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Exergy Based Sustainability Analysis of Steam Generation and Utilization in Nigerian Pharmaceutical Industries

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Abstract

Exergy based sustainability analysis of steam generation and utilization in Nigerian pharmaceutical industries has been presented. Two pharmaceutical plants were considered which include JUHEL and DANA plants located in Awka, Anambra state and Minna, Niger state, respectively. The objective of the study is to perform a comprehensive energy and exergy analyses of steam boilers for JUHEL and DANA pharmaceutical industries and determine the utilization efficiency and sustainability index of the process heat at different operating conditions. The exergy of the component system was evaluated and the analysis done using an Engineering equation software (EES). The results obtained show that the fuel utilization efficiency varies from 30.4 to 67.2 % for energy efficiency and 17.5 to 55.6 % for exergy efficiency for JUHEL plant. Similarly, the FUE for DANA plant vary from 22.4 to 68.9 % for energy efficiency and 16.6 to 54.9 % for exergy efficiency. The environmental effect factor (EEF) showed increasing trend for all increased values of ambient temperature. The environmental effect factor increased with increased air flow rate (AFR) for both plant. The EEF for both plants was calculated at 4.8 for JUHEL and 5.04 for DANA plants. Similarly, the sustainability index was found at 0.209 and 0.197 for JUHEL and DANA plants respectively. Waste exergy ratio was recorded at 0.84 for JUHEL and 0.87 for DANA plant. However, JUHEL plant recorded slight improved values of (WER) of 0.02 % at lower AFR. The study suggests a retrofitting of the existing pharmaceutical plants and a time-series analysis will be necessary to show how the plant's irreversibilities change with time for proper optimization.

Keywords: Energy, Exergy, Sustainability Index.

1. INTRODUCTION

Steam boiler applications for process heat generation in pharmaceutical and chemical industries cannot be over emphasized, particularly for medicinal herbs processing and drying, sterilizing as well as purifying. The medicine production in a pharmaceutical plant needs to be precise, which means the heat produced must be adequately utilized and system components must be efficient with less heat losses. The low capacity utilization of process heat in most pharmaceutical industries shows there exists large losses between system components. This large gap clearly indicates the level of technical inefficiency in the existing energy conversion systems of the plant. The application therefore, of the exergy concept to ascertain the causes and level of system inefficiencies, low utilization efficiency as well as the environmental sustainability indicators makes this study unique.

The subject of sustainability is becoming more important with environmental and cost reduction characteristics. Following the increase in global energy need, the number of thermal generating plants and process heat production will increases year to year. The increase in energy source costs and the negative effects of wastes on the environment requires sustainable/renewable energy sources. Sustainability is necessary to overcome present ecological, economic, and developmental problems (Dincer and Rosen, 2005). Exergy-based sustainability has been applied to thermodynamic system for example, Karakoc *et al.,* (2013) performed an exergo-sustainability analysis in a turbojet engine. The results show that the exergetic efficiency was calculated at 29.2%, waste exergy ratio 70.8%, exergetic destruction ratio 0.41 and environmental effect factor 2.43, while exergetic sustainability index approaches a maximum value of 0.41. Also Aydin *et al*., (2013) performed an exergetic sustainability investigation of a gas turbine power plant. The study indicates that exergetic sustainability index for the gas turbine plants was 0.651 while the steam turbine stood at 0.978. The findings recommend an improvement in the overall efficiency and reviewed exergetic sustainability indicators. In all these application of exergy-based sustainability in thermal plants, non-exist for boiler integrated application like the pharmaceutical plant in consideration.

However, the application of exergetic sustainability analysis in pharmaceutical plants in Nigeria is not in open literature. Consequently, this study examines detailed exergy and energy utilization efficiencies of steam in to pharmaceutical plants in Nigeria. The effective parameters based on the local operating conditions will be well understood with exergy application. The findings from such study will prove useful in the design and optimization of efficient pharmaceutical plants and improvement in environmental sustainability. Additionally, as Nigeria is considering and employing the updated national energy plan with more importance on energy efficiency strategies, in both pharmaceutical, chemical, manufacturing, steel and power sectors, this research will offer an insight to the performance of pharmaceutical plants in Nigeria. And also proffer possible future enhancement for effective energy and efficiency of process heat generation in pharmaceutical industries.

