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Energetic analysis of fruit juice processing operations in Nigeria

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Abstract

Energy and exergy studies were conducted in an orange juice manufacturing industry in Nigeria to determine the energy consumption pattern and methods of energy optimization in the company. An adaptation of the process analysis method of energy accounting was used to evaluate the energy requirement for each of the eight defined unit operations. The types of energy used in the manufacturing of orange juice were electrical, steam and manual with the respective proportions of 18.51%, 80.91% and 0.58% of the total energy. It was estimated that an average energy intensity of 1.12 MJ/kg was required for the manufacturing of orange juice. The most energy intensive operation was identified as the pasteurizer followed by packaging unit with energy intensities of 0.932 and 0.119 MJ/kg, respectively. 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 be increased to reduce the level of inefficiency of the plant. The suggestion has been limited to equipment modification rather than process alteration, which constitutes additional investment cost and may not be economical from an energy savings perspective.

Keywords: Fruit juice; Energy; Exergy; Processing operations

1. Introduction

Energy is a highly important resource for human and industrial activities. It exists in many forms and can be classified as renewable and non-renewable. Renewable energy sources include solar, hydro (water), wind and geothermal energy. Non-renewable energy sources include fossil fuels and nuclear energy. Most production industries worldwide depend heavily on energy derived from non-renewable resources. This form of energy, obtained mostly from petroleum products, has played a key role in the production processes including those involving heat transfers, mass transfer and mechanical processing and handling [1]. Nigeria is naturally endowed with abundant energy resources including solar, hydro and fossil fuels (petroleum and coal). The major sources of industrial energy in the country are fossil fuels including fuel oil (petroleum), natural gas, coal and, electricity generated by the thermal and hydro power stations. The supply of electricity in the country is in acute shortage due in part to the dearth of underlying power generating technology and old facilities of the power stations, and also due to the problems in the transmission and the distribution of the energy. Consequently most companies in the country now rely mainly on the use of heavy-duty generating plant for the supply of their electrical energy, which is used for operations such as air conditioning, lighting and some machining processes.

The increasing energy demands coupled with the finite energy resources, the rising cost of fossil fuels and the considerable environmental impacts connected with their exploitation necessitate the needs to understand the mechanisms, which degrade the quality of energy and energy systems. The processes that degrade the quality of energy resources can only be identified through a detailed analysis of the whole system. This account for the extensive work that has been done on energy accounting system of

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Nomenclature

c_p	heat capacity (J/kg K)
C_f	calorific value of fuel (J/kg)
E_m	manual energy (J)
E_p	electrical energy (J)
E_t	thermal energy (J)
E_x	exergy (J)
e_x	specific exergy (J/kg)
h	specific enthalpy (J/kg)
H	enthalpy (J)
I	inefficiency
N	number of persons involved in operation
P	rated equipment power (kW)
p	pressure (kN/m^2)
R_s	production of entropy (J/K h)
S	entropy (J/K)
s	specific entropy (J/kg K)
t	time (h)
T	temperature (K)
w	mass flow rates (kg/h)
W	work per unit time (W)
W_f	quantity of fuel (l)
x_s	weight fraction (kg/kg)
η	power factor (assumed to be 0.8)
γ	fuel exergy grade function
ψ	ratio of exergy in products to total exergy input

Subscripts

f	fuel
i	denotes the number of unit operation
j	denotes type of energy ($j=1$ represents electrical energy, $j=2$, manual energy, $j=3$, thermal energy)
k	section of plant; entrance or exit stream
l	heat exchange surface (l_{in}, input; l_{out}, output)
l_w	liquid water
m	manual energy
o	property of the surroundings
p	constant pressure
p	electrical energy
q	process stream (q_{in}, input; q_{out}, output)
r	useful reversible
seo	sum of energy per unit operation
t	thermal energy
tt	total sum of energy
u	useful

many industrial-processing operations with the aim of improving the design and performance of energy transfer systems. These include beverage industry [2], rice processing [3], sunflower oil expression [4], palm-kernel oil processing [5,6], cashew nut processing [7], poultry processing [8], cassava-based foods [9]. Other related works are Miller [10] and Tekin and Bayramoglu [11]. The energy balance analysis is apparently based on the first law of thermodynamics in which information on the system is employed to attempt to reduce heat losses or enhance heat recovery [12]. However, this law is lacking on valuable information on energy degradation and on quantifying the usefulness or quality of the heat content in various streams leaving the process as products, wastes, or coolants.

These limitations of energy balance analysis are overcome by the concept of exergy, which is based on the first law and the second law of thermodynamics, both of which were established by the works of William Rankine, Rudolph Clausius, William Thomson (later Lord Kelvin), von Mayer and Carnot in the 19th century [12]. The first law describes the conservation of energy, while the second law is used to describe the quality and the quantity of energy and material. Exergy is a thermodynamics property of a system that provides a measure of the maximum useful work that a given system may attain as the system is allowed to reversibly transits to a thermodynamic state, which is in equilibrium with its environment. The rest of the energy from the system amounts to energy losses called anergy [12–14]. Exergy analysis entails identifying the useful energy obtainable from an energy source and utilizing this exergy maximally thereby minimizing anergy in the process. The location of energy degradation in a process is possible and this may lead to improved operation or technology. The quality of heat in a reject stream can also be quantified. So the main aim of exergy analysis is to identify the causes and to calculate the true magnitudes of exergy losses. Exergy analysis provides a much more accurate description of the thermodynamic performance of a system, and hence is better able to identify the best opportunities for resource minimization. This suggests that exergy analysis method will identify resource efficiency and resource saving opportunities [15].

