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Evaluation of Energy and Exergy Efficiency of Steam Generation and Utilization in Nigerian Pharmaceutical Industries

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ABSTRACT

The energy-exergy efficiency of process heat generation and utilization in the Nigerian pharmaceutical industry was evaluated. Two pharmaceutical plants were considered which include JUHEL and DANA plants located in Awka, Anambra state and Minna, Niger state, respectively. The result obtained showed that the energy and exergy efficiencies in JUHEL boiler were found at 30.4% and 17.5% respectively, followed by the distillation unit which recoded 42.3% energy efficiency and 22.6% exergy efficiency. Similarly, energy and exergy efficiencies in DANA boiler were recorded at 22.4% and 16.6% respectively followed by the autoclave unit which recorded 37.3% and 34.3% efficiencies. Other components of the plants with low energy and exergy efficiencies include; the steam headers, condensers and preheaters. Total exergy destruction in JUHEL and DANA plants was found at 13532KW for JUHEL and 14086KW for DANA. On component exergy destruction, JUHEL and DANA boilers recorded 6778KW and 7789KW which accounted for about 38% and 42.3% of the plants total exergy destruction respectively. However, the condenser and autoclave recorded 16% and 5% of the total exergy destruction in JUHEL plant while the same components recorded 15% and 5% of total destruction in DANA plant. The study also showed that for a 1°C increase in ambient temperature, the exergy destruction in both plants increased by about 0.9%. Furthermore, variations in boiler inlet pressure showed that the rate of exergy destruction reduced with reduction in boiler inlet pressure.

Keywords: Energy, Exergy, Exergy Destruction.

INTRODUCTION

The nexus between energy conversion, energy efficiency, energy supply and ecological concerns requires an enhanced use of energy resources for better efficiency. To actualize the goal of judicious use of resources and improved environmental sustainability, advanced thermodynamic techniques are required. There exist difficulties in using the conventional first law of thermodynamics alone for analysing efficiencies of thermodynamic systems used for process heat generation (boilers). The reason being that it gives misleading information about the efficiency of an energy conversion system since it fails to provide a measure of how nearly the performance of a system approaches ideality. For this reason, the combined approach of the first and second laws of thermodynamics, a concept called exergy, becomes imperative. Exergy as a thermodynamic tool can describe energy resource utilization as well as material loss to the environment and other secondary components in pharmaceutical or manufacturing plants. This makes it possible to quantify material flow within the environment and level of environmental sustainability. Many Nigerian pharmaceutical, chemical and utility sectors use steam boilers as their means of energy conversion. In pharmaceutical industries, the generated heat is used in secondary applications like in the distillers and the autoclave. In these units, components losses exits during heat transfer. The assessment of the complex thermodynamic process of the entire system and the needed improvement cannot be achieved with first law of thermodynamics alone [1] [2]. [3] performed a complete exergy analysis of a coal fire boiler based component wise modelling. The combustion efficiency for the fired coal was examined based on the simulated working data and the state properties of the plant. The result shows that the highest irreversibility occurs in the combustion process. [4] evaluated the performance of a steam boiler in a brewery in Nigeria using energy and exergy analysis. The exergy losses in the different boiler subsystems: combustion chamber, mixing section and heat exchanger were estimated. The exergy losses of the secondary component occurred in the combustion chamber followed by the heat exchanger. The energy and exergy analysis of steam boiler and autoclave in fibre cement process was presented by [5]. The result showed that high exergy destruction rates was due to exhaust steam, condensate, and autoclave shell heat loss. Further, in terms of economic analysis, [6] considered the cost of exergy stream for industrial boilers fired with different fuels. The study shows that the exergy destruction cost was dominant in the combustion chamber and the economizers. Also, the exergy destruction cost was marginal with different fuel. Other cost analysis of industrial turbines has be presented in [7]. [8] carried out an energy and exergy analysis of a boiler with different fuels. He compared different types of coal like Indian coal, imported coal, mixture of both (60% imported+40 % Indian) and LPO oil and conclude that the first law efficiency was 76.54%, 83.03%, 80.60%, and 88.20% respectively. Also the exergetic efficiency of the boiler plant were recorded as 37%, 37.7%, 37.8% and 40.1% respectively for the fuels. [9] established an approach for the physical and chemical exergy study of steam boilers**.** Energy and exergy efficiencies obtained for the entire boiler was 69.56% and 38.57% at standard reference state temperature of 25^{0}C for an evaporation ratio of 12. Similarly, [10] performed an exergy analysis of a boiler in a cogeneration thermal plant and concluded that the exergy destruction of the boiler at a load of 1.1 MW was 83.35% and 76.33 % for load of 5.6 MW. It was finally concluded that the system efficiency decreases at higher load and thus the exergy destruction. [11] evaluated and optimized a fluidized bed boiler in ethanol plant using irreversibility analysis. The results showed that the exergy efficiencies of the boiler, deaerator, and pre-heater were 25.82%, 40.13%, and 2.617%, respectively. [12] presented an exergy analysis of a commercial tomato paste plant. Similarly, in a phosphoric acid factory, [13] studied energetic and exergetic interaction for a steam turbine which powers the system. [14] performed both energy and exergy analysis of a steam boiler and an autoclave in fiber based cement processing. The result presents values of 72.04 and 69.98% respectively in terms of energy and exergy. [15]