2.1 MATERIALS AND METHODS

2.1.1 PLANT DESCRIPTION

The process flow diagrams of the JUHEL and DANA pharmaceutical plants are presented in Fig. 1. The plants are similar in components and process flow but differ in operating conditions. The plant comprises: the Fire tube boiler, Distillers, Condensers and the Autoclaves, Preheaters and Pumps. JUHEL plant uses a Reverse osmosis unit for primary filtration of water, while DANA uses Activated Carbon filters. Water is fed into the three pass, fire-tube boiler which is basically composed of a combustor and a heat exchanger. The combustion chamber is the turbo-engine component of the boiler where fuel supplied by the feeding nozzles of an electric burner mixes with air flow coming from a forced draft fan and burns, releasing a stream of high temperature combustion product into the heat exchanger pipes. As it flows through the pipes, the pipes get very hot and thus transfer heat to the water which surrounds them. The water then gets heated up and turns into steam. While the flue gas is exhausted from the system through the flue gas stack, the steam is distributed through the steam line to the various operation devices such as the autoclaves, distillation units and condensers.

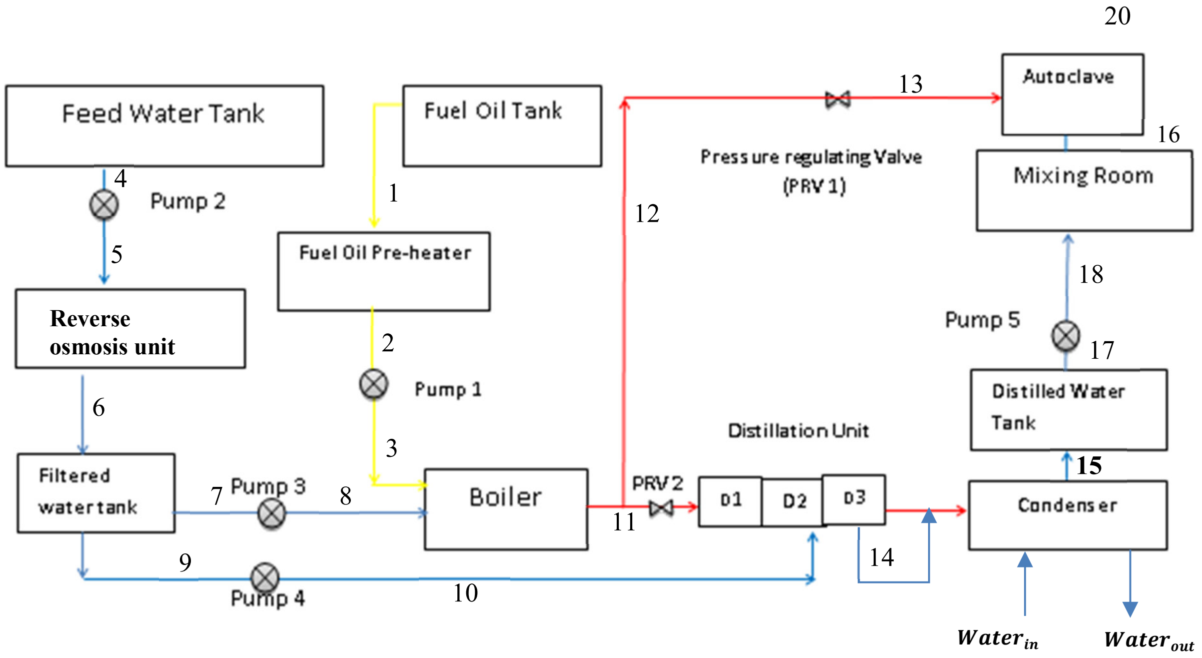

Fig. 1: Flow diagram of JUHEL/DANA pharmaceutical plants showing all the state points

Furthermore, a schematic diagram of the boiler with its accessories is shown in Fig. 2.

