ANNALS of Faculty Engineering Hunedoara – International Journal of Engineering
ISSN 1584-2665 (printed version); ISSN 2601-2332 (online); ISSN-L 1584-2665

[1.]I.O. OHIJEAGBON, [2.]H.K. IBRAHIM,
[3.]O.A. ADEWUYI, [4.]A.A. FAYOMI

ENERGY AND EXERGY ANALYSIS OF A THERMALLY DRIED GALVANIZED ROOFING SHEETS PRODUCTION PROCESS

[1-4.] Department of Mechanical Engineering, University of Ilorin, Ilorin, NIGERIA

Abstract: Energy and exergy analysis of a thermally dried galvanized roofing sheets production plant was investigated. Data related to the operating units of the plant were analysed and used for the parametric analysis of the energy and exergy performance of the plant. The highest energy efficiency experienced in the pre-curing operation was in the pre-mixing and mixing operating units with a value of 90.91% each. The energy efficiency in the boiler and autoclave units of the curing operations were found to be 78.02 and 82.04% respectively. The boiler had a higher exergy efficiency of 58.31% compared to the autoclave with an exergy efficiency of 19.06%. The parametric analysis of the autoclave shows that the energy efficiency and exergy destruction both increased from 75.33 to 84.71% and from 54.72 to 95.70% as the exit temperature reduced from 100 to 30°C, while the exergy efficiency reduced from 45.28 to 4.30% within the same exit temperature range. The overall energy and exergy efficiencies of the plant were obtained as 80.03% and 42.13%. The method provides an approach to mitigate operational losses and enhance efficient utilization of energy of thermally dried galvanized roofing sheets production plants and similar industrial processes.

Keywords: Production plant, galvanized roofing sheets, thermally dried, energy and exergy performance

1. INTRODUCTION

The role of improving the energy efficiency of industrial processes has become of keen interest in recent years. This is part of a global attempt to control the consumption of scarce resources. Consequently, stake holders have focused study on reducing energy consumption and at the same time increasing the value of industrial output and profit margin (Khattak et al., 2012). It has been observed that the indicator of sustainability may be related to the thermodynamic characteristics of the product during material processing (Sekulic, 2009). The production processes may consume much energy for effective operations as it required energy flow in terms of mass transfer, heat and work in exchange of matter and energy within the systems (Querol et al., 2013). Increase in cost of fuel and environmental concerns have made efficient utilization of fuel and material resources inevitable as a design consideration in industrial plants (Gundersen, 2009; Juric and Zupanovic, 2012). Furthermore, as a result of high cost of energy, increasing world population and decreasing fossil fuel resources, the optimum utilization and management of energy consumption have become vital (Aghbashlo, 2013). A further understanding of energy consumption of industrial plants is needed, both for design and operational decisions. Energy is a very critical input in manufacturing industries and in most cases outweighs other inputs such as raw materials, labour and maintenance cost. Energy analysis based on the first law of thermodynamics is a fundamental approach to estimate the quantity of energy involved in energy conversion processes. However, it provides no information about the quality of energy in the processes. Due to the deficiencies and limitations of energy analysis, exergy analysis which provides a more realistic view of operating systems and processes have been widely adopted in recent times to analyse energy conversion systems (Dincer and Rosen, 2013).

The exergy of a system is based on the second law of thermodynamics and is described as the maximum theoretical useful work obtainable as the system is brought into complete thermodynamic equilibrium with its environment (Tsatsaronis, 2007). Exergy is a property of both the system and the environment when both are considered as part of a composite system (Bakshi et al., 2011). The Main difference between energy and exergy is that exergy is a measure of quality and can be consumed (Rosen, 2007). It has been reported that useful part of a given amount of any energy form, such as heat or enthalpy can be determined by considering exergy analysis for industrial operations and processes (Ohijeagbon et al., 2012). The main objective of exergy analysis of systems is to provide a clear picture of the processes, in order to quantify the sources of inefficiency, and to distinguish the quality of energy consumption. Exergy analysis has the potential of selection of optimal operating conditions and to reduce the experimental impacts. The characteristic of quality is very important in energy conversion as loss of quality can occur during a process without leading to immediate loss of quality to the environment. Exergy analysis has been cited by many researchers and practicing engineering scientists to be a powerful tool to determine both the quality and quantity of energy in industrial systems, such as, product manufacture, performance of machines operations, resource control, maintenance, recycling and disposal (Ohijeagbon et al., 2013).