presented results comprising data on energy and exergy optimization for a sugar factory. The results showed an efficiency of 72.2% and 37.4% in terms of energy and exergy, respectively for the plant. However, the application of exergy 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.

MATERIALS AND METHODS

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. Fuel is 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 transfers 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.

DEVELOPED METHODS

Detailed exergy balance for the various components is presented in line with the general exergy balance for a control volume [15]. 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:

$$\sum ex_{in} + ex_Q = \sum ex_{out} + ex_W + E_D$$

(1)

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

$$ex_{in,out} = [(h(T_1P_1) - h(T_0P_0)) - T_0\{(s(T_1P_1) - s(T_0P_0)\}]$$

(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 [16]:

$$[?][?][?]s = c_p ln[\frac{T}{T_0}] - R * ln[\frac{P}{P_0}]$$

(3)

$$[?][?][?]h = c_p[T - T_0]$$

(4)

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

$$ex_{in,out} = [?][?][?]c_p[T - T_0] - T_0\left\{c_p ln[\frac{T}{T_0}] - R^* ln[\frac{P}{P_0}]\right\}[?][?][?]$$

(5)

$$\dot{E}_1 = \sum_i x_i E_{xi}^{CH} + RT_0 \sum x_i ln x_i$$

(8)

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

$$ex_Q = [1 - \frac{T_0}{T_Q}]Q_{in}$$

(6)

$$ex_W = W = c_p[?][?][?]h$$

(7)

The developed expressions from equations 5 through 7 are necessary and sufficient to perform the component exergetic balance as follows:

The exergy at point 1 comprises the chemical exergy of fuel oil at standard temperature and pressure of 25°C and 1.013 bar, respectively. It is obtained using the following relationship:

The mole fractions of constituents of the fuel are represented with the term $\boldsymbol{x}_i$ while the chemical exergy of the fuel is denoted by E_{xi}^{CH}.

The exergy at point 2 comprises the chemical exergy and slight physical which is added to the mass stream due to temperature variations at point 2. The exergy calculation is achieved using the following expression:

$$\dot{E}_2 = \sum_i x_i E_{xi}^{CH} + RT_0 \sum x_i ln x_i + h(T_2P_2) - h(T_0P_O) - T_0[s(T_2P_2) - s(T_0P_O)]$$

(9)

Equation 9 can be represented as:

(10)

Following similar pressure conditions at point 2 and the ambient, the physical exergy term which comprises the pressure term is zero. Consequently, the exergy at point 2 can be written as:

$$\dot{E}_2 = \sum_i x_i E_{xi}^{CH} + RT_0 \sum x_i ln x_i + h(T_2P_2) - h(T_0P_0) - T_0[c_p ln\frac{T_2}{T_0}]$$

(11)

Exergy balance around the fuel preheater is obtained as follows:

$$\dot{E}_1 = \dot{E}_2 + \dot{D}_{FPH}$$

(12)

Exergetic efficiency when applied to the fuel preheater is obtained with the relationship:

(13)

The exergy at point 3 is obtained by incorporating the pressure variation due to the pump with the relationship as:

(14)

Pump work can be expressed as:

$$\dot{W}_{Pump1} = v_{f@P_2}(P_3 - P_2)$$

(15)

Exergy balance around the pump therefore takes the form:

$$\dot{E}_2 + \dot{W}_{PUMP1} = \dot{E}_3 + \dot{D}_{P1}$$

(16)

The exergy efficiency for the pump is expressed with the relationship:

The physical exergy at point 4 (for water) is negligibly small since its temperature is nearly ambient; and its pressure is same as the ambient pressure.