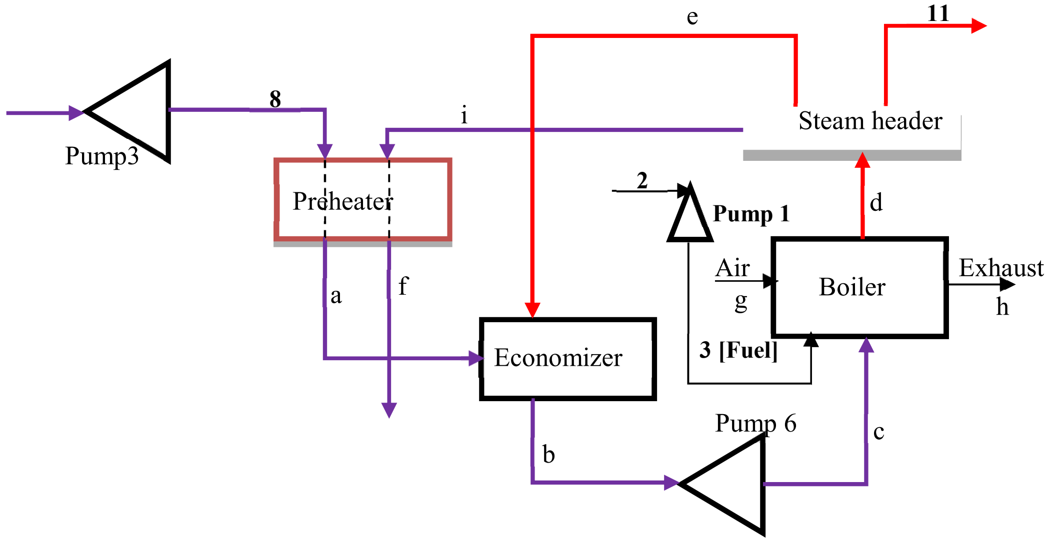

Fig. 2: Material flow of a fire tube boiler

2.1.2 DEVELOPED METHODS

Detailed exergy balance for the various components is presented in line with the general exergy balance for a control volume (Bejan and Tsatsaronis, 1995; Kotas, 1995; Tsatsaronis, 2007). The general exergy models for a control volume comprising exergy influx ex_{in}, efflux ex_{out}, heat input Q_{in} and work output W_{out} can be expressed under steady state conditions as:

$$\sum ex_{in} + ex_Q = \sum ex_{out} + ex_W + E_D \qquad (1)$$

Where the specific exergy is expressed at a temperature ***T*** and pressure ***P*** all referenced at the ambient temperature $\boldsymbol{T_0}$ and pressure $\boldsymbol{P_0}$ as follows:

$$ex_{in,out} = [(h(T) - h(T_0)) - T_0\{(s(T) - s(T_0)\}] \qquad (2)$$

In order to properly account for the properties of the system regarding the specific heat capacity at referenced temperatures, the pressure and other properties, the entropy change is here accounted for by employing the thermodynamic first law and necessary simplifications to obtain the expression for the entropy and enthalpy change below (Rajput, 2009):

$$\Delta s = c_p ln\left[\frac{T}{T_0}\right] - R * ln\left[\frac{P}{P_0}\right] \qquad (3)$$

$$\Delta h = c_p[T - T_0] \qquad (4)$$

Substituting these two expressions in equation 1, we obtain the term for calculating the physical exergy streams for the four structures as:

$$ex_{in,out} = \left\| c_p[T - T_0] - T_0\left\{c_p ln\left[\frac{T}{T_0}\right] - R * ln\left[\frac{P}{P_0}\right]\right\}\right\| \qquad (5)$$

Additionally the exergy of heat and that due to work interaction is expressed as obtained in the expression below:

$$ex_Q = \left[1 - \frac{T_0}{T_Q}\right] Q_{in} \qquad (6)$$

$$ex_W = W = c_p \Delta h \qquad (7)$$

2.2 ENVIRONMENTAL SUSTAINABILITY INDICATORS

Environmental sustainability indicators are exergy based indices which comparatively assesses the performance of energy conversion systems based on exergy efficiency, useful system output, and the environmental impact of such systems which must result due to large thermodynamic irreversibilities. These environmental sustainability indicators are expressed as follows:

2.2.1 Waste Exergy Ratio (WER)

The waste exergy ratio quantifies the degree of cumulative thermodynamic irreversibilities in a plant with respect to the available external exergy input to the system. For thermal power plants and boilers, the available external exergy input is the chemical exergy of the fuel used. The waste exergy ration is obtained mathematically as the overall exergy waste (or destruction) for the system on the total exergy input. This is expressed as (Aydın *et al.*, 2013):

$$\text{WER} = \frac{\dot{D}_{Preheater} + \dot{D}_{Economizer} + \dot{D}_{Boiler} + \dot{D}_{Pump6}}{\left[1 - \frac{T_0}{T_{Boiler}}\right] * \dot{m}_{Fuel\,Oil} * LHV_{Fuel\,Oil}} \qquad (8)$$

2.2.2 Environmental Effect Factor (EEF)

The environmental effect factor quantifies the degree of cumulative thermodynamic irreversibilities in a plant with respect to the plants net exergy efficiency. It also comparatively relates the extent to which a plants useful output is severely affected due to relatively high thermodynamic irreversibilities resulting in environmental concerns. The EEF is obtained as the ratio of the waste exergy ratio upon the exergy efficiency. This is expressed as (Aydın *et al.*, 2013):

$$EEF = \frac{\text{WER}}{\psi} = \frac{\dot{D}_{Preheater} + \dot{D}_{Economizer} + \dot{D}_{Boiler} + \dot{D}_{Pump6}}{\left[1 - \frac{T_0}{T_{Boiler}}\right] * \dot{m}_{Fuel\,Oil} * LHV_{Fuel\,Oil} * \psi} \qquad (9)$$

