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RELATIONSHIP BETWEEN EXERGY, ENERGY, ECONOMICS AND ENVIRONMENT

F.N.* Osuolale and O.O. Ogunleye

**Department of Chemical Engineering,
Ladoke Akintola University of Technology, Ogbomoso**

***Corresponding author. E-mail:funmikorede@ yahoo.com. Phone no 080-544-591-43**

ABSTRACT

Exergy analysis of processes has gained popularity overtime and has been used in detecting, quantifying and minimising inefficiencies in processes. This paper illustrates these and goes a step further in showing the relationship between exergy, energy, economics and environment. In today's world of energy sensitivity, environmental concern and economics nose diving an understanding of exergy and its impact among these ties becomes highly significant. The study shows the potential usefulness of exergy analysis in solving energy related environmental problems, and in reducing cost of operating and designing processes and hence, ultimately leading to sustainable development.

Keywords: Exergy analysis, energy analysis, exergoeconomics, environment and sustainable development

INTRODUCTION

Process industries are large consumers of energy. Chemical industries consumed more than one third of the energy used by all manufacturing process.(U.S department of energy,2004) The finite sources of energy, the energy crises of the 1970's as well as the attendant environmental implications of unutilised energy released to the environment has necessitated the need for efficient use of energy. The concern is not only for stakeholders in the industries but academia alike to develop methodologies for achieving this.

Process design Engineers are faced with the dilemma of innovative design that will result in reduction of both capital costs and energy costs of processes and / or dynamic modifications of existing processes for greater efficiency of such processes. In this regard thermodynamic analysis of processes is applicable. The thermodynamic analysis is based on the second law of thermodynamics rather than the first law and has been applied through pinch analysis, equipartition principle and exergy analysis (Demirel, 2004). In the recent past, heat integration of processes have been carried out using pinch analysis with the resultant energy saving in processes that led to the retrofitting of some and evolving of energy efficient new processes (Al-Riyami et al.,2001). Pinch methodology however is restricted to analysing for minimum utility consumption in processes and or minimum number of heating units for heat exchange equipments such as heat exchangers, heaters and coolers. Exergy analysis is one method of analysis that overcomes this restriction and encompasses the total energy systems in processes including distillation columns, turbines, compressors, reactors and pumps. Exergy analysis is a measure of the quality of energy and is the maximum work produced or the minimum required depending on weather the system produces or requires work in bringing the system through reversible process with the environment.

Exergy being a measure of the quality of energy allows costing of the utilized energy in every part of the production route in any giving process. Detection of inefficient processes in terms of energy and cost allocation makes room for development of efficient process which will lengthen reserves of existing energy sources and allows for optimum usage of material thereby ultimately leading to sustainable development. This makes energy-economics a prime target. Also, increasing awareness of the environmental concerns such as ozone layer depletion, acid rain and global climate change demand need for close minimization of the impacts of emissions as a result of utilized energy to the environment. This can be brought about by increasing the efficiency of resource utilization and thus bringing about the energy-environment link into limelight. One major link between all these players is exergy

This study therefore is set to give more light on the links between exergy and energy, economics and environment.

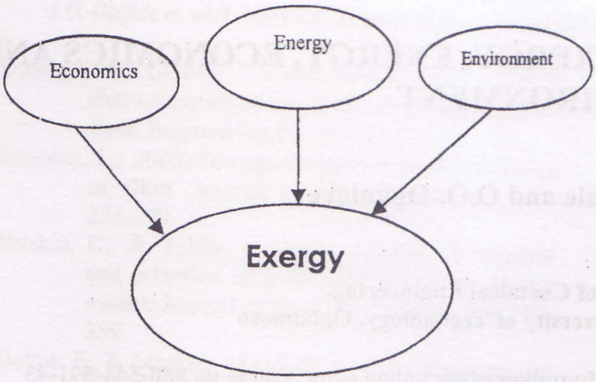

Figure 1: The energy-economy-environmental link of exergy

CONCEPT OF EXERGY

The first law of thermodynamics is about conservation of energy. Energy can not be destroyed but can be transformed from one form to the other. First law for an open system is written as

Input –output = accumulation 1

The energy input consist of all the net heat transferred ΣQ; all the net external work transferred ΣWs; and the energy brought into the system as a result of mass entering it $\sum m_1\left(u' + pv + \frac{v_2}{g_c} + \frac{g_z}{g_c}\right)_1$

The energy output is the energy associated with the mass leaving the system

$\sum m_2\left(u' + pv + \frac{v_2}{g_c} + \frac{g_z}{g_c}\right)_2$

The energy accumulated in the system

$\int dm\left(u' + pv + \frac{v_2}{g_c} + \frac{g_z}{g_c}\right)$

Substituting the given equations in equation 1 while neglecting the potential and kinetic energy terms and assuming a steady state flow gives:

$\Sigma Q + \Sigma Ws = \sum m_2(u' + pv)_2 - \sum m_1(u' + pv)_1$ 2

$\Sigma Q + \Sigma Ws = \Sigma m_2 h_2 - \Sigma m_1 h_1$ 3

The sigma summation takes care of the fact that there may be more than one inlet and outlet stream and here the convention that heat and work entering the system be taking as positive is used.