Although extensive literature exists concerning the destruction of exergy, only a limited amount of work has been reported on specific study of exergy analysis of many industrial processes. Exergy analysis has been carried out for such industrial processes as cement production [16], nutrient recovery processes [17] and basic metal industries [18] to determine the locations of exergy destructions. Other studies on exergy have been focused on its application to economic planning of industrial operations, household and sectoral energy utilization [19,20]. To the best of the authors' knowledge no work has been conducted on the exergy analysis of fruit juice industries.

The focus of attention in this work is thus to analyse the energy and exergy of fruit juices processing industry in Nigeria. The need for adequate storage and processing, as well as for all year availability of fruits, has made the industry very important and on the forefront of various research works [20]. Fruit juice processing involves operations such as sorting, sterilization, storage mechanism, refrigeration, extraction, mashing and evaporation. These operations require high and regular energy supply to function, thus an efficient energy system is needed. This can be accomplished by a proper understanding of the concepts of exergy. Previous exergy analysis has been carried out on other industrial processes such as food processing [1,21–23] but limited research has been recorded on the fruit juice processing industry. Inefficient industrial energy use could lead to huge economic losses. Excessive energy consumption adds to the costs of goods produced especially in the energy intensive industries. In view of this, attempts should be made for higher efficiency of utilization of fuel, electricity, steam energy and labour, these being the major components of manufacturing cost.

It is revealed from the search of literature that there has not been any study done to determine the energy consumption and exergy analysis in the processing operations of fruit juice in Nigeria. A careful study of energy, entropy and exergy is required to improve the design and performance of energy-transfer system. The objectives of the study were to determine the energy consumption pattern and inefficiency in exergy expenditure of the plant. The quantities of exery losses and waste were determined and located, and ways to address these losses and wastes were suggested.

2. Methodology

A fruit processing plant located in western Nigeria was selected for this study. There are eleven unit operations in this plant as shown in Fig. 1. Fruits were received and weighed by the use of master weighing machines which is capable of weighing truck loaded with fruits. The exact weight of fruits was obtained by subtracting the weight of vehicle when empty from its weight when loaded with fruits. The received fruits were loaded by the use of a basket conveyor into the bin house where they were stored for about 3 days before processing commenced. The bin house is cuboids in shape with a capacity of about fifteen thousand tonnes. Inside the bin house are various segments or platforms that are maintained at refrigerating temperature to prevent fruits from decay.

Fruits processing began by sorting out the bad fruits manually from those to be processed. The remaining fruits were cleaned by a machine that was specially designed for washing fruits so as to get rid of dirt and other unwanted particles. Incorporated with this machine was a conveyor for carrying the fruits, fibre brush for washing and water pipes for water supply into the machine. The fruits are then grated during which the outer covers of the fruits that can cause the bitterness of the extracted juice are slightly removed so as not to damage the fleshly part. The grater is incorporated with grating rollers, electric motor and water pipes.

The fruit juice is extracted from the fruits by crusher and then screw finished to separate the seeds from the juice. The juice is subsequently centrifuged to give clarity to it and stored temporary in the holding tank where it is blended with other components. Further processing of the juice extracts is carried out in the pasteurizer where the micro-organisms present in the juice extracts are eliminated by the use of heat from the steam generated by the boiler unit. The juice must not be heated beyond certain temperature to prevent the juice from loosening its natural qualities. The fruit extracts is eventually packaged in the packaging unit which consists of the following machines-aseptic filler, capping machine, carton packer and shrink wrapper.