2.2.3 Exergy Efficiency

This is the general performance index of a plant based on the concept of availability. The exergy efficiency is obtained with the expression (Cengel and Boles, 2007; Rajput, 2009):

$$\psi = \frac{exergy\ in\ product}{\dot{e}_{FUEL}} = \frac{[h(T_d, P_d) - h(T_0, P_0)] - T_0[s(T_d, P_d) - s(T_0, P_0)]_{Steam}}{\left[1 - \frac{T_0}{T_{Boiler}}\right] * \dot{m}_{Fuel\,Oil} * LHV_{Fuel\,Oil}} \qquad (10)$$

2.2.4 Exergetic Sustainability Index

The exergetic sustainability index is a non-dimensional term which explains the extent by which an energy conversion system total useful output exceeds the total internal thermodynamic irreversibilities. This term assists in thermodynamically assessing by what fraction a system's useful output overcomes the seemingly inherent net exergetic destruction in the system. Thus, a system with exergy output far larger than the total destruction rate will have sustainabilities greater than unity while systems with comparatively large destruction at par with the plant output are not sustainable. Appropriately, the reciprocal of the environmental effect factor is termed the exergetic sustainability index and provides a platform for comparison between the environmental degradation due to exergetic output from each system (Aydin et al., 2013);

$$SI = \frac{\left[1-\frac{T_0}{T_{Boiler}}\right]*\dot{m}_{Fuel\,Oil}*LHV_{Fuel\,Oil}*\psi}{\dot{D}_{Preheater}+\dot{D}_{Economizer}+\dot{D}_{Boiler}+\dot{D}_{Pump6}} \tag{11}$$

Substituting for values of exergy efficiency, the SI can be written as:

$$SI = \frac{\dot{E}_d = [h(T_d,P_d)-h(T_0,P_0)]-T_0[s(T_d,P_d)-s(T_0,P_0)]_{Steam}}{\dot{D}_{Preheater}+\dot{D}_{Economizer}+\dot{D}_{Boiler}+\dot{D}_{Pump6}} \tag{12}$$

$$SI = \frac{Exergy\ of\ product}{Grand\ exergy\ destruction} \tag{13}$$

3.1 RESULTS AND DISCUSSION

3.1.1 Utilization Efficiency of JUHEL and DANA Plants Based on Energy and Exergy Efficiencies

The fuel utilization efficiency (FUE) is the ratio of all the useful energy extracted from the system to the energy of the fuel input at a particular condition.The fuel utilization efficieincy was considered at full load conditions of the system and components performances were expressed in terms of energy and exergy efficiencies.The fuel utilization efficiency varies from 30.4 to 67.2 % for energy efficiency and 17.5 to 55.6 % for exergy efficiency for JUHEL plant (Fig. 3a). Similarly, the FUE for DANA plant vary from 22.4 to 68.9 % for energy efficiency and 16.6 to 54.9 % for exergy efficiency (Fig.3b). Components with high utilization efficiency include the pumps, distilled water tank, distillation unit, and fuel preheater. The reason for the high FUE is attributed to low entropy generation which results in low exergy destruction. In the boiler system, the difference between the flame temperatures and the working fluid is responsible for the low FUE. However, the variations in components FUE and performance could be ascribed to large variations in operating parameters, faulty components and level of maintenance.