Several applications of exergy analysis conducted on a number of industrial processes had been reported in previous studies, and these include metallurgical, agricultural and food processes, and cement and silicon production processes (Balomenos et al., 2011; Koroneos et al., 2005; Shukla, 2015; Takla et al., 2013). Waheed et al. (2008), carried out an energy and exergy study of a fruit juice manufacturing industry. The exergy analysis revealed that, the pasteurizer was responsible for most of the inefficiency (over 90%) followed by packaging (6.60%). It was suggested that the capacity of the pasteurizer could be increased to reduce the level of inefficiency of the plant. The exergy efficiency of an olive oil refining plant and determined exergetic destructions in each device in the plant was studied by Bozoglan and Hepbasli (2010). The functional exergetic efficiency of the plant that was investigated was obtained to be 12%. The maximum value of the exergy destruction rate was experienced in the boiler, followed by distillation unit and steam generator respectively (Bozoglan and Hepbasli, 2010). The comprehensive benefit of conducting an exergy analysis is to achieve sustainable development. A sustainable development usually requires data acquisition to be planned in such a way as to collect vital information that enables analysis of an energy-intensive system for lower cost and high efficiency (Alta and Ertekin, 2014). Exergy analysis serves as a very useful tool for decision and policy making in order to ensure that modern industrialization does not put economic interest above ecological sustainability (Gong and Wall, 2001). In spite of the several exergy analysis of industrial systems, however, attention is yet to be directed towards the production processes of galvanized roofing sheets and the mutual interdependencies among its components. While it is necessary to investigate the production processes of galvanized roofing sheets, the impact of autoclave curing on the production process should also be investigated because of its anticipated significant effect. Autoclave curing had been used in several industrial processes to facilitate the quality and properties of industrial products (Kumar et al., 2016; Preglej et al., 2011; Wang and Shie, 2009).

The aim of this study is to conduct an energy and exergy analysis of a thermally dried galvanized roofing sheets production process in order to ascertain more efficient ways of managing energy resources in this industrial sector. The study focuses on investigating the parametric energy and exergy performance of a galvanized roofing sheets production plant which implements autoclave curing in its production chain. Application of the second law in the study is significant in recognising the quality of energy in various operating units that make up the production plant, in order to identify the operating units which requires better enhancement of energy utilization.

2. METHODS

— Description of production of the galvanized roofing sheets processes

A galvanized roofing sheets processing factory located in Lagos; Nigeria was selected for this study. Ten major operating units in the entire process were identified as shown in Figure 1 and listed in Table 1. Four major raw materials namely cellulose, kaolin, cement, silica is pulverised and sent into a huge container called the mixer. Water was added to the mixture and stirred in the mixer. Thereafter the mixture is transferred to the selectifier to filter out impurities and excess water and dumped into a drainage system. The mixture, now called slurry is then transferred to a pre-mixer with addition of water to make up for excessive loss of water from the filtration stage in order to prevent the slurry from too much hardening. The slurry is then transferred to the forming machine by means of conveyor belts to be flattened and moulded into the desired shape and size. The forming machine consists of the main drive, a forming drum, sieves, orientation screws and agitators. The main drive is powered by an electric motor and is connected to the forming drum by means of gears. The sieved slurry is then passed through the forming drum which rolls in an anticlockwise motion to that of the conveyor. The forming drum is set into motion by the main drive and flattens the slurry by compressing it to the main drive. The compressed material is then passed through an automatic cutting machine where it is cut and trimmed into the desired shape and size. At this stage, the product is then transferred by means of automatic rollers to the pre-curing chamber where it is left to dry before it is transferred to the autoclave for the final curing.

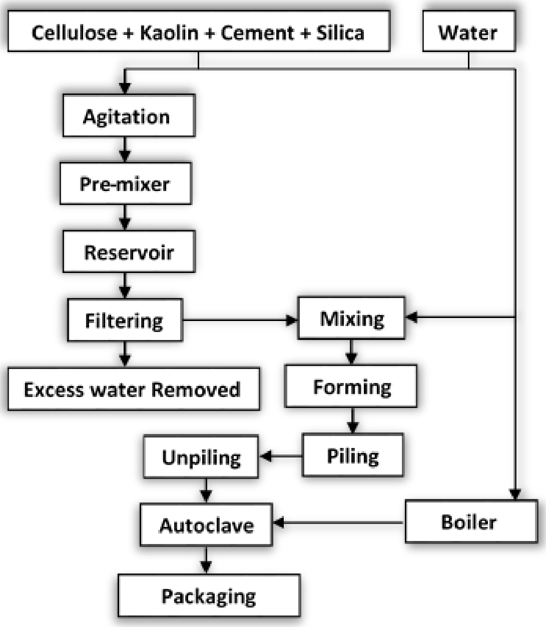

Figure 1: Flow diagram for the galvanized roofing sheets production processes

— Data acquisition

For the purpose of data collection and simplicity, the entire operating plant was divided into ten operating units. Relevant operational parameters of each operating unit of the production processes was collected and documented. The detail of the data acquisition is presented in Appendix Tables A1 and A2 respectively. The data on operating time, input and output power, and inlet and exit temperatures of the operating units are presented in Table 1. The operating units are categorized into pre-curing and curing operations respectively. The pre-curing operations which are primarily based on electrical energy data comprises of eight distinct units, namely; agitation, pre-mixing, reservoir, filtering, mixing, forming, piling, and unpiling respectively. And the curing operations which is based on thermal energy resources consist of the boiler and autoclave operating units. The firing rate of diesel fuel utilized in the boiler was used to estimate the energy input for the boiler and autoclave respectively.