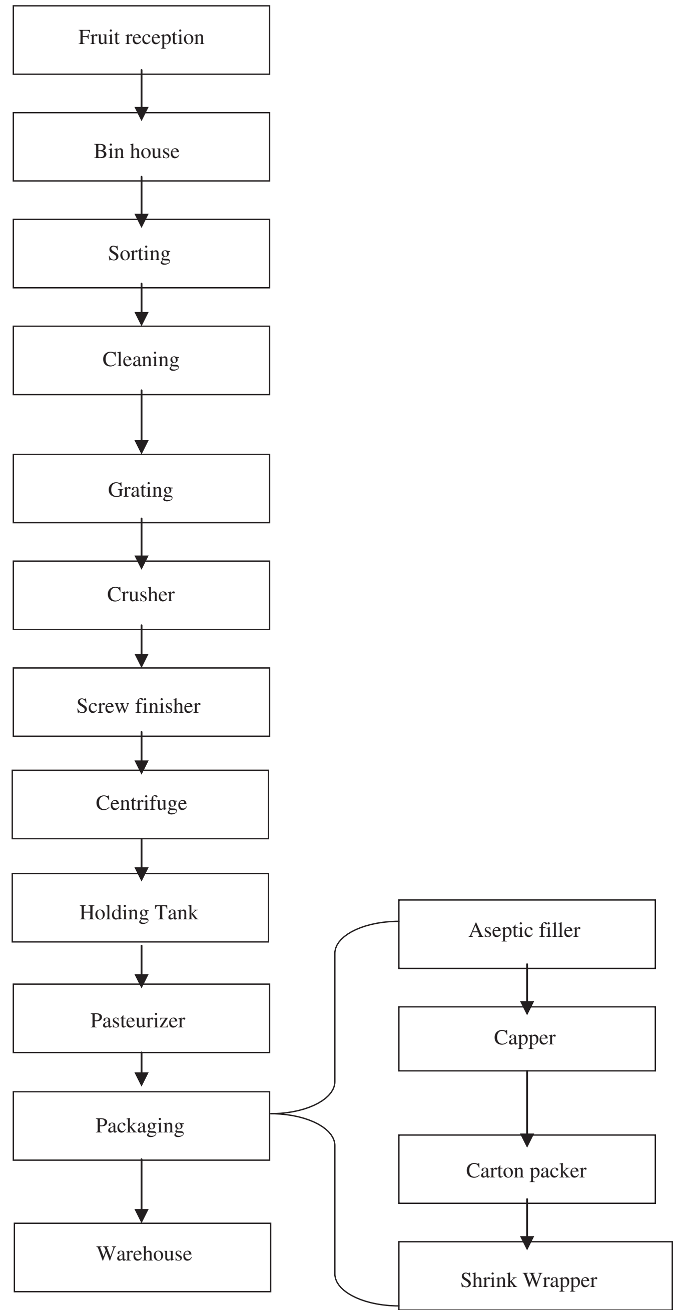

Fig. 1. Flow diagram of the fruit juice processing operation.

All of the above operations run on batch process. The account of energy input into each of these operations was determined by noting and quantifying the type of energy used, which are either one or a combination of electrical, thermal and manual energy. All electric motors in the plant were identified, and the amperage and horsepower rating, number of phases and voltage were noted to enable the estimation of electrical energy.

2.1. Data acquisition

The plant utilized electrical, steam, chemical and manual energy for production. For simplicity and purpose of data collection the production process was divided into eight unit operations. The total processing period was about 20 days long and adequate availability of energy during this period is of high importance. The required parameters for evaluating energy and exergy in each unit operation of orange juice processing were either measured directly or collected from the production factory.

An inventory of the motors and power rating of the machines were made. Most of the parameters were obtained from the factory's energy department. The data were collected from the factory over a period of 2 months. The measuring quantities used in the course of the data acquisition include (i) a stopwatch for measuring the time spent in each unit, (ii) a measuring cylinder for measuring the amount of fuel consumed and (iii) a weight balance for measuring the quantity of orange fruits used. The data for energy input into each of the unit operations are presented in Tables 1 and 2. The sensitivities of the apparatus used in the course of the study were calculated as detailed in Table 3 and the error analysis of the data was performed using the following equation:

$$error = \frac{measured\ value - true\ value}{true\ value} \times 100\%. \quad (1)$$

2.2. Estimation of energy input into each unit operation

The energy components from each source were calculated for 10,000 kg of orange fruits by using the following procedure:

2.2.1. Electrical energy

The electrical energy usage by the equipment was obtained as the product of the rated power of each motor and the number of hours of operation. A motor efficiency of 80% was assumed to compute the electrical inputs [4].

Mathematically

$$E_p = \eta P t, \quad (2)$$

where E_p is the electrical energy consumed in kWh, P the rated power of motor in kW, t the hours of operation in h and η the power factor (assumed to be 0.8).

2.2.2. Manual energy

This was estimated based on the values recommended by Odigboh [24]. According to him, at the maximum

Table 1
Required parameters for evaluating energy and exergy in orange juice production

Unit operation	Required parameters	Value
Sorting	Number of persons involved in sorting	4
	Time taken for sorting (h)	5
Cleaning	Electrical power (kW)	4.48
	Time taken for cleaning (h)	5
	Number of persons involved in cleaning	2
Grating	Electrical power (kW)	5.97
	Time taken for grating (h)	6
Crusher	Electrical power (kW)	17.90
	Time taken for grating (h)	6
Screw finisher	Electrical power (kW)	5.97
	Time taken for screw finishing (h)	6
Centrifuge/holding tank	Electrical power (kW)	7.46
	Time taken (h)	6
	Weight fraction of water in juice (kg/kg)	0.96
	Temperature of surrounding (K)	298
	Juice inlet temperature (K)	298
	Juice outlet temperature (K)	310
	Density of orange juice (kg/l)	1.018
Pasteurizer	Electrical power (kW)	15.01
	Time taken for Pasteurizing (h)	6
	Steam mass requirement (kg/h)	4500
	Weight fraction of water in juice	0.96
	Steam inlet temperature (K)	453
	Temperature of surrounding (K)	298
	Juice inlet temperature	310
	Juice outlet temperature	371
	Density of orange juice (kg/l)	1.018
Packaging	Electrical power (kW)	65.42
	Time taken for packaging (h)	6
	Number of persons involved in packaging	35
	Temperature of surrounding (K)	298
	Juice inlet temperature (K)	371
	Juice outlet temperature (K)	311