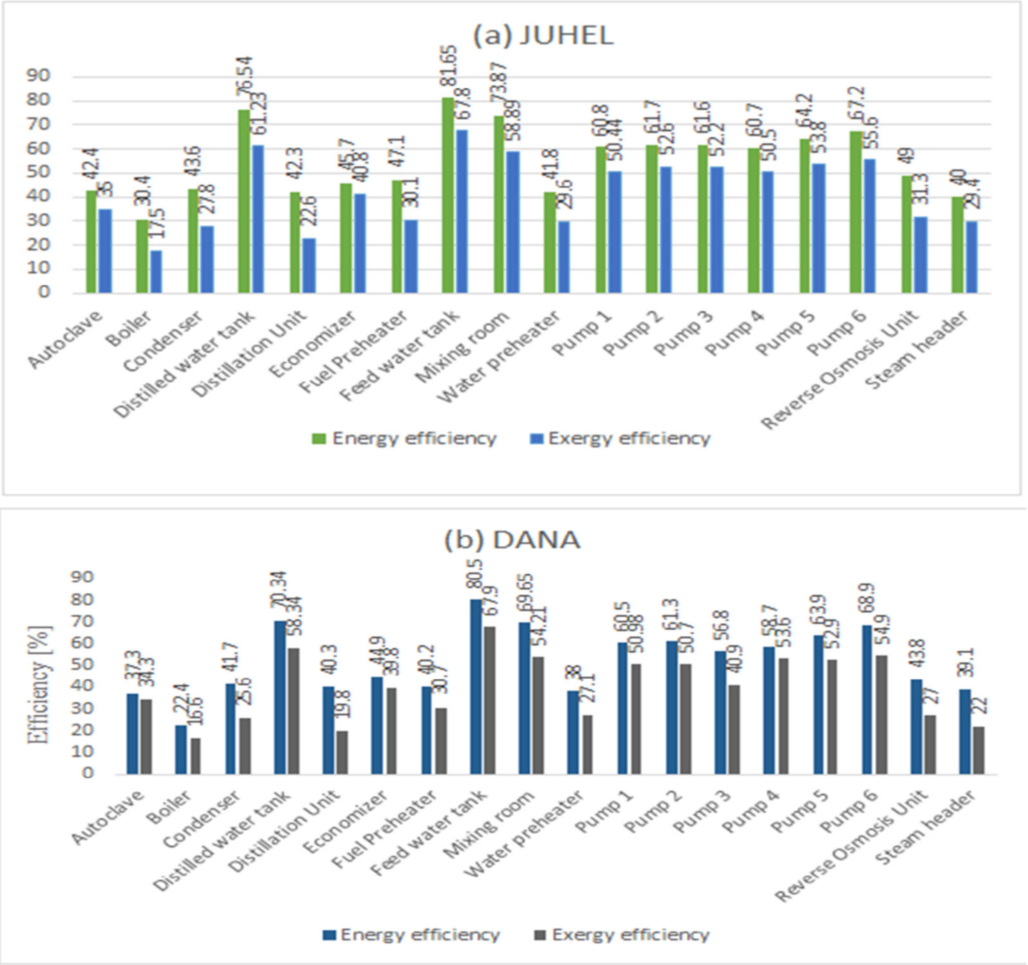

Fig. 3: Utilization efficiency of the plant components based on energy and exergy efficiencies (a) JUHEL plant and (b) DANA plant

3.1.2 The Effect of Ambient Temperature on Exergetic Sustainability Indicators

The effect of AT on sustainability indicator for JUHEL plant (Fig. 4a) and DANA plant (Fig. 4b) at temperature range between 298 ≤ T ≤ 335 K is presented. The environmental indicators include: overall exergy efficiency (OEE), environmental effect factor (EEF), waste exergy ratio (WER) and sustainability index (SI). The OEE decreases from about 17.7 % at 298 K to 12.8 % at 330K for JUHEL plant (Fig. 5a) and decreases from about 16.6% at 298 K to 12.2% at 335 K for DANA plant (Fig.5b). At the same temperature range, the exergetic sustainability index decreases from 0.209 to 0.189 for JUHEL plant and 0.197 to 0.178 for DANA plant. Between the AT limit of 298 ≤ T ≤ 335 K the SI dropped approximately by 10 % for both plants respectively. Similarly between the operating limits AT 298 ≤ T ≤ 335 K the environmental impact was about 12.25 %. For JUHEL plant and 12.08 for DANA plant. Nonetheless, the EEF shows increasing trend for all increasing values of AT.