At point 5, the physical exergy following increased pressure by virtue of the pump can be expressed as:

$$\dot{E}_5 = [h(T_5 P_5) - h(T_0 P_0)] - T_0[c_p ln\frac{T}{T}$$

(18)

However, since the temperature at point 5 is nearly ambient, the physical exergy is merely obtained by the pressure variation of the water at pump inlet and outlet. Accordingly, the physical exergy at point 5 is reduced to:

$$\dot{E}_5 = T_0[R.ln\frac{P_5}{P_0}]$$

(19)

Pump work is expressed as:

$$\dot{W}_{Pump2} = v_{f@P_4}(P_5 - P_4)$$

(20)

The exergy balance around the water pump and exergetic efficiency is written as:

$$[?][?]_{P1} = \frac{\dot{E}_3 - \dot{E}_2}{\dot{W}_{PUMP1}}$$

(17)

$$\dot{E}_4 + \dot{W}_{PUMP2} = \dot{E}_5 + \dot{D}_{P2}$$

(21)

$$[?][?]_{P2} = \frac{\dot{E}_5 - \dot{E}_4}{\dot{W}_{PUMP2}}$$

(22)

Exergy at points 5 and 6 are same and expressed as:

$$\dot{E}_5 = \dot{E}_6$$

(23)

$$\dot{E}_5 = \dot{E}_6 + \dot{D}_{ACF}$$

(24)

At the filtered water tank, exergetic conditions at inlet and outlet are similar. The expressions as well as the exergy balance is obtained as:

$$\dot{E}_6 = \dot{E}_7 = \dot{E}_9$$

(25)

Exergy balance around the filtered water tank is expressed as:

$$\dot{E}_6 = \dot{E}_7 + \dot{E}_9 + \dot{D}_{FWT}$$

(26)

At point 8, the exergy is obtained with the expression:

$$\dot{E}_8 = [h(T_8 P_8) - h(T_0 P_0)] - T_0[c_p ln\frac{T_8}{T_0} - R.ln\frac{P_8}{P_0}]$$

(27)

Exergy balance around pump 3, and its exergy efficiency is obtained as:

$$\dot{E}_7 + \dot{W}_{PUMP3} = \dot{E}_8 + \dot{D}_{PUMP3}$$

(28)

$$[?][?]_{PUMP3} = \frac{\dot{E}_8 - \dot{E}_7}{\dot{W}_{PUMP3}}$$

(29)

Where the pump work is obtained as follows:

$$\dot{W}_{Pump3} = v_{f@P_7}(P_8 - P_7)$$

(30)

Similarly, exergy balance around pump 4, and its exergy efficiency is obtained as foll)ows:

$$\dot{E}_9 + \dot{W}_{PUMP4} = \dot{E}_{10} + \dot{D}_{PUMP4}$$

(31)

$$[?][?]_{PUMP4} = \frac{\dot{E}_{10} - \dot{E}_9}{\dot{W}_{PUMP4}}$$

(32)

Where the pump work is obtained as:

$$\dot{W}_{Pump4} = v_{f@P_9}(P_{10} - P_9)$$

(33)

With respect to the operating temperature and pressure at point 10, the exergy at this point is obtained as:

$$\dot{E}_{10} = [h(T_{10}P_{10}) - h(T_0P_0)] - T_0[c_p ln\frac{T_{10}}{T_0} - R.ln\frac{P_{10}}{P_0}]$$

(34)

Exergy balance around the preheater is obtained with the expression:

$$\dot{E}_8 + \dot{E}_i = \dot{E}_a + \dot{E}_f + \dot{D}_{Preheater}$$

(35)