Table 1: Operating parameters of the galvanized roofing sheets production processes

Operation/unit	Operation time (hr)	Power input P_{in} (kW)	Power output P_{out} (kW)	Inlet temperature T_{in} (°C)	Exit temperature T_{out} (°C)
Agitation	2.00	17.20	14.00	30.00	30.53
Pre-Mixing	0.25	4.40	4.00	30.53	32.05
Reservoir	0.12	4.40	2.00	32.05	31.85
Filtering	0.33	4.40	3.60	31.85	34.15
Mixing	0.25	4.40	4.00	34.15	36.55
Forming	8.00	12.00	9.60	36.55	37.85
Piling	8.00	30.00	24.00	30.00	30.00
Unpiling	8.00	20.00	16.00	30.00	30.00
Boiler	7.00	6076.21	4740.52	267.00	175.00
Autoclave	7.00	6076.21	4984.65	175.00	50.00

3. THEORETICAL ANALYSIS

— Input and output energy of pre-curing operating units

The input and output energy of each operating unit were respectively determined from the input and output power of the units. The input power is the rated electrical power input of each operating unit, while the output power represents the actual electrical power output of the operating units. Hence, the electrical energy input and output were determined by equations (1) and (2) [6]:

$$E_{in} = fPt/1000 \tag{1}$$

$$E_{out} = Pt/1000 \tag{2}$$

where, $E_{in/out}$ is the input or output electrical energy in MJ, P the power in kW, t the operation time in seconds and f the power factor, assumed to be 0.8.

— Input and output energy of curing operating units

The input energy of both the boiler and autoclave was determined from the thermal energy supplied from combustion of fossil fuel utilised in the boiler to generate the steam used for curing in the autoclave. And this was determined by equation (3) (Qureshi and Ghosh, 2013):

$$E_{in} = C_f \dot{m}_f / 1000 \tag{3}$$

where E_{in} is the thermal energy consumed (MJ), C_f the calorific value of fuel used, the higher heating value of diesel of 45,482.52 kJ/kg was used as the calorific value (Ohijeagbon et al., 2014), while $\dot{m}_f$ is the firing rate of the fuel consumption in kg/s. The firing rate of the fuel is given as 512 kg/h.

The output energy of the boiler and autoclave was first of all obtained from the output power as stated in equation (4), and subsequently by equation (5) which represent the output energy.

$$P_{out} = \dot{m}_s (h_s - h_w) \tag{4}$$

where, P_{out} is the output power in kW, $\dot{m}_s$ is the rate of steam generation in kg/s. The operating steam capacity of the boiler unit is given as 7,000 kg/h. h_s and h_w are the enthalpy of steam and water in the boiler and autoclave, respectively at the higher and lower operating temperatures of both units.

$$E_{out} = P_{out} t / 1000 \tag{5}$$

where E_{out} is the output energy in MJ, and t is operating time in seconds.

— Exergy input and output of pre-curing operating units

The exergy input and output of the operating units were obtained as being equivalent to the input and output energy respectively as stated by equations (1) and (2). This is attributed to the actual and useful work of constant volume systems to be identical as a result of the surrounding work been equal to zero (Cengel and Boles, 2006). Also, the electrical and shaft work of a system can be assumed to be equivalent to one another (Dincer et al., 2004)

— Exergy input and output of curing operating units

The exegy input and output of the boiler and autoclave was derived from the stand point that the exergy content of heat is the maximum amount of work that can be extracted from a quantity of heat flow (Gundersen, 2009). The exergy input of the boiler and autoclave can therefore be determine with respect to the energy input and inlet temperatures in the boiler and autoclave as expressed by equation (6), while the exergy output of the boiler and autoclave were determined with respect to the energy output and exit temperatures in the boiler and autoclave as expressed by equation (7) (Reddy et al., 2010)

$$E_{x,in} = E_{in} \cdot \left(1 - \frac{T_o}{T_{in}}\right) \tag{6}$$

$$E_{x,out} = E_{out} \cdot \left(1 - \frac{T_o}{T_{out}}\right) \tag{7}$$

where, $E_{x,in}$ is the exergy input in MJ, T_o the temperature of a standard environment at 1 atmospheric pressure ($T_o = 25°C$), and T_{in} and T_{out} are the boundary temperature at inlet and exit respectively.