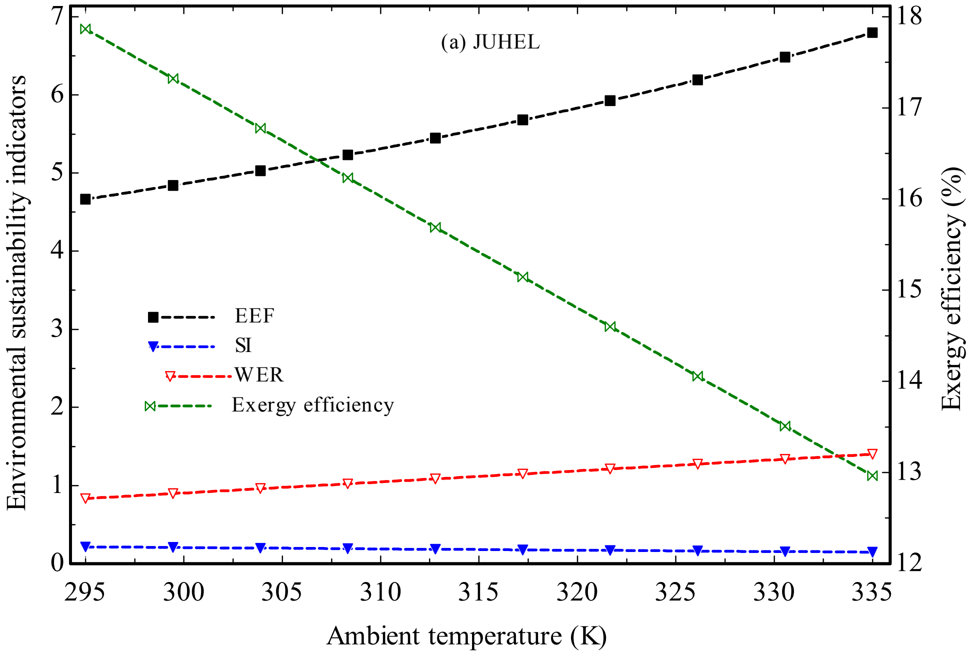

Fig. 4a: The effect of ambient temperature on sustainability indicators in JUHEL plant.

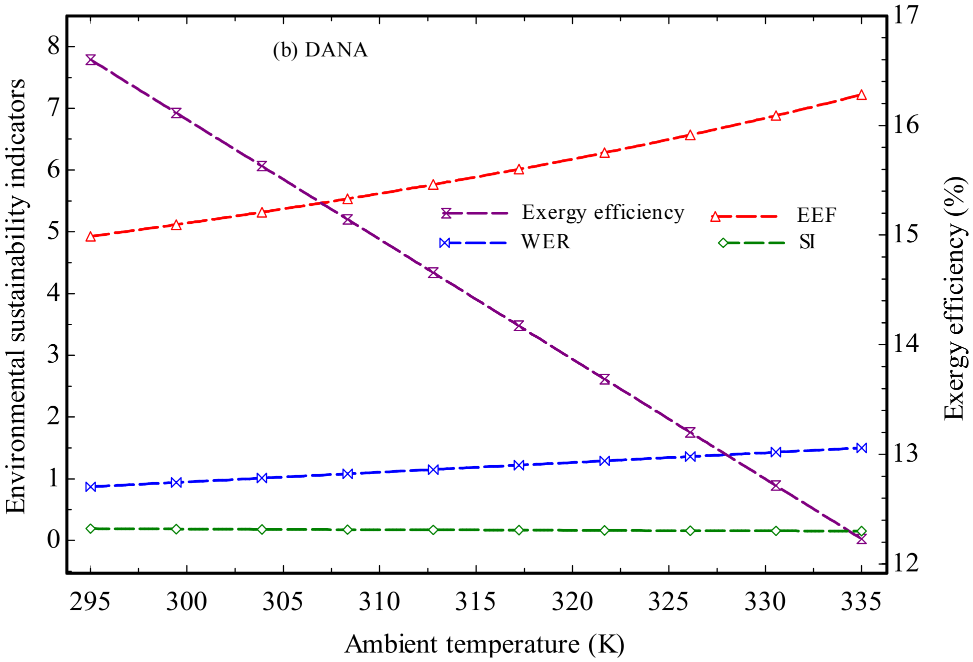

Fig. 4b: The effect of ambient temperature on sustainability indicators in DANA plant

3.1.3 The Effect of Inlet Boiler Pressure on Exergetic Sustainability Indicators

The effect of inlet boiler pressure is presented in Fig. 5 for the two plants JUHEL (Fig.5a) and DANA (Fig. 5b).

The results showed that all the exergetic sustainability indicators recorded slight improved values for all increased boiler inlet pressure. The EEF dominates and is high for the two plants at the considered pressure range between 10 and 26 bars.