Table 2
Operating parameters for generators, boiler and orange juice

Generators operating conditions	
Power factor (PF)	0.8
KVA	500
KW	400
Load during production	60–75%
Diesel usage (l/h)	85
Boiler operating conditions	
Mass steam requirement (kg/h)	4500
Diesel usage (l/h)	75
Operating temperature (°C)	180
Operating pressure (bar)	7–9
Orange juice	
Mass flow rate of juice (kg/h)	1289.47
Heat capacity of juice (kJ/kg K)	4.0858
Heat capacity of water (kJ/kg K)	4.1868

Table 3
Sensitivities of apparatus used in the study

Equipment	Precision at good maintenance (%)	Accuracy at good maintenance (%)	Accuracy at no good maintenance (%)
Measuring cylinder	0.01	0.02	0.02–0.04
Stop watch	0.02	0.03	0.03–0.07
Weighing balance	0.03	0.05	0.05–0.10
Thermocouples	0.05	0.06	0.06–0.10

continuous energy consumption rate of 0.30 kW and conversion efficiency of 25%, the physical power output of a normal human labourer in tropical climates is approximately 0.075 kW sustained for an 8–10 h workday.

Mathematically,

$$E_m = 0.075Nt \ \ (\mathrm{kWh}), \tag{3}$$

where 0.075 is the average power of a normal human labour in kW, N the number of persons involved in an operation and t the useful time spent to accomplish a given task in hours.

2.2.3. Thermal energy

The thermal energy derived from the fossil fuel (diesel) which is used to run the internal combustion engine for the generation of electrical power and the quantity of diesel used in the steam boiler was estimated by multiplying the quantity of fuel consumed by the corresponding calorific value of the fuel used [25].

Mathematically,

$$E_t = C_f W, \tag{4}$$

where E_t is the thermal energy consumed (J), C_f the calorific value of fuel used (J/l) and W the quantity of fuel used (l).

The energy usage for stages out of production such as plant start-up, shutdown and plant cleaning/sterilization has been included in the energy sequestered in each of the operations.

2.3. Enthalpy and enthalpy change

The heat energy evolved by steam is measured by a property known as enthalpy (H). At constant pressure, the thermal effect for the reaction is obtained from the enthalpy of vapourization. This is the difference in the enthalpy between the vapour and the liquid state of steam.

2.4. Exergy model equations

Exergy E_x for a closed system may be defined mathematically as [12,14,26]

$$E_x = V(p - p_o) - S(T - T_o) - \sum_i n_i(\mu_i - \mu_{io}). \tag{5}$$

The exergy of a flow crossing the system boundaries of an open system can be writen as

$$E_x = (H - H_o) - T_o(S - S_o) - \sum_i \mu_i(n_i - n_{io}), \tag{6}$$

where

$$H = U + p_o V. \tag{7}$$

In the above equations, the extensive quantity, U denotes the internal energy, S the entropy, H the enthalpy, V the volume and n_i the number of moles of substance i, and the intensive quantity T the temperature, p the pressure and μ_i the chemical potential of the substance i. The subscript "o" denotes the conditions of the reference environment. The third term in Eqs. (5) and (6) takes account of the contribution due to the chemical transformation of the system. This term is neglected in this study because the processes involved no chemical reaction.

The exergy difference ΔE_x between the outgoing and incoming streams for a steady flow process is defined as

$$\Delta E_x = \dot{W}_u - T_o \dot{R}_s, \tag{8}$$

where $\dot{W}_u$ is the useful work, R_s the production of entropy and T_o the ambient temperature. The exergy difference ΔE_x is defined in terms of each component exergy $e_{x,q}$ per unit mass and the mass flow rate w_q:

$$\Delta E_x = \sum_{q_{out}} w_q e_{x,q} - \sum_{q_{in}} w_q e_{x,q}, \tag{9}$$

where each component exergy is defined as

$$e_{x,q} = h_q - T_o s_q. \tag{10}$$

From Eq. (8) it is obvious that the exergy change is a balance of useful work and the entropy production term, which can be regarded as work lost because of irreversibilities. For a reversible process, $\dot{R}_s = 0$ and thus, the exergy change of a reversible process equals to most the useful work associated with a work-producing process or the least useful work required by a work-consuming process. It is evident from the foregoing that the exergy change and the creation of entropy are the energy bounds of the process or set of processes.

2.5. Utilities exergy

All energy requirements result in the usage of primary utilities such as fuel, cooling water, steam, hot air and electricity. Electrical utilities are however included in the useful work, $\dot{W}_u$, term. Process streams consist of raw materials, products, wastes and intermediate materials, which are produced as the raw materials undergo the corresponding transformation. In order to produce an energy-efficient design, it is often desirable to separate heating and cooling utilities streams from process streams in Eq. (8). It follows that:

$$\Delta E_{x,proc} = \dot{W}_u + \Delta E_{x,util} - T_o \dot{R}_s, \tag{11}$$

where the change in utility exergy $\Delta E_{x,util}$, which in this work consists of steam only, can be determined through the following expression:

$$\Delta E_{x,\,util} = H_{util,\,1} - H_{util,\,2} - T_o(S_{util,\,1} - S_{util,\,2}). \tag{12}$$