— Energy and exergy efficiency of the operating units

The energy and exergy efficiency of the pre-curing and curing operating units are expressed as follows:

$$\text{Energy efficiency } (\eta) = \frac{\text{Energy output}}{\text{Energy input}} \times 100\% = \frac{E_{out}}{E_{in}} \times 100\% \tag{8}$$

$$\text{Exergy efficiency } (\eta_{II}) = \frac{\text{Exergy output}}{\text{Exergy input}} \times 100\% = \frac{E_{x,out}}{E_{x,in}} \times 100\% \tag{9}$$

— Irreversibility and exergy destruction

The irreversibility of each operating unit was obtained as:

$$I = E_{x,in} - E_{x,out} \tag{10}$$

while, the exergy destruction was determines as:

$$\psi = \frac{\text{Irreversibility}}{\text{Exergy input}} \times 100\% = \frac{I}{E_{x,in}} \times 100\% \tag{11}$$

— Overall energy and exergy efficiency and exergy destruction of the plant

The overall energy and exergy efficiency and exergy destruction of the entire plant was determined as follows:

$$\text{Overall energy efficiency, } (\eta_p) = \frac{\sum \text{Energy output}}{\sum \text{Energy input}} \times 100\% = \frac{\sum E_{out}}{\sum E_{in}} \times 100\% \qquad (12)$$

$$\text{Overall exergy efficiency, } (\eta_{II_p}) = \frac{\sum \text{Exergy output}}{\sum \text{Exergy input}} \times 100\% = \frac{\sum E_{x,out}}{\sum E_{x,in}} \times 100\% \qquad (13)$$

$$\text{Overall exergy destruction, } \psi_p = \frac{\sum \text{Irreversibility}}{\sum \text{Exergy input}} \times 100\% = \frac{\sum I}{\sum E_{x,in}} \times 100\% \qquad (14)$$

4. RESULTS AND DISCUSSIONS

— Energy performances of the pre-curing and curing operations

The input and output power of the thermally dried galvanized roofing sheets operation comprises basically electrical and thermal energy sources. The pre-curing operations had input power ranging between 4.40-20 kW, equivalent to 3.96-864.00 MJ of electrical energy as presented in Tables 1 and 2. However, the curing operations had input power of 6076.21 kW in both the boiler and autoclave unit operations which was from a thermal energy source. The highest input and output electrical energy of 864.00 and 691.20 MJ experienced in the piling unit operation in the pre-curing stage was as a result of the highest values of input and output power of 30.00 and 24.00 kW, and the operation time of 8 hours in contrast to operating time between 0.12-2.00 hours of other operating units in the pre-curing stage, such as; agitation, pre-mixing, reservoir, filtering and mixing respectively. The highest energy efficiency experienced in the pre-curing operation was in the pre-mixing and mixing operating units with a value of 90.91%, while the energy efficiency in the boiler and autoclave units of the curing operations were respectively 78.02 and 82.04%. The inlet and exit temperatures of 175.00°C and 50.00°C which resulted in a cumulative energy output of 125,613.18 MJ was responsible for a higher energy efficiency in the autoclave operation in contrast to the boiler with a feed water inlet temperature of 80.00°C and steam temperature of 175.00°C, which gave a lower cumulative energy output of 119,461.10 MJ. The overall energy efficiency of the entire plant was obtained as 80.03%. It should be noted that the temperature of the hot products of combustion exiting the combustion chamber into the heat exchanging unit of the boiler is given as 267.00°C and was responsible for the temperature of steam generated in the boiler given as 175.00°C as presented in Table 1. Consequently, energy efficiency may be enhanced during curing operation in the autoclave by generating and sustaining higher temperature steam input. Also, higher thermal energy efficiency may be achieved in the boiler and autoclave by reduction in the input energy of the system; however this may lead to reduction in output temperatures. Hence, to avoid reduction in temperature of the output stream in the boiler as the input thermal energy is lowered, a means to further raise the temperature of the output stream at the same input energy level would be necessary. Such a device as a super-heater or a heat recovery system would be appropriate.

Table 2: Energy and exergy analysis of the galvanized roofing sheets production processes

Operation/ unit	Energy input E_{in} (MJ)	Energy output E_{out} (MJ)	Exergy input $E_{x,in}$ (MJ)	Exergy output $E_{x,out}$ (MJ)
Agitation	123.84	100.80	123.84	100.80
Pre-Mixing	3.96	3.60	3.96	3.60
Reservoir	1.90	0.86	1.90	0.86
Filtering	5.23	4.28	5.23	4.28
Mixing	3.96	3.60	3.96	3.60
Forming	345.60	276.48	345.60	276.48
Piling	864.00	691.20	864.00	691.20
Unpiling	576.00	460.80	576.00	460.80
Boiler	153,120.49	119,461.10	68,644.13	40,024.73
Autoclave	153,120.49	125,613.18	51,302.11	97,76.18