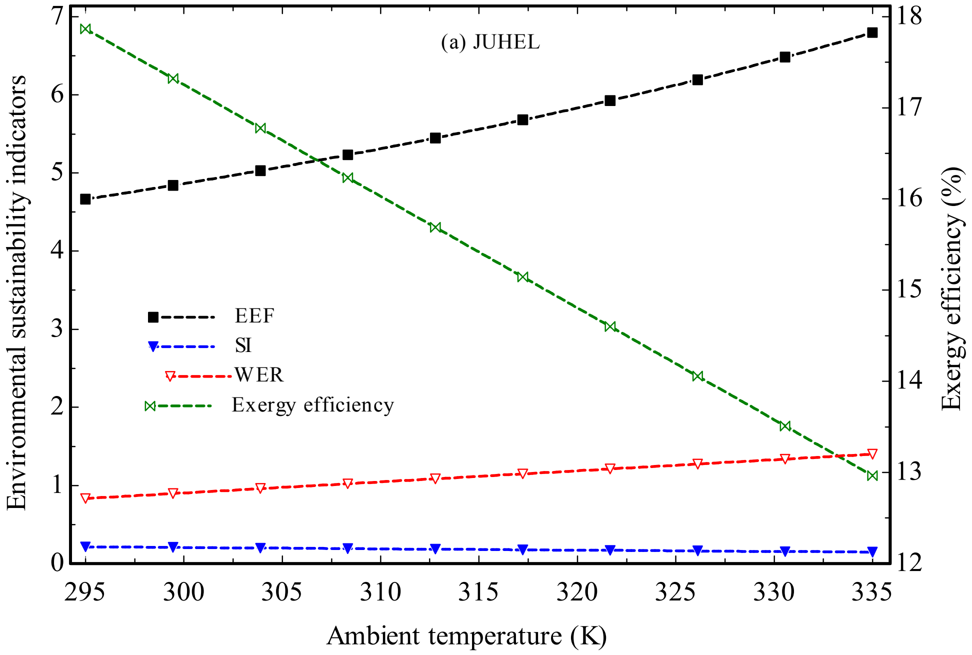

Fig. 5a: The effect of boiler inlet pressure on sustainability indicators in JUHEL plant.

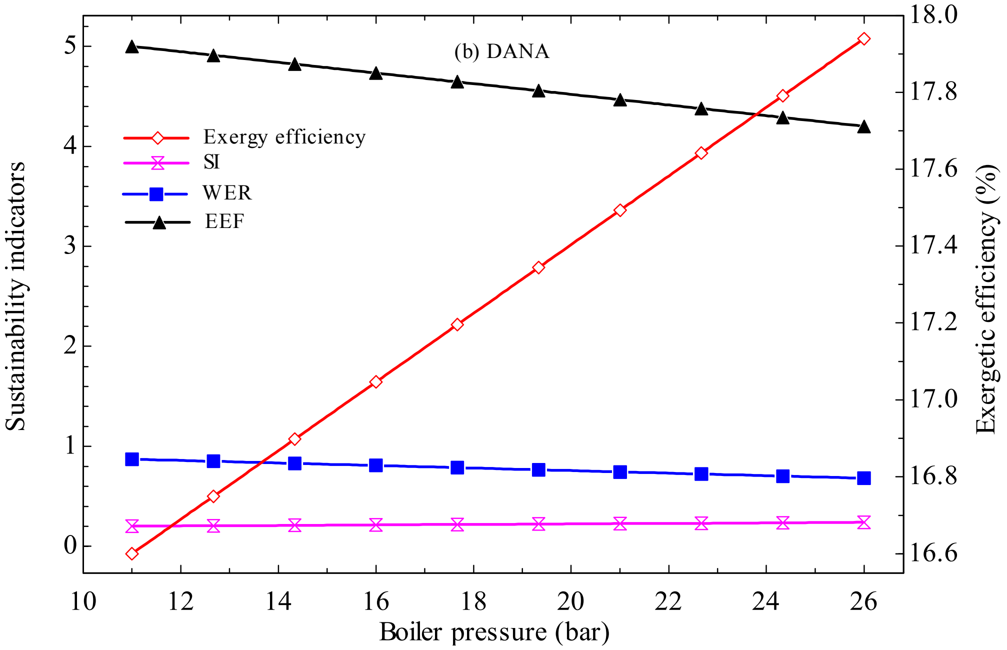

Fig. 5b: The effect of boiler inlet pressure on sustainability indicators in DANA plant.

3.1.4 The Effect of Air Flow Rate on Exergy Destruction and Sustainability Indicators

The effect of Air Flow Rate on Environmental Sustainability Indicators is presented in Fig. 6(a) and Fig.6(b) for JUHEL and DANA plants respectively. For air flow increase from 22kg/s to 30kg/s, the waste exergy ratio increased from 0.83 to 0.98 for JUHEL and 0.87 to 0.91 for DANA plant. Similarly, the Environmental Effect Factor increased slightly from 4.6 to 4.98 for JUHEL and from 5.05 to 5.54 for DANA plant. The Sustainability Index decreased between 0.209 to 0.201 for JUHEL and 0.197 to 0.180 for DANA plant.