The enthalpies and entropies of steam can be obtained from the standard data table. The exergy change of the process stream can be determined using Eqs. (8) and (9), which may be evaluated by using the tabulated data for enthalpies and entropies or by using predictive equations based on specific heat capacity. The most simple equation to estimate the exergy changes corresponding to the case of constant specific heat capacity and negligible residual exergies over the temperature range being considered [27] is

$$e_{x,2} - e_{x,1} = c_p(T_2 - T_1)\left[1 - \frac{T_o}{(T_2 - T_1)_{ml}}\right], \tag{13}$$

where

$$(T_2 - T_1)_{ml} = \frac{T_2 - T_1}{\ln(T_2/T_1)}. \tag{14}$$

The specific heat constant of fruit juice can be determined by using the following expression:

$$c_p = c_{lm}(0.3823 + 0.6183x_m), \tag{15}$$

where x_m is the weight fraction of water juice.

2.6. Inefficiency

Exergy study allows a system to be analysed more comprehensively by determining where in the system the exergy is destroyed by internal irreversibility and its causes. Inefficiency can be defined as the ratio of the irreversibility in each section to the irreversibility over all sections. This is defined mathematically as

$$I_k = \frac{(T_o\dot{R}_s)_k}{\sum_k^{all\ sections}(T_o\dot{R}_s)_k}. \tag{16}$$

2.7. Work production and electricity generation from fossil fuel

Shaft work is produced from electric and fossil-fuel work production. The efficiencies for shaft work production from electricity are [34]:

$$\eta_{m,e} = W/W_e, \tag{17}$$

$$\psi_{m,e} = E^W/E^{W_e} = W/W_e = \eta_{m,e}. \tag{18}$$

For fuel, these efficiencies are:

$$\eta_{m,f}(W/m_f H_f), \tag{19}$$

$$\psi_f = E^W/m_f\varepsilon_f = W/m_f\gamma_f H_f = \eta_{m,f}. \tag{20}$$

The efficiencies for electricity generation from fossil fuel are:

$$\eta_{e,f} = W_e/m_f H_f, \tag{21}$$

$$\psi_{e,f} = E^{W_e}/m_f\varepsilon_f = W_e/m_f\gamma_f H_f \cong \eta_{e,f}. \tag{22}$$

It can therefore be inferred that the exergy efficiencies for electricity generation process can be taken as equivalent to the corresponding energy efficiencies.

The efficiencies for the fossil fuel-driven kinetic energy production processes, which produce a change in kinetic energy Δke in a stream of matter m_s, are as follows [34]:

$$\eta_{ke,f} = m_s\,\Delta k\,e_s/m_f H_f, \tag{23}$$

$$\psi_{ke,f} = m_s\,\Delta k\,e_s/m_f\varepsilon_f, \tag{24}$$

$$= m_s\,\Delta k\,e_s/m_f\gamma_f H_f = \eta_{ke_f}. \tag{25}$$

3. Results and discussions

The energy and exergy accounting data were analysed based on an input of 10 tonnes of orange fruits during an 8-h working shift. The primary source of electrical energy used in the factory was either from the national grid or from the company's power generating set. During production, the electrical energy was supplied mainly from one of the three power generating units with the others on stand by. The electrical energy and exergy consumption data for all equipments requiring electrical energy were obtained as well as their operating time. Steam energy and exergy data were obtained from the boiler equipment. The fuel used for generating steam was diesel and its quantity was determined based on diesel consumption on an hourly basis. Manual energy and exergy data were obtained based on a total of 50 workers per shift out of which about 41 workers were involved in the production process due to the automation level of the factory.

3.1. Energy expenditure

Analysis of data on total energy consumption by the plant provides useful information on the energy sources available. The daily diesel consumption required for generating electrical energy and boiler diesel consumption for steam generation during the 20-day processing period is presented in Fig. 2. As can be seen in the figure, diesel fuel is the primary source from which both electrical and steam energy consumed in the industry is generated. At the initial stage of production the mass flow rate of the fruits being processed through the energy intensive equipment was low, hence the minimal amount of diesel consumed. As the processing days increase the amount of fruits processed increased and the load on the equipment was at its peak hence the energy consumed was high. This explained why diesel consumption at this period was high. It can also be seen that the diesel consumption by the generating set was higher than that of boiler for more than 80% of the production days implying that electrical energy demand in the company is more that the steam energy. This becomes evident if all the electrical energy requires for lighting and cooling load is estimated.

Fig. 3 depicts the type of energy used by percentage of total energy cost in fruit juice processing operations. The average hourly diesel consumption by the generating set and the boiler was 85 and 75 l, respectively. During the 20 days processing period a total of 18,967 and 10,323 l of diesel was consumed by the generator and the boiler, respectively. This means of procuring energy is extremely expensive since a litre of diesel in the country is about ₦ 115.00 (US $ 0.96) and the energy cost represented about two-third of the total cost of production. The electrical energy consumption accounted for about 65% of the total energy cost while the remaining 35% is contributed by the cost of the thermal energy.