Exergy computations at the state points ***i***, ***a***, and ***f*** is obtained with following expressions:

$$\dot{E}_i = [h(T_i,P_i) - h(T_0,P_0)] - T_0[s(T_i,P_i) - s(T_0,P_0)]$$

(36)

$$\dot{E}_a = [h(T_a,P_a) - h(T_0,P_0)] - T_0[s(T_a$$

(37)

$$\dot{E}_f = [h(T_f,P_f) - h(T_0,P_0)] - T_0[s(T_f$$

(38)

Exergetic efficiency for the preheater is obtained as:

$$[?][?]_{Preheater} = \frac{\dot{E}_i - \dot{E}_f}{\dot{E}_a - \dot{E}_8}$$

(39)

At the economizer, exergy balance is expressed by:

$$\dot{E}_a + \dot{E}_e = \dot{E}_b + \dot{D}_{Economizer}$$

(40)

Streams at points ***a***, and ***e***, form the component fuel, while the stream at ***b*** forms the product. Accordingly, the exergetic efficiency for this component is expressed as:

$$[?][?]_{Economizer} = \frac{\dot{E}_b}{\dot{E}_a + \dot{E}_e}$$

(41)

At state point ***e***, and ***b***, the exergy is a function of steam temperature and pressure and can be obtained with the following functions:

$$\dot{E}_b = [h(T_b,P_b) - h(T_0,P_0)] - T_0[s(T_b,P_b) - s(T_0,P_0)]_{Hot\ water}$$

(42)

$$\dot{E}_e = [h(T_e,P_e) - h(T_0,P_0)] - T_0[s(T_e,$$

(43)

Similarly, exergy balance around pump 6, and its exergy efficiency is obtained as follows:

$$\dot{E}_b + \dot{W}_{PUMP6} = \dot{E}_c + \dot{D}_{PUMP6}$$

(44)

$$[?][?]_{PUMP6} = \frac{\dot{E}_c - \dot{E}_b}{\dot{W}_{PUMP6}}$$

(45)

Where the pump work is obtained as:

$$\dot{W}_{Pump6} = v_{f@P_b}(P_c - P_b)$$

(46)

With respect to the operating temperature and pressure at point c, the exergy at this point is obtained as:

$$\dot{E}_c = [h(T_c,P_c) - h(T_0,P_0)] - T_0[s(T_c,P_c) - s(T_0$$

(47)

At the boiler, the exergy balance is written as:

$$\dot{E}_g + \dot{E}_c + \dot{E}_Q = \dot{E}_d + \dot{E}_h + \dot{D}_{Boiler}$$

(48)

Where the term $\dot{E}_Q$ is the exergy of heat in the boiler, and $\dot{E}_h$ is the exergy associated with the exhaust. Terms of Equation 48 are expressed as follows:

$$\dot{E}_g = [h(T_g P_g) - h(T_0 P_0)] - T_0[c_p ln\frac{T_g}{T_0} - R.ln\frac{P_g}{P_0}]$$

(49)

The expression above represents the exergy of air at inlet to the boiler. The exergy of heat in the boiler is obtained as:

$$\dot{E}_Q = [1 - \frac{T_0}{T_{Boiler}}]\dot{Q}_{Boiler}$$

(50)

With respect to the mass of oil burnt and its calorific value, Equ. 50 is written as:

$$\dot{E}_Q = [1 - \frac{T_0}{T_{Boiler}}] * \dot{m}_{Fuel\,Oil} * LHV_{Fuel\,Oil}$$

(51)

At the exhaust, approximated exergy at the exhaust is estimated with the relationship:

$$\dot{E}_h = [h(T_h P_h) - h(T_0 P_0)] - T_0[c_p ln\frac{T_h}{T_0} - R.ln\frac{P_h}{P_0}]$$

(52)

Values for the specific heat are obtained based on the mass fractions of exhaust constituents.

