SPECO) method is the one used in this study for exergy cost analysis. In fact, it represents a general, systematic, simple and unambiguous approach based on specific exergies and costs per exergy unit in order to define exergetic efficiencies and to calculate the auxiliary costing equations for components of thermal systems. It was applied for different types of processes (Lazzaretto and Tsatsaronis, 2006). In the present work, the results of the exergy and exergoeconomic analyses using the SPECO method of a sulfuric acid production process are presented.

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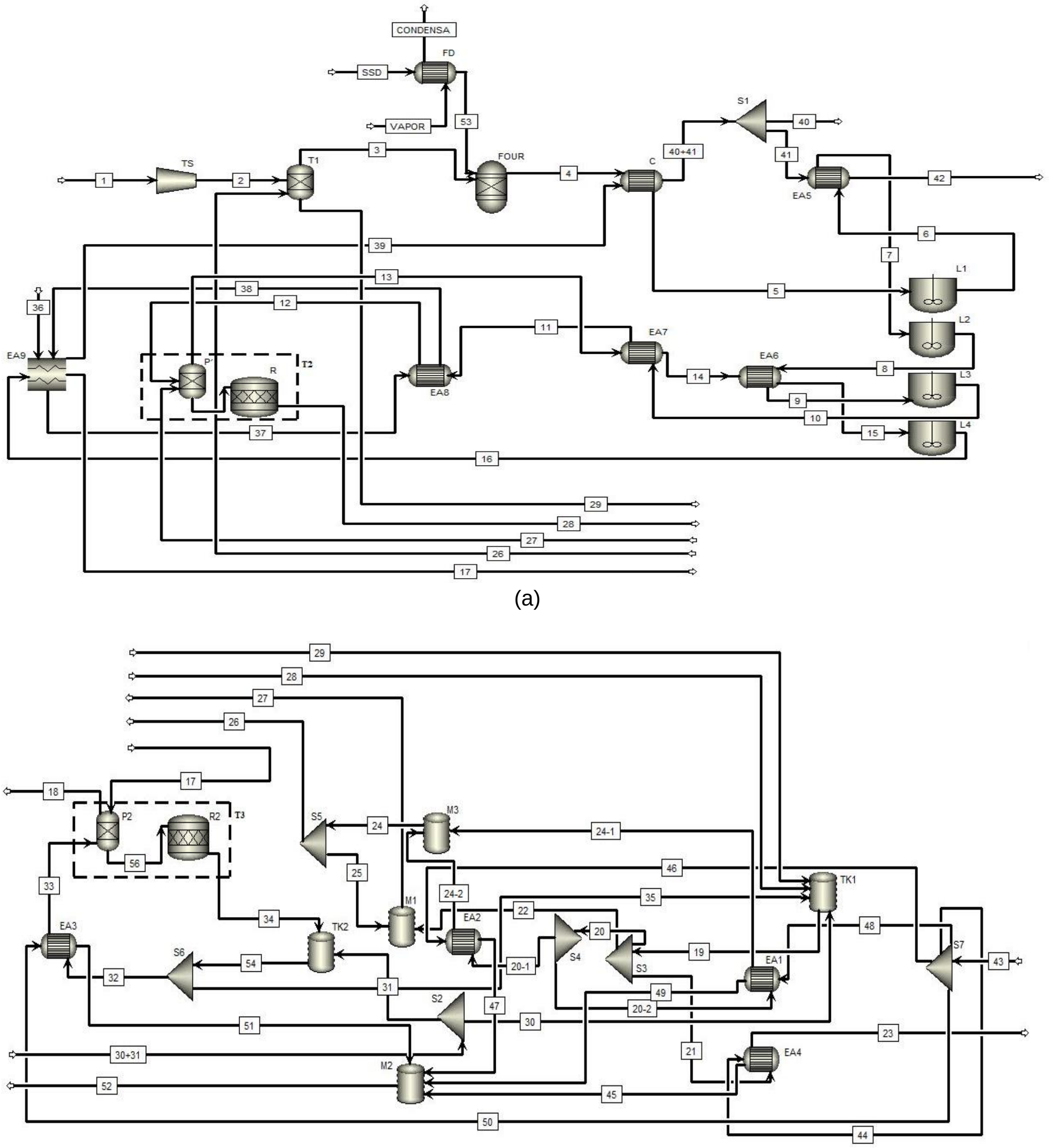
2. Process description

The studied H_2SO_4 production unit, shown in Figures 1a and b, produces 1500 t/d. This unit, simulated by Aspen Plus® uses the double absorption contact process, which contains the following four production steps:

- Sulfur combustion
- Conversion of SO_2 to SO_3
- Absorption of SO_3 by concentrated H_2SO_4 (98.5 %)
- Cooling of the produced H_2SO_4



(a)

(b)

Figure 1: (a) First part of the flowsheet of the sulfuric acid production plant. (b) Second part of the flowsheet of the sulfuric acid production plant.

3. Exergy, economic and exergoeconomic assessment

3.1 Exergy analysis

The plant is thermally isolated so the process is assumed to be adiabatic. The exergy balance for any equipment in the process is expressed by Eq(1) (Bejan, 1966):

$$\sum \boldsymbol{Ex_{input}} - \sum \boldsymbol{Ex_{output}} = \boldsymbol{I} \tag{1}$$

The general exergy balance is expressed as indicated in Eq(2) where the difference that results in balancing of all entering and leaving exergy flows is denoted as exergy loss (Mabrouk et al., 2017).

$$\sum(1-\frac{T_0}{T})Q - W + (\sum_i m_i Ex_i)_{in} - (\sum_i m_i Ex_i)_{out} = Ex_{destruction} = T_0 S_{generation} = I \tag{2}$$

3.2 Economic analysis

The Total Revenue Requirement method (TRR method), based on the strategy adopted by the Electric Power Research Institute was used in this work to perform the economic analysis of the process. The method is based in the following parameters (Bejan et al., 1996):

- Estimation of the Total Capital Investment (TCI)
- Calculation of the Total Revenue Requirement (TRR)
- Calculation of the Levelized Costs (LC)

3.3 Exergoeconomic analysis

The principal aim in an exergoeconomic analysis is the determination of the unit cost of product. SPECO method assigns a cost value to every exergy unit of each material and energy stream entering and leaving components. The analysis includes all investment data for each component of the system neglecting any simplification. There are three main steps in the SPECO method, as follows: (i) quantifying the energy and exergy streams; (ii) defining the fuel and product for components; and (iii) considering the cost balance equations (Lazzaretto and Tsatsaronis, 2006).

A cost balance states that the sum of all exiting exergy stream cost rates equals the sum of all entering exergy stream cost rates plus $\dot{Z}_k$. In order to estimate the exergy destruction cost of the system components, the cost balance equations developed for the system should be solved.

For the plant units receiving electrical work and transferring heat from the surface, the exergoeconomic balance equation is presented as in Eq(3) (Atmaca and Yumrutus, 2014).

$$\sum_j (c_j \dot{Ex}_j)_k + c_{w,k}\dot{Ex}_w = c_{q,k}\dot{Ex}_{q,k} + \sum_i (c_i \dot{Ex}_i)_k + \dot{Z}_k \tag{3}$$

In order to better understand the exergoeconomic evaluation and, furthermore, to optimize the system, some performance parameters should be defined. The exergoeconomic factor, f_k, expresses the contribution of the capital cost to the sum of capital cost and cost of exergy destruction of a component k. It is defined as (Bejan et al., 1996):

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + c_{F,k}\dot{Ex}_{D,k}} \tag{4}$$

where $c_{F,k}$ is the unit exergetic cost of the fuel and $Ex_{D,k}$ is the corresponding exergy destruction of the unit. Another useful variable in thermoeconomic evaluations is the relative cost difference. It is defined as (Bejan et al., 1996):

$$r_k = \frac{c_{P,k} - c_{F,k}}{c_{F,k}} \tag{5}$$

where $c_{p,k}$ is the unit exergetic cost of the products and $c_{F,k}$ is the unit exergetic cost of the fuel.

The cost rate of exergy destruction is defined as (Bejan et al, 1996):

$$\dot{C}_{D,k} = c_{P,k}\dot{Ex}_{D,k} \tag{6}$$

4. Results and discussion

4.1 Process exergy balance

The total exergy losses in the studied H_2SO_4 production plant were found to be about 88 MW. The combustion stage was the responsible of the main exergy losses. It contributed with a 68 % of the total exergy losses. A 31 % of this percentage was registered in the combustion oven (F). These losses would be associated to the irreversibility of the combustion reaction and to the high temperature inside the equipment. The overall exergy efficiency ($\eta_{Ex,g}$), was found to be 44.7 %. Figure 3 presents the exergy diagram of the studied unit.