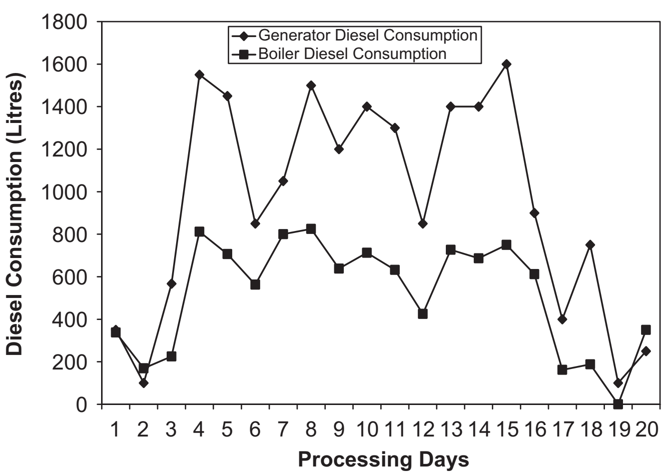

Fig. 2. Daily diesel consumption for orange juice processing.

The total energy requirements for the eight defined unit operations are exemplified by the time and energy use data in Table 4. For this case study, the total energy consumption per 10 tonne of orange fruit was estimated to be 11,196.46 MJ while the average energy intensity was 1.12 MJ/kg. The mean values of errors between the measured value and true value for total energy consumption and energy intensity were 0.125 and 0.023, respectively. The standard deviation of the differences and the worst-case error for the two indices were, respectively, 0.152 and 0.06. The proportion of the electric, thermal and manual energy in the total energy consumption is 18.51%, 80.91% and 0.58%, respectively. It can be seen from the table that the most energy intensive unit was the pasteurizer, which accounted for round 83.22% of the total energy input, followed by the packaging unit with 10.60%, totally both 93.82% of the energy. Sorting unit consumed the least energy, which is about 0.05% of the total energy input. This variation in the energy consumption by each unit operation is a function of the type of operation in addition to other operational factors such as the age of the equipment and the extent to which available plant capacity is used.

For steam energy obtained from diesel fuel, the energy intensity value was 0.906 MJ/kg. This signified the highest amount of consumed energy. Similar results have been obtained for other food processing industries [1,28]. The energy intensity for manual energy was 0.00648 MJ/kg representing the least type of energy consumed. This was as a result of the level of mechanization of the industry. Fig. 4 shows a diagram of an energy account and mass flow of the process stream based on symbols suggested by Singh [29]. It clearly presents all unit operations, the energy consumed by these operations and the mass flow of the process stream

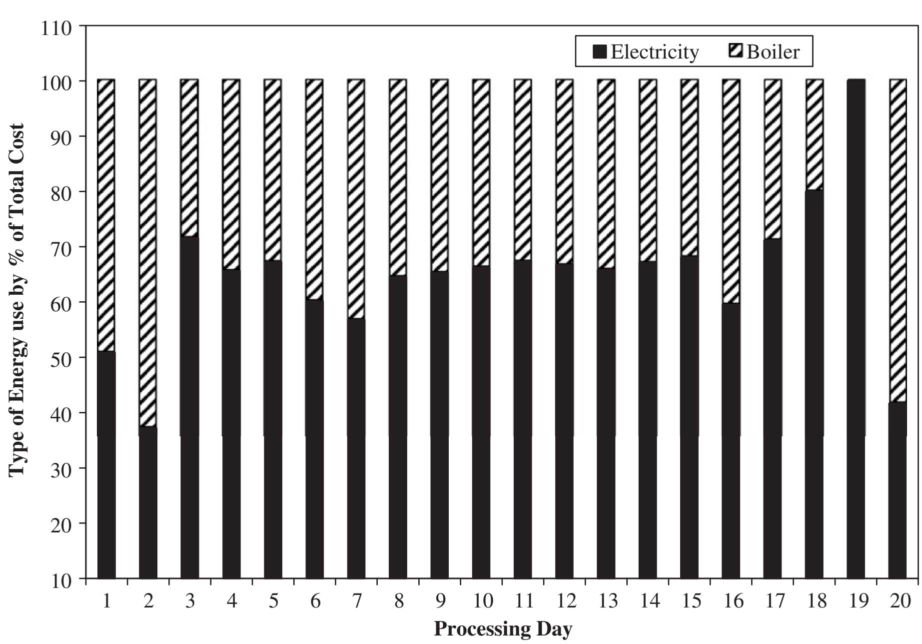

Fig. 3. The type of energy used by percentage of total energy cost in fruit juice-processing operations.