The exergy of superheated steam at point ***d*** is obtained with the relationship:

$$\dot{E}_d = [h(T_d,P_d) - h(T_0,P_0)] - T_0[s(T_d,P_d) - s(T_0,P_0)]_{Steam}$$

(53)

(54)

Exergetic efficiency for the boiler takes the form:

The exergy of steam delivered to the distillers at point 11 is obtained as:

$$\dot{E}_{11} = [h(T_{11},P_{11}) - h(T_0,P_0)] - T_0[s(T_{11},P_{11}) - s(T_0,P_0)]_{Steam}$$

(55)

Total exergy destruction in the boiler can be summed as:

$$\dot{D}_{TOTAL} = \dot{D}_{Preheater} + \dot{D}_{Economizer} + \dot{D}_{Boiler} + \dot{D}_{Pump6}$$

RESULTS AND DISCUSSION

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.

Effect of Ambient Temperature on Exergy Destruction Rate

The effect of ambient temperature (AT) on the components performance and the entire plant is presented in Fig. 4a for JUHEL plant and Fig. 4b for DANA plant. The study showed that for a 1°C increase in ambient temperature, the exergy destruction in both plants increased by about 0.9%. Furthermore, the result showed that for AT increase from 295K to 330K, the total exergy destruction increased from 13532KW to 14500 KW in JUHEL plant and from 14086KW to 15200 in DANA plant. On component exergy destruction, JUHEL boiler increased from 6778KW to 7593KW while DANA boiler increased from 7789KW to 8652KW. Exergy destruction in both boilers accounted for about 50% and 55.3% of the plants total exergy destruction respectively. However, the condenser and autoclave recorded 16% and 5% of the total exergy destruction in JUHEL plant while the same components recorded 15% and 5% of total destruction in DANA plant.

The Effect of Inlet Boiler Pressure on the Exergy Destruction Rate

The effect of boiler inlet pressure was investigated for pressure range between 10 and 26 bars for JUHEL and DANA plants, Figs.5(a) and (b). The result showed that increase in boiler inlet pressure resulted in decreased exergy destruction and increased exergy efficiency. Moreover, for a pressure increase from 10 to 26bars, the total exergy destruction decreased from 13532KW to 12894KW in JUHEL and to 14086KW to 13478KW in DANA. This showed that exergy destructions in both plants decreased by about 1% for every 0.8% increase in pressure.

CONCLUSION

The study revealed that variations in ambient temperature and other operating parameters such as boiler inlet pressure and air flow rate influences the performance of pharmaceutical plants. Results obtained showed that the energy and exergy efficiencies in JUHEL boiler were found at 30.4% and 17.5% respectively, followed by the distillation unit which recoded 42.3% energy efficiency and 22.6% exergy efficiency. Similarly, energy and exergy efficiencies in DANA boiler were recorded at 22.4% and 16.6% respectively followed by the autoclave unit which recorded 37.3% and 34.3% efficiencies. Other components of the plants which recorded low utilization efficiency include: the steam headers, condensers and preheaters. The analysis of exergy destruction rate showed that for a 1°C increase in ambient temperature, the exergy destruction increases by about 0.9 %. Total exergy destruction for JUHEL and DANA plants was found at 13532KW for JUHEL and 14086KW for DANA. On component exergy destruction, JUHEL and DANA boilers recorded 6778KW and 7789KW which accounted for about 50% and 55.3% of the plants total exergy destruction respectively. However, the condenser and autoclave recorded 16% and 5% of the total exergy destruction in JUHEL plant while the same components recorded 15% and 5% of total destruction in DANA plant.

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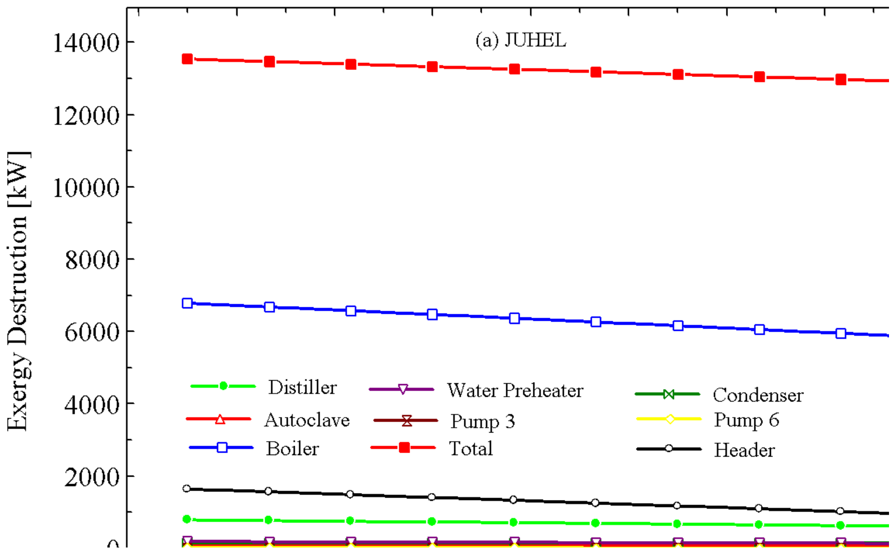