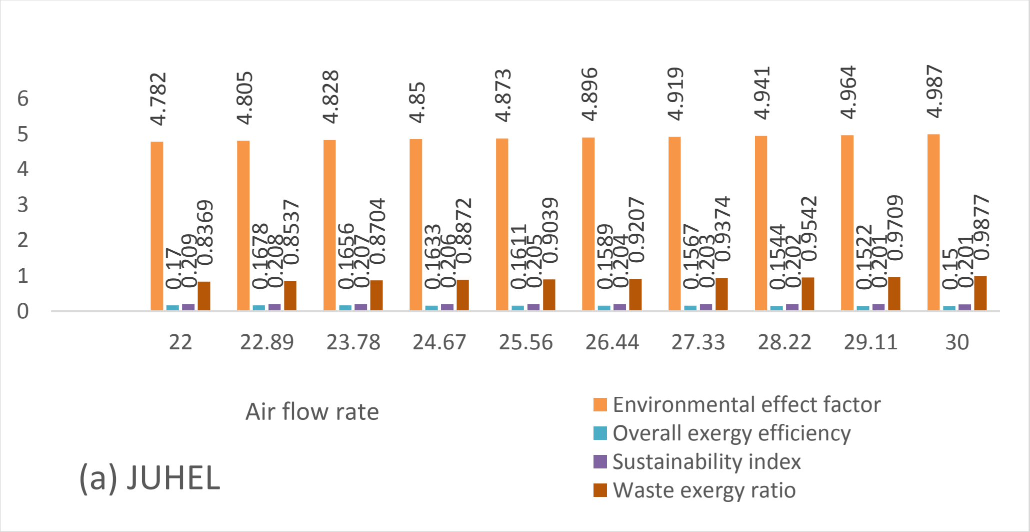

Fig. 6a: The effect of air flow rate on sustainability indicators in JUHEL plant.

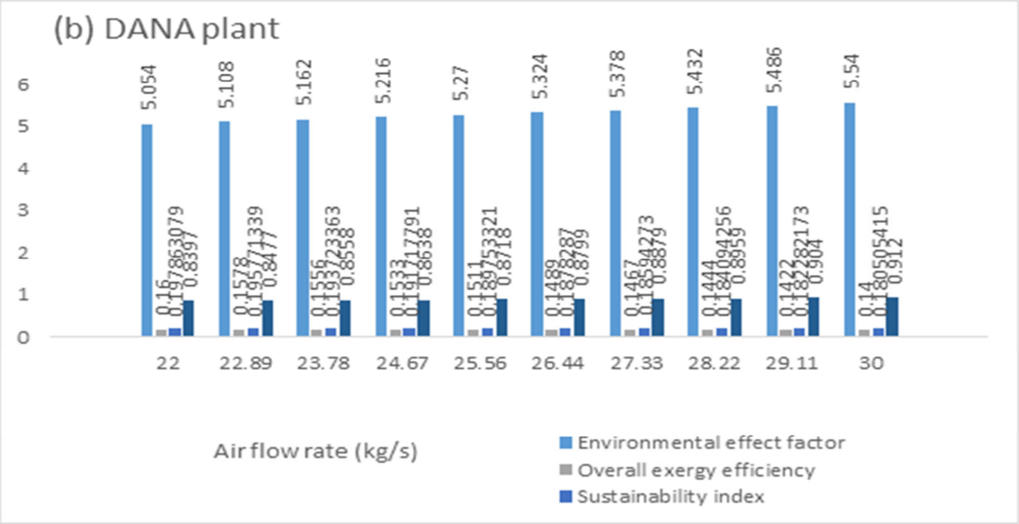

Fig. 6b: The effect of air flow rate on sustainability indicators in DANA plant

4.1 CONCLUSION

The energy-exergy based performance and sustainability analysis of pharmaceutical plants in Nigeria was studied. Detailed exergy analysis at the state points was studied with the operating data for the two plants. Some of the operating data considered include ambient temperature, boiler inlet pressure and air flow rate. The variations of this parameters were studied based on their corresponding effect on exergy destruction, exergy utilization efficiency, environmental effects and sustainability index. However, high exergy losses are recorded in the boiler, autoclave and the distillers for the two plants. The boiler chamber was found to have the highest level of exergy destruction, this is so because of inherent contributions of losses from more than one source.

4.2 Findings

The following findings were made after conclusion of the research:

The fuel utilization efficiency (FUE) varies from 30.4 to 67.2 % for energy efficiency and 17.5 to 55.6 % for exergy efficiency for JUHEL plant. Similarly, the FUE for DANA plant vary from 22.4 to 68.9 % for energy efficiency and 16.6 to 54.9 % for exergy efficiency.

The findings also showed that for a 1^{O}C increase in ambient temperature (AT), the exergy destruction increased by about 0.9 % in the components and about 0.11% for the overall exergy destruction (ED). However, the boiler, preheater and the autoclave recorded the highest exergy destruction.

Additionally, between the ambient temperatures limit of $298 \leq T \leq 335$ K the sustainability index (SI) reduced by about 10% for JUHEL and DANA plants respectively while the environmental impact was about 12.25 % for JUHEL plant and 12.08 for DANA plant. The environmental effect factor (EEF) showed increasing trend for all increasing values of ambient temperature. However, EEF values for DANA plant was slightly higher by about 0.01% at higher AFR.

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