Table 4
Time and energy use data in orange juice processing

i		Operation time (h)	Electrical energy, $E_{p,i}$ (MJ)	Thermal energy, $E_{t,i}$ (MJ)	Manual energy, $E_{m,i}$ (MJ)	Total energy, $E_{seo,i}$ (MJ)	$(E_{seo,\ i}/E_{tt}) \times 100$ (%)
1	Sorting	5.00	–	–	5.40	5.40	0.05
2	Cleaning	5.00	64.43	–	2.70	67.13	0.60
3	Grating	6.00	90.20	–	–	90.20	0.81
4	Crusher	6.00	309.26	–	–	309.26	2.76
5	Screw finisher	6.00	90.20	–	–	90.20	0.81
6	Centrifuge/ holding tank	6.00	128.86	–	–	128.86	1.15
7	Pasteurizer	6.00	259.20	9,059.40	–	9,318.60	83.22
8	Packaging	6.00	1,130.11	–	56.70	1,186.81	10.60
	Total		$E_{p,tt} = 2072.26$	$E_{t,tt} = 9059.40$	$E_{m,tt} = 64.80$	$E_{tt} = 11{,}196.46$	100.00
	Percent of total (%)		18.51	80.91	0.58	100.00	

$$E_{p,tt} = \sum_{i=1}^{8} E_{p,i},\quad E_{t,tt} = \sum_{i=1}^{8} E_{t,i},\quad E_{m,tt} = \sum_{i=1}^{8} E_{m,i},\quad E_{seo,i} = \sum_{j=1}^{3} (E_{te,i})_j,\quad E_{tt} = \sum_{i=1}^{8} E_{seo,i}.$$

through the production stages, starting from the raw materials, waste product, and intermediate material to the final products. It should be noted that after the crushing process, the mass flow through the remaining processes took place at steady rate.

3.2. Exergy expenditure

Despite the widespread use of energy analysis to describe industrial systems, it alone can frequently give an incomplete and misleading picture of the resource efficiency of a process and the opportunities for resource minimization [30]. Conceptually the exergy calculation was divided into process stream and steam exergies. These exergies are incorporated together in Eq. (11) from which the entropy production in the system can be determined. Exergy accounts for individual process were presented in order to identify major losses and evaluate the potential for further technical improvements in the manufacturing processes. The results obtained for the different stages represent an overall evaluation of the manufacturing process from an exergy perspective.

Exergy analysis has been applied to the overall production of orange juice by the evaluation of the unit processes involved in production. Table 5 presents the exergy change in juice, useful work, steam exergy, entropy generated and the inefficiency associated with each unit operation. The change in the juice exergy is only associated with operations where there is change in the inlet and outlet temperatures of the juice. Consequently there is exergy change in the centrifuge-holding tank, pasteurizer and packaging operations. There is no exergy change in the sorting, cleaning, grating, crushing and screw finishing operations because these operations take place without any appreciable change in temperature between the inlet and the outlet of the processes. The negative value of exergy change during packaging was due to the drop in temperature of the juice during the process. The exergy of the coolant used for cooling the juice after pasteurizing was neglected because its effect is minimal.

The useful work input comprises of both electrical and manual energy. This is because electrical energy is an energy source that consists of pure exergy while the inability to account for the entropy generated by a human labourer justified its inclusion in the useful work. The highest entropy was generated in the pasteurizer followed by packaging and crushing unit with respective values of 18,630.81, 1364.92 and 309.26 MJ. The corresponding inefficiency of the pasteurizer, packaging and crushing unit is 90.09%, 6.60% and 1.50%, respectively, while the sum total of the inefficiencies in the remaining five units is just 1.81%. The high entropy generated in the pasteurizer is due to the irreversibility within the system as a result of high temperature difference between the inlet and outlet stream of the juice in the pasteurizer. This results show that heating process is highly inefficient. This is always the case for exergy calculations and is due to the fact that the exergy value of heat is often much lower than its energy value, particularly at temperatures close to reference temperature [31]. The high destruction of exergy implies that the energy has lost some of its ability to produce work resulting in reduction in its quality.

Although direct comparison of the results of this work is not possible because of lack of reports on similar processes, but the present results show good trend with the results of some previous related works. For example, the 90% inefficiency in the pasteurizer compared well with the 68% inefficiency in the evaporator unit of a tomato paste production plant [27] and the 73% inefficiency of the preheater unit of the Tanzanian Portland Cement Company [32] judging from the fact that the percentage rating of the inefficiency is a relative value. These two plants consist of many units where the contributions of utilities exergy change are significantly high.

The high exergy destruction in the pasteurizer may be reduced by an increase in the capacity of the holding tank