— Exergetic performances of the pre-curing and curing operations

The values of the exergy input and output in the pre-curing operations were equivalent to the respective energy inputs and outputs of each unit operation. This was because the actual and useful work are considered to be the same, since the surrounding work is considered of no consequence on the system. Consequently, the exergy efficiencies were equal to the energy efficiencies in the pre-curing operations. However, the exegy input of the boiler and autoclave in the curing operation, based on the second law of thermodynamics was obtained as 68,644.13 and 51,302.11 MJ, while the exergy ouput were determined as 40024.73 and 9776.18 MJ respectively as presented in Table 2. Although the boiler had a lower energy output compared to the autoclave, however its higher exergy output of 40,024.73 MJ compared to 9,776.18 MJ for the autoclave, resulted in a higher exergy efficiency of 58.31% compared to the autoclave with an exergy efficiency of 19.06% as shown in Figure 2. Analysis of the exergy destruction shown in Figure 2 indicates that the highest exergy destruction of 80.94% was experienced in the autoclave followed by the reservoir and the boiler with an exergy destruction of 54.55 and 41.69 % respectively. Bouapetch et al. (2014) in their study, energy and exergy analysis of steam boiler and autoclave in fiber cement process, obtained a similar high exergy destruction of the autoclave to be 87.14%. Bouapetch et al. (2014) attributed the high exergy destruction to exhaust steam, condensate and autoclave shell loss respectively. Furthermore, since the input and output thermal energy and exergy values of the curing operations far outweighs the electrical energy and exergy values of the pre-curing operations presented in Table 2, therefore the most critical operating unit is the autoclave. Consequently, an enhanced exergetic performance of the autoclave unit is expected to result in overall enhanced performance of the entire system. The overall exergy efficiency and exergy destruction of investigated plant was determined as 42.13% and 57.87% respectively. The low value of the exergy efficiency of the autoclave unit which was 19.06% was fundamentally responsible for the value of the obtained overall exergy efficiency of the plant.

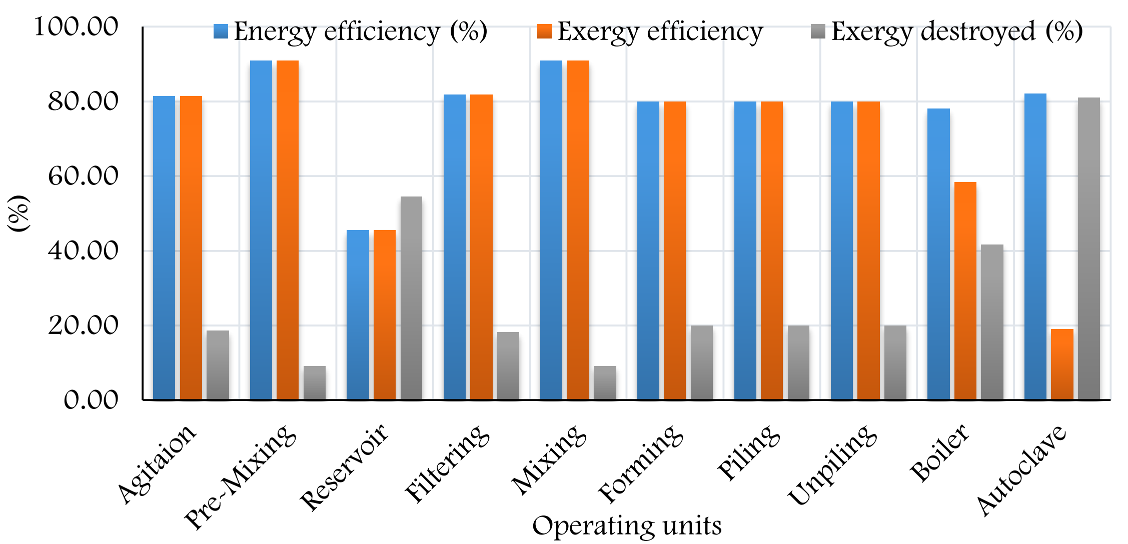

Figure 2: Exergetic efficiencies of the operating units

— Enhancement of exergetic performance of the autoclave operating unit

The exergetic performance of the autoclave which have been identified as the unit requiring greatest margin for improvement in its operation may be enhanced accordingly. For a constant input energy, the exergetic performance of the autoclave may be further enhanced either by reducing the exergy input as indicated in equation (9) or by increasing the exergy output of the unit operation. Furthermore, to increase the exergy output of the autoclave, it is imperative to increase the energy output as indicated by equation (7). And to reduce the energy output, the initial temperature of the autoclave unit have to be increased as indicated by equation (4). The required increased temperature of the unit can be made possible through a heat recovery and pre-heating system which will further lead to enhanced energy utilisation of the entire curing operation.

Figure 3 shows the exergetic parametric analysis of the autoclave unit operating at a constant inlet temperature, input energy and input exergy of 175.00°C, 15,3120.49 MJ and 51,302.11 MJ respectively. The parametric analysis indicates that the autoclave unit experiences significant increase in exergy destruction from 54.72 to 95.70% as the exit temperature reduced from 100 to 30°C, while the exergy efficiency experienced a reduction from 45.28 to 4.30% within the same exit temperature range. The energy efficiency however only experienced a slight increase from 75.33 to 84.71%. From the parametric analysis shown in Figure 3 therefore, it could be deduced that the autoclave unit operation can be enhanced by raising the exit temperature. In other words, sustenance of high exit temperature via insulating shields would further enhance the exergetic performance of the unit. Furthermore, the exergetic parametric analysis of the plant with respect to the exergy destruction of the autoclave unit illustrated in Figure 4 clearly shows increasing exergy efficiency of the plant from 41.94 to 63.18% as the exergy destruction of the autoclave unit reduces from 82.00 to 16.67%, and consequently the exergy destruction of the plant was reduced from 58.06 to 36.82% respectively.