The second law however deals with entropy generation with-in the systems and for an open system, it is given as (Holman, 1980)

Entropy production =Entropy outflow-Entropy inflow + Entropy accumulation. 4

The entropy outflow is giving by $m_2 s_2$ where s_2 is the entropy per unit mass flow at exit. The entropy inflow includes that of mass transport $m_1 s_1$ and from heat at control volume boundary $\sum Q/T_o$. The entropy accumulation is given by $\int(d(ms))$. For a steady state flow, substituting all the terms in equation 4 gives

$\sum m_2 s_2 - (\sum m_1 s_1 + \sum Q/T_o)$ 5

$\sum Q = \sum T_o m_2 s_2 - \sum T_o m_1 s_1$ 6

Exergy analysis combines the principles of conservation of mass and energy as well as the second law of thermodynamics. It was introduced by Keenan and Rant in 1950's as a tool for process analysis (Hinderink et.al., 1996, Cornellissen, 1997). Exergy is the maximum available work which can be obtained when a system is compared with a reference environment which is assumed to be in equilibrium and enclose other systems. Combining equations 3 and 6 gives the available work Ws as

$Ws = m(\Delta h - T_o \Delta s) = \Delta B$ 7

$Ws = \Delta H - T_o \Delta S = \Delta B$ 8

Exergy is conserved when a system is at equilibrium with the environment that is, all processes of the system and the environment are reversible. However, in real processes, irreversibility I always occur and hence leads to loss or destruction of exergy. The thermodynamic imperfections of processes are quantified as exergy destruction which is the wasted potential for the production of work.

$I = W_s - \Delta B$ 9

Exergy analysis of a system determines how well a system is performing compared to its optimum possible performance. It reveals the room for the improvement in the process. Exergy analysis of a system also quantifies the losses and wastes in a system, determines the location of losses and waste in the system as well as types of losses in the system.

Exergy Calculation

In exergy analysis of open systems, the three governing equations that are normally used are conservation of mass equation, conservation of energy equation and exergy balance equation (Bejan, 1997; Rosen and Dincer, 2003). The reference surrounding needs to be carefully considered. The departure from the reference environment is a function of the irreversibility of the system. Exergy of a system in dry season may be more than the exergy of the same system in wet season depending on the chosen reference. A common ambient temperature and pressure are $T_0 = 298^0K$ and $P_0 = 1$ atm (Cornelissen, 1997).

In calculating exergy of streams, the chemical terms, physical terms and mixing terms are commonly used where the chemical term is

$$B = m\left[\sum_j \left(\mu_j^* - \mu_{0,j}\right) x_j\right] \qquad 10$$

The physical term is

$$B = m\left[(h - h_0) - T_0(s - s_0)\right] \qquad 11$$

The mixing term from the concept of exergy change of mixing is described by (Smith et al., 2001)

$$\Delta_{mix} m = m - \sum x_i m_i \qquad 12$$

By using enthalpy and entropy changes of mixing, the basic energy equation can still be applied.

$$\Delta_{mix} B = \Delta_{mix} H - T_o \Delta_{mix} S(T,P) \qquad 13$$

2.2 Entropy

Entropy has three components, thermal, pressure and mixing.

The thermal entropy component is evaluated as

$$\Delta S_T = \frac{\Delta H}{T - T_o} \ln \frac{T}{T_o}$$

The pressure component is given by

$$\Delta S_p = -R \ln \frac{P}{P_o} \qquad 15$$

And the mixing component is given by

$$\Delta S_{mix} = nR \sum f_i \ln x_i$$

Work Equivalent of Heat

If Q_z is a heat source at an absolute temperature Tz and if To is the ambient temperature, then the work equivalent of heat is given by

$$W_{max} = \frac{(T_z - T_o)}{T_z} Q_z$$

This is the absolute theoretical maximum work recoverable.

EXERGY AND ITS IMPLICATIONS

Exergy and Energy

The concept of exergy has a wide application in process industries in quantifying the efficiency of processes and reducing its irreversibilties. Every real process is irreversible; exergy analysis aims at minimizing the irreversibility by pinpointing the location of actual losses in processes and the magnitude of the losses. Exergy analysis in recent years has been popular with researchers and has found application in a variety of industries such as crude oil refineries, petrochemical plants, thermal plants, chemical plants and manufacturing industries.(Sengupta et.al; 2006, Demirel, 2006, Suresh et.al; 2006, Al Muslim et. al; 2005,Al muslim and Dincer; 2005, Demirel; 2004, Rivero et. al; 2004, Zivkovic et.al; 2004, Rivero; 2002,Dincer and Cengel; 2001,Cornelissen;1997).

Previous studies have revealed that exergy analysis gives better insights into the thermodynamic performance of processes and should be applied in lieu of energy analysis. This is because energy analysis is based on