Fig. 5: The effect of boiler inlet pressure on exergy destruction rate (a) JUHEL plant and (b) DANA plant

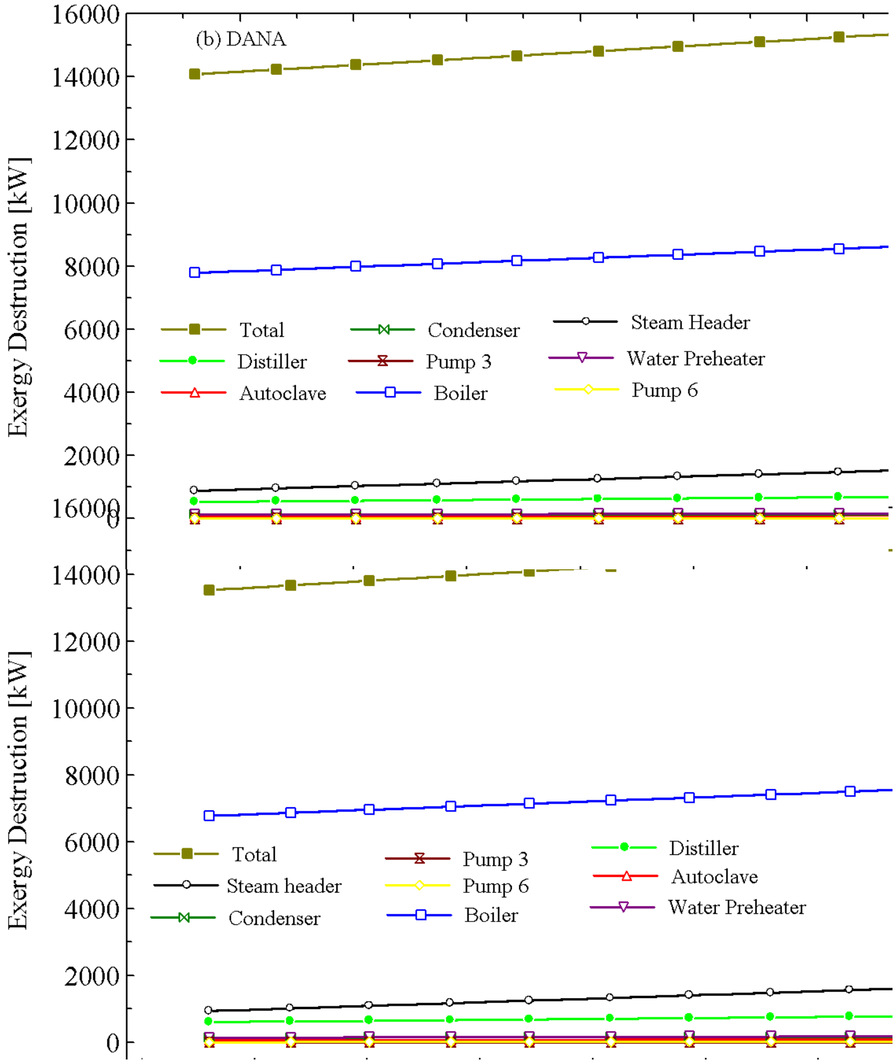
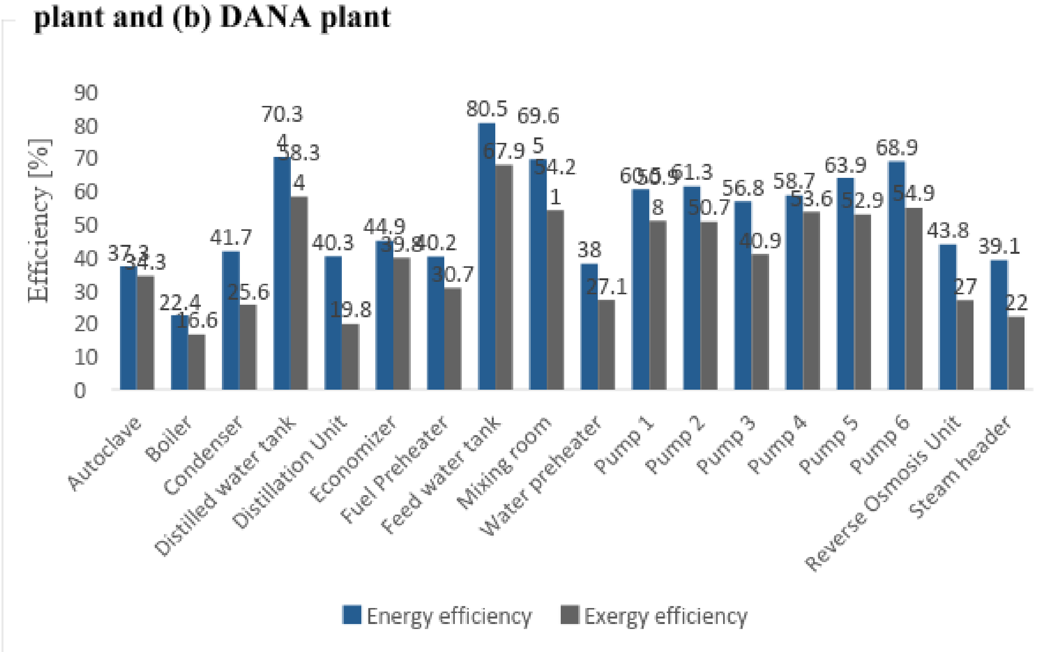