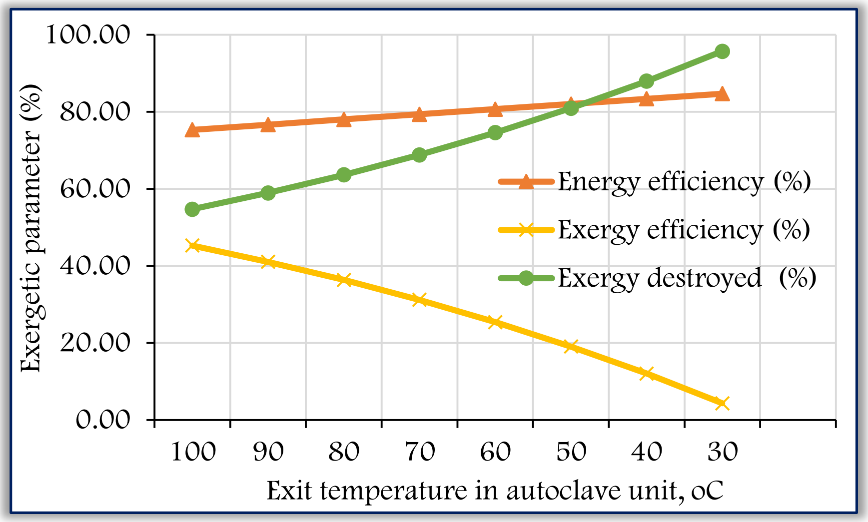

Figure 3: Exergetic parametric analysis of the autoclave

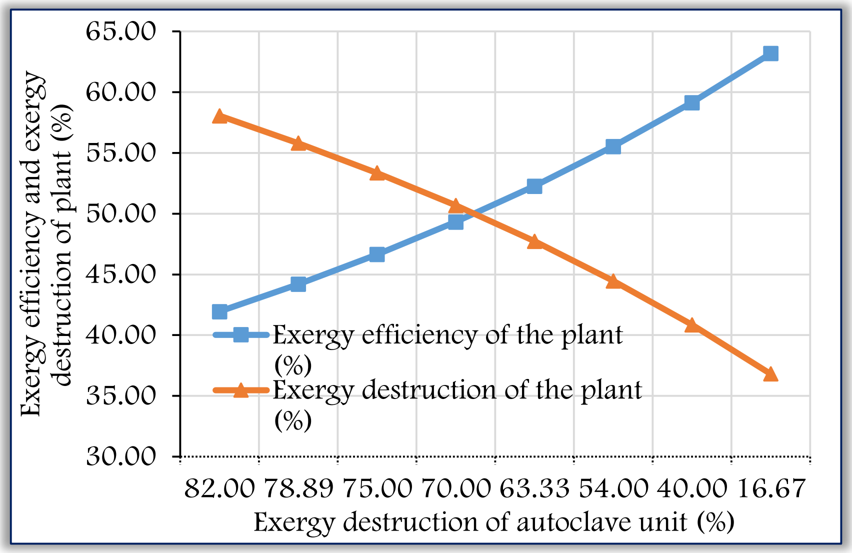

Figure 4: Exergetic parametric analysis of the plant with respect to exergy destruction of autoclave unit

5. CONCLUSIONS

The study investigated the energy and exergy analysis of a thermally dried galvanized roofing sheets production processing plant. An energy management and data communication process was adopted for the purpose of data acquisition. Data related to operating units of the plant, such as operation time, input and output power, inlet and exit temperatures, operating steam capacity and firing rate of boiler were collected and analyzed. Analyzed data were used for evaluating the parametric energy and exergy analysis of the galvanized roofing sheets production processes. The result revealed that the pre-curing operations had input power ranging between 4.40-20 kW and was equivalent to 3.96-864.00 MJ of electrical energy. The curing operations had input power of 6076.21 kW in both the boiler and autoclave and was derived from a thermal energy source. The highest input and output electrical energy of 864.00 and 691.20 MJ was obtained in the piling unit as a result of the highest values of input and output power of 30.00 and 24.00 kW, and the operation time of 8 hours in contrast to operating time of between 0.12-2.00 hours of other operating units in the pre-curing stage. The highest energy efficiency experienced in the pre-curing operation was in the pre-mixing and mixing operating units with a value of 90.91%, while the energy efficiency in the boiler and autoclave units of the curing operations were obtained as 78.02 and 82.04% respectively.