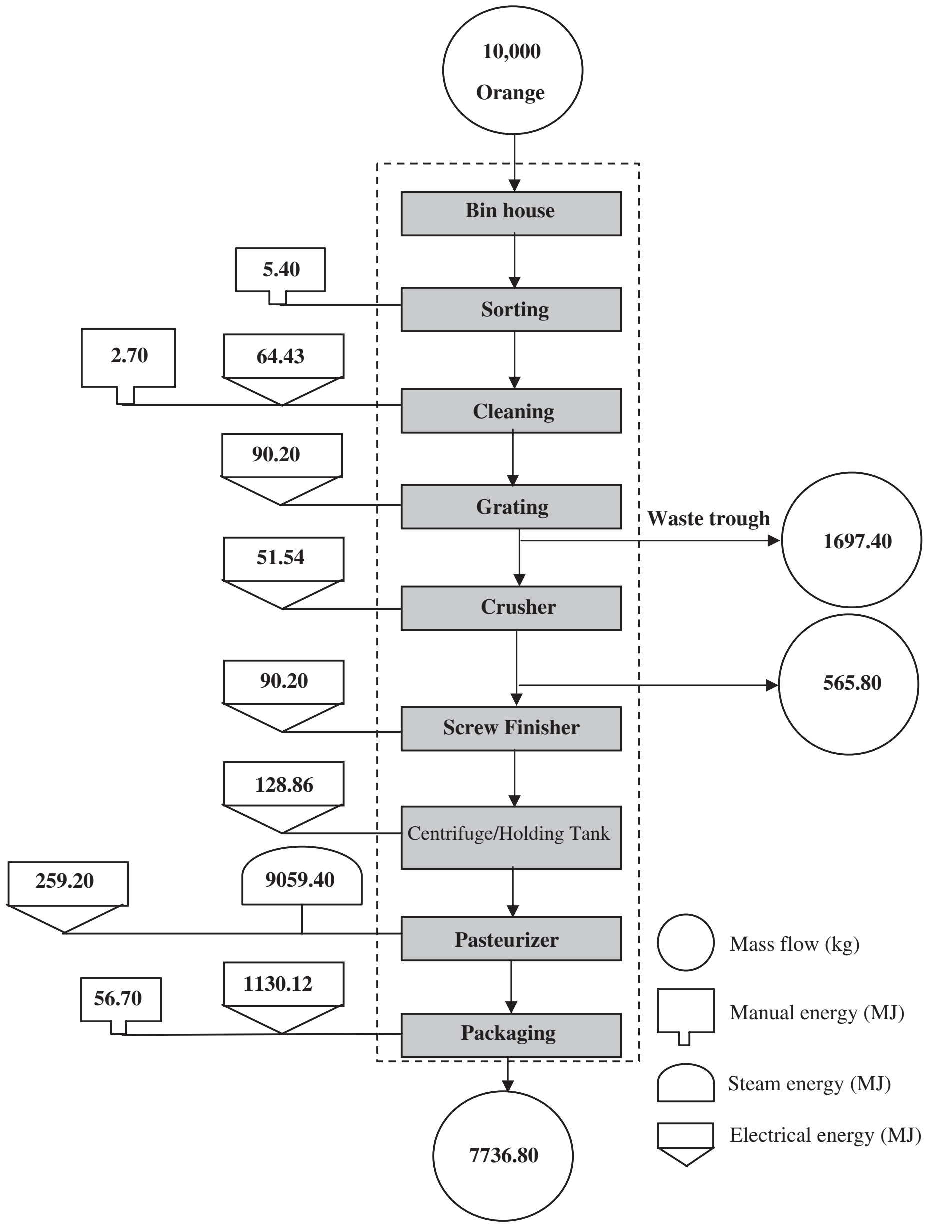

Fig. 4. Energy accounting and mass flow diagram for orange juice processing.

Table 5
Exergy balance in an orange juice processing plant

Unit operation	Exergy change of the juice (MJ)	Useful work (MJ)	Utilities exergy change (MJ)	Production of entropy (MJ)	Inefficiency (%)
Sorting	–	5.40	–	5.40	0.03
Cleaning	–	67.13	–	67.13	0.32
Grating	–	90.20	–	90.20	0.44
Crusher	–	309.26	–	309.26	1.50
Screw finisher	–	90.20	–	90.20	0.44
Centrifuge/holding tank	7.22	128.86	–	121.64	0.59
Pasteurizer	236.41	259.20	18,608.02	18,630.81	90.09
Packaging	−234.81	1130.11	–	1364.92	6.60
Total	8.82	2080.36	18,608.02	20,679.56	100.00

which will result in the reduction of the load on the boiler following similar suggestion made by Dalsgärd [33]. This will enable a longer production time and thus reduce avoidable energy wastage and the corresponding exergy destruction that will occur by plant start-up, shutdown, cleaning and sterilization. If this suggestion is taken, it may help the company to reduce its high expenditure on energy and thus improve the profit margin. Another way to reduce the high exergy destruction in the pasteurizer is by the introduction of the heat integration between the pasteurizer and the packaging units. Heat integration for minimum utilities consumption corresponds to minimum production of entropy as well as to minimum ideal work given away by the process utilities streams [27].

4. Conclusions

An energy and exergy analysis was conducted in an orange juice manufacturing industry. Results of the energy analysis showed that electricity and steam energy are the major types of energy sources used in the processing of the orange juice. The company used as the case study depended largely on the use of electrical energy generated by the company's generator, which is not cost effective. The total energy intensity for the fruit juice production was 1.12 MJ/kg.

The exergy analysis was conducted by the use of an exergy balance of the unit operations in the industry. The exergy destruction was pinpointed and the degree of thermodynamic imperfection of the processes was determined. The major exergy loss took place at the pasteurizer with an inefficiency of over 90%, this was as a result of the use of steam for the heating of the process stream. One method of improving the thermodynamic performance of the plant is by the use of process heat integration. It is necessary to repair any leakage on the steam pipelines to reduce lost of energy. Improvement of the electrical power supply from the national grid is extremely important for cost effective manufacturing.

It can be seen that high-quality energy is usually more costly but exergy analysis can provide insights into cost effectiveness through the conduct of the account of irreversibility gains or energy capability reductions associated with such changes and temperature degradation, elevation or head loss and composition changes. It can be concluded that exergy balance is a powerful diagnostic tool to identify and quantify energy degrading processes since it enables the types, locations and quantities of energy losses to be evaluated for the analysis, design and improvement of energy systems.

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