Fig. 4: The effect of ambient temperature on exergy destruction rate in (a) JUHEL plant and (b) DANA plant



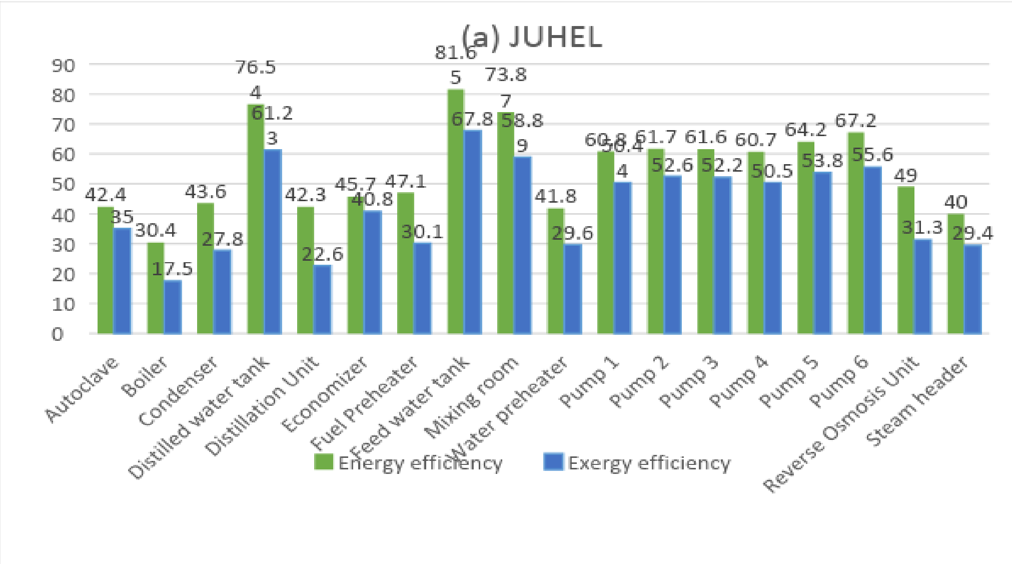


Fig. 3: Utilization efficiency of the plant components based on energy and exergy efficiencies (a) JUHEL plant and (b) DANA plant