Moreover, the values of the exergy input and output in the pre-curing operations were equivalent to the respective energy inputs and outputs of each operating unit. As a result, the exergy efficiencies were equal to the energy efficiencies in the pre-curing operations. On the other hand, the exegy input of the boiler and autoclave in the curing operation were obtained as 68,644.13 and 51,302.11 MJ, while the exergy output were determined as 40024.73 and 9776.18 MJ respectively. Furthermore, the boiler had a higher exergy efficiency of 58.31% compared to the autoclave with an exergy efficiency of 19.06%. Consequently, the highest exergy destruction of 80.94% was obtained in the autoclave followed by the reservoir and the boiler with an exergy destruction of 54.55 and 41.69 % respectively. The parametric analysis of the autoclave show that exergy destruction increased significantly from 54.72 to 95.70% as the exit temperature reduced from 100 to 30°C, as exergy efficiency reduced from 45.28 to 4.30% within the same exit temperature range. The energy efficiency of the autoclave only increased slightly from 75.33 to 84.71% with reduction in exit temperature. Also, increasing exergy efficiency of the plant as the exergy destruction of the autoclave unit reduces resulted in reduction in the exergy destruction of the plant from 58.06 to 36.82%. The overall energy and exergy efficiency and exergy destruction of investigated plant are 80.03%, 42.13% and 57.87% respectively.

Appendix: Data acquisition

Table A1: Operational data of pre-curing sub-system of the plant

Unit Operation	Operational Parameters	Values
Agitation of Raw Materials	Total input power of each pump and electric motors	4.3 kW
	Total output power of each pump and electric motors	3.5 kW
	Stirring Time	2 hrs.
	Number of electric motors	5
	Number of pumps for charging raw materials into mixer	5
	Water inlet Temperature	30.00 °C
	Temperature After Mixing	30.53 °C
Pre-mixer	Electrical input power of pump	5.5 kW
	Output power of pump	5 kW
	Time taken for mixing	0.25 hr.
	Inlet temperature of aggregate mixture	30.53 °C
	Temperature After Mixing	32.05 °C
	Size of mixer	0.8 m^3
	Total quantity of mixture	0.68 m^3
Reservoir	Electrical input power	5.5 kW
	Output power	2.5 kW
	Time taken	0.12 hr.
	Inlet temperature of mixture	32.05 °C
	Outlet temperature of mixture	31.85 °C
	Size of reservoir	1.0 m^3
Filter	Electrical input power	5.5 kW
	Output power	4.5 kW
	Time taken	0.33 hr.
	Inlet temperature of mixture	31.85 °C
	Outlet temperature of mixture	34.15 °C
	Quantity of water filtered (m^3)	0.02
Mixer	Electrical input power	5.5 kW
	Output power	4.0 kW
	Time taken	0.25 hr.
	Inlet temperature of mixture	34.15 °C
	Outlet temperature of mixture	36.55 °C
	Quantity of water filtered (m3)	0.25
Forming machine	Electrical input power	15.0 kW
	Output power	12.0 kW
	Time taken	8.00 hrs.
	Rate of sheet forming	306 sheet/hr.
	Inlet temperature of mixture	36.55 °C
	Outlet temperature of mixture	37.85 °C
Piling	Electrical input power	37.5 kW
	Output power	30.0 kW
	Time taken	8.00 hrs.
	Inlet temperature of mixture	30.00 °C
	Outlet temperature of mixture	30.00 °C
	Rate of piling	162 sheet/hr.
Unpiling	Electrical input power	25 kW
	Output power	20 kW
	Time taken	8.00 hrs.
	Inlet temperature of mixture	30.00 °C
	Outlet temperature of mixture	30.00 °C
	Rate of unpiling	60 sheet/hr.

Table A2: Operational data of curing sub-system of the plant

Unit Operation	Operational Parameters	Values
Boiler	Firing type	Dual fuel (internal)
	Combustion fuel	Diesel
	Operating steam capacity	7000 kg/hr.
	Firing rate of fuel	512 kg/hr.
	Calorific value/high heating value of diesel	45,482.52 kJ/kg
	Operating feed water temperature	80.00 °C
	Temperature of combustion flue gas	267.00 °C
	Temperature of steam evolved	175.00 °C
	Temperature of exhaust flue gas	161.71 °C
	Operational time	7.00 hrs.
Autoclaving	Inlet curing temperature	175.00 °C
	Temperature of product before/after curing	50.00 °C
	Time taken for curing	7 hrs.