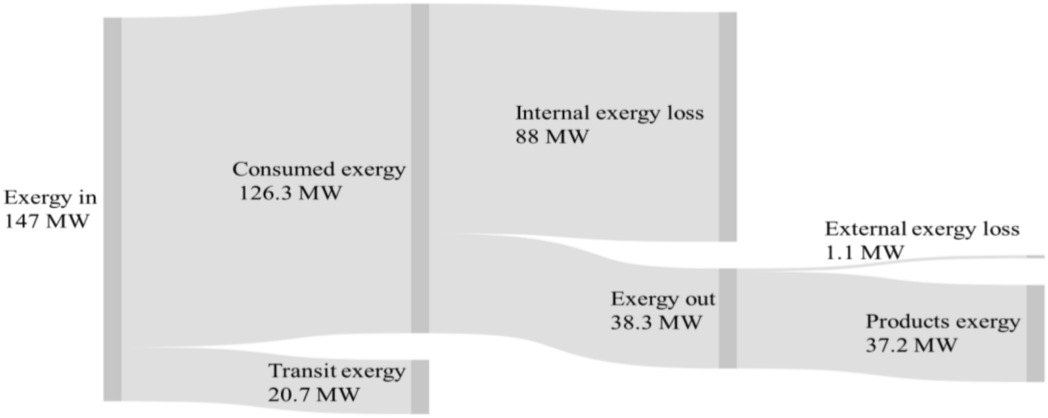


Figure 3: Exergy diagram

4.2 Economic analysis

The economic data were obtained from actual supplier quotations of the company. The cost data for carrying charges, fuel, raw materials and operating and maintenance were obtained from the purchasing and Energy Management Department of the company. The estimation of the process TCI was attributed to the purchased equipment costs (PEC) (Bejan et al., 1996). These prices, updated with the technical properties of the equipment concerned, were introduced in the "Aspen Economic Analyzer" module of the Aspen Plus® software. The TCI was found to be 57.3 M$. The economic and operational parameters are presented in Table 1. The TRR over the life of the reference plant was determined as a function of the economic and operational parameters and the annual OM costs for the reference year 2012. This data is presented in Table 2. The corresponding calculated value was TRR = 167.3 $.

Table1: Economic and operational parameters of the studied unit.

Economic parameter	Value
Interest rate (i)	12 %
Average nominal inflation rate (t)	2 %
Capital Recovery Factor (CRF)	0.134
Total annual hours of system operation at full load	8760 h
Plant economic life (n)	20 y
Unit cost of electricity (2012)	0.09$ /kWh per day
Fuel cost (2012)	179$/tep

Table 2: Product prices of both exergoeconomic and economic analysis for the reference plant (10^{-3}\$/kg).

Product	Economic Analysis	Exergoeconomic analysis	Market price
H_2SO_4	3.20	4.00	7.25
Steam HP	8.00	0.70	7.93

4.3 Exergoeconomic analysis

The obtained results of the linear equation system with all component main cost equations and its respective auxiliary equations are presented in Table 3. In fact, the average cost per exergy unit of the entering sour gas,

the process water and atmospheric air were negligible, since they were considered free. The highest exergoeconomic costs were registered at the levels of the filtered air flows as well as at the exit of the following equipment: the blower (TS), the dry air and the drying tower (T1), being 1.01 \$/kWh and 2.16 \$/kWh, respectively. It was revealed that the costs increased in upper streams. The reason could be that, when the same stream enters and exists several components, the expenses of each component ($\dot{Z}$ costs) are acquired by the exiting streams, so in the end, the more one stream flows through different components, the bigger the costs associated to this stream. Moreover, the combustion gas stream presents a relatively high exergy cost (0.32 \$/ kWh). It was found also that the streams associated with the conversion step presented high exergy costs due to the inter-bed cooling of these streams. It should be noted that the exergoeconomic costs of the exiting flows (final products) of the system should reflect all the financial costs of the unit under study, which correspond to the TRR_L (Almirall, 2009). In the studied case, basically, the final products of the studied unit are H_2SO_4 and HP steam. Table 3 indicates the average hourly costs of the H_2SO_4,and HP stream produced by the unit under study and determined by economic and exergoeconomic analysis. The cost of the obtained H_2SO_4 by the exergoeconomic analysis was found to be a 25 % higher than that obtained by the economic analysis. This fact could mean that the market price of the product does not always reflect its production cost. However, a slight difference in the price of HP steam was observed when calculated by economic analysis, relative to the market price. On the other hand, the difference between the calculated prices by the two types of analysis was considerable and could be associated to the simplifying assumptions used in the calculation (Almirall, 2009). These results are comparable to those obtained by Almirall (2009) on a H_2SO_4 production unit in Germany.
Table 4 summarizes the calculation of the exergoeconomic evaluation parameters of the plant equipment.

Table 3: Exergy flow rates, cost flow rates and unit exergy costs associated with each stream of the plant.

Stream Designation	c_i (\$/kWh)	Ex (kW)	$\dot{C}_i$ (\$/h)
Combustion air	1.006	1859	1871
Dried air	2.160	14996	32392
Combustion gases	0.324	100311	32501
1st bed inlet	0.471	72514	34154
1st bed outlet	0.471	68411	32222
2nd bed inlet	0.471	62289	29338
2nd bed outlet	0.471	64890	30563
3rd bed inlet	0.003	60443	181.32
3rd bed outlet	0.003	61646	184.93
Heat exchanger inlet	0.003	55437	166.31
F. Abs. tower inlet	0.276	56180	15511
F. Abs. tower outlet	0.539	58366	31494
Steam HP	0.001	8653	12.97

Table 4: Exergoeconomic parameters for the reference plant

Equipment	c_F (\$/kWh)	c_P (\$/kWh)	$\dot{Z}$ (\$/h)	$\dot{C}_D$ (\$/h)	*F* (%)
Blower (TS)	0.18	1.006	1 453	600	70.8
Drying tower (T1)	0.10	0.134	7.10	24.79	22.3
Oven (FOUR)	0.03	0.324	109	8 743	1.22
Boiler (C)	0.06	0.001	223	37.03	85.8
Converter (R)	0.31	0.152	282	758.6	27.1
Heat exchanger (EA5)	15.8	0.091	13.0	274.8	4.51
Abs. tower (T2)	0.004	0.004	58.4	42.8	57.7
Abs. tower (T3)	0.53	0.157	88.1	105	45.6

The oven from a thermal-economic point of view, this equipment is considered to be the most important component of the studied process. It had a value of "compound" cost of investment and loss of exergy ($\dot{C}_D$+$\dot{Z}$) very high, in the order of 8850 \$/h, since it contributed with a 31 % of the overall process exergy losses. On the other hand, the blower (TS) also had an important ($\dot{C}_D$ + $\dot{Z}$) value of 2054 \$/h, although it contributed less to the overall exergetic losses (596 kW) than the combustion oven. Furthermore, the superheater (C), presented the largest exergoeconomic factor (about 86 %) despite the importance of its exergy losses. This fact is due to its relatively too expensive PEC.

5. Conclusions

The obtained results have provided important information regarding the exergetic performance of the entire plant and its components through exergy destructions and exergy efficiencies. The exergy analysis showed that the total exergy losses associated with this unit are in the order of 88 MW, of which, approximately, 67 % are located in the combustion stage. The exergoeconomic analysis indicated that the combustion oven had the highest "compound" investment cost and exergy losses, in the order of 8850 $/h and an exergoeconomic factor of 1.22 %. In general, better plant performance could be achieved by reducing exergy destruction through better insulation and operation as well as by reducing investment and exergetic destruction costs. The obtained results also showed the existence of a large consumption of cold utilities. This energy could be used, even partially, considering the thermal integration of the sulfuric units with the other units of the plant. Furthermore, cold production through absorption machines for air conditioning. Moreover, the hot water loop for the cooling of the ammonia to -33 ° C could be used by a water-NH_3 absorption machine or ejector refrigeration unit reducing the consumption of the electrical energy of this unit. Further studies could focus on the selection of the most appropriate insulation material for different sections of the plant. The “farm-to-fork” method can best-evaluate the whole resource destruction in producing. This can be attained by combining exergy and life cycle assessment (LCA) concepts into a comprehensive framework named exergetic life cycle assessment (ELCA).

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