References

[1] Khattak, S.H., Greenough, R. and Brown, N.: Suitability of exergy analysis for industrial energy efficiency, manufacturing and energy management, ECEEE 2012 Summer Study on Energy efficiency in industry, 2-080-12, 237-245. 2012.
[2] Sekulic, D.P.: An entropy generation metric for nonenergy systems assessments. Energy. Vol. 34, 587-592. 2009.
[3] Querol, E., Gonzalez-Regueral, B. and Perez-Benedito, J.L.: Practical Approach to Exergy and Thermoeconomic Analyses of Industrial Processes, Springer. 2013.
[4] Juric, V. and Zupanovic, D.: Ecological Impacts of Diesel Engine Emissions. Human - Transport Interaction Review, Vol. 24 (2), 151-160. 2012.
[5] Aghbashlo, M., Mobli, H., Rafiee, S. and Madadlou, A.: A review on exergy analysis of drying processes and systems. Renewable and Sustainable Energy Reviews, Vol. 22, 1-22. 2013.
[6] Dincer, I. and Rosen, M. A.: Exergy: Energy, Environment and Sustainable Development, Second ed. London: Elsevier. 2013.
[7] Tsatsaronis, G.: Definitions and nomenclature in exergy analysis and exergoeconomics. Energy, Vol. 32, 249- 253. 2007.
[8] Bakshi, B.R., Gutowski, T.G. and Sekulic, D.P: Thermodynamics and the Destruction of Resources, New York: Cambridge University Press. 2011.
[9] Rosen, M.A.: Exergy Concept and its Application. 2007 IEEE Canada Electrical Power Conference, 473-478. 2007.
[10] Ohijeagbon, I.O., Jekayinfa, S.O., and Waheed, M.A.: Cumulative exergetic assessment of LPFO utilized steam boilers. Int. J. Exergy, 11 (1), 119-135. 2012.
[11] Ohijeagbon, I.O., Waheed, M.A., and Jekayinfa, S.O.: Methodology for the physical and chemical exergetic analysis of steam boilers. Energy, 53, 153-164. 2013.
[12] Takla, M., Kamfjord, N.E., Tveit, H., and Kjelstrup, S.: Energy and exergy analysis of the silicon production process, Energy, 58, 138-146. 2013.
[13] Balomenos, E., Panias, D., and Paspaliaris, I.: Energy and exergy analysis of the primary aluminum production processes: a review on current and future sustainability. Mineral Processing and Extractive Metallurgy Review: An International Journal, 32 (2), 69-89. 2011.
[14] Koroneos, C., Roumbas, G. and Moussiopoulos, N.: Exergy analysis of cement production. Int. J. Exergy, 2 (1), 55-68. 2005.
[15] Waheed, M.A., Jekayinfa, S.O., Ojediran, J.O. and Imeokparia, O.E.: Energetic analysis of fruit juice processing operations in Nigeria. Energy, 33 (1), 35-45. 2008.
[16] Bozoglan, E. and Hepbasli, A.: Performance improvements for olive oil refining plants, International Journal of Energy Research, 34 (6), 476-493. 2010.
[17] Alta, Z.D. and Ertekin, C.: A review on exergy analysis of food production processes. Proceedings International Conference of Agricultural Engineering, Zurich, 06-10.07.2014. 2014.
[18] Gong, M. and Wall, G.: On exergy and sustainable development-part 2: indicators and methods. Exergy, an International Journal (Exergy Int. J.). 1 (4) 217-233. 2001.
[19] Wang, H. and Shie, J.: Effect of Autoclave Curing on the Compressive Strength and Elastic Modulus of Lightweight Aggregate Concrete. Journal of ASTM International, 6 (6), 1-11. 2009.
[20] Kumar, K.V., Safiulla, M. and Ahmed, A.N.K.: An approach to optimize autoclaves for curing FRP Composites. International Journal of Engineering Research and Advanced Technology, Special volume, 2 (1), 597- 604. 2016.
[21] Preglej, A., Karba, R., Steiner, I. and Skrjanc, I.: Mathematical model of an autoclave. Journal of Mechanical Engineering, 57 (6), 503-516. 2011.

[22] Qureshi, M.N. and Ghosh, S.: Effect of curing conditions on the compressive strength and microstructure of alkali-activated GGBS paste. International Journal of Engineering and Science Invention, (2), 24-31. 2013.
[23] Ohijeagbon, I.O., Waheed, M.A., Jekayinfa, S.O. and Lasode, O.A.: 'Exergetic modelling of oil-fired steam boilers. Nigerian Journal of Technology, 33 (4), 523-536. 2014.
[24] Cengel, Y.A. and Boles, M.A.: Thermodynamics: An Engineering Approach, 5th ed., McGraw Hill. 2006.
[25] Gundersen, T.: An Introduction to the Concept of Exergy and Energy Quality, Third ed. Norway: Department of Energy and Process Engineering. 2009.
[26] Reddy, V.S., Kaushik, S.C., Tyagi, S.K. and Panwar, N.L.: An approach to analyse energy and exergy analysis of thermal power plants: a review. Smart Grid and Renewable Energy, 1, 143-152. 2010.
[27] Bouapetch, W., Srinophakun, T.R., Prakaypan, W. and Paterson, A.: Energy and exergy analysis of steam boiler and autoclave in fiber cement process. KMUTNB: IJAST, 7 (2), 37-46. 2014.
[28] Shukla, K.N., Rangnekar, S. and Sudhakar, K.: A comparative study of exergetic performance of amorphous and polycrystalline solar PV modules. Int. J. Exergy, 17 (4), 433–455. 2015.
[29] Dincer, I., Hussain, M.M. and Al-Zaharnah, I.: Exergy and energy use in the utility sector of Saudi Arabia, Desalination, 169, 245-255. 2004.

ANNALS of Faculty Engineering Hunedoara – International Journal of Engineering
ISSN 1584 – 2665 (printed version); ISSN 2601 – 2332 (online); ISSN–L 1584 – 2665

Faculty of Engineering Hunedoara,
5, Revolutiei, 331128, Hunedoara, ROMANIA
http://annals.fih.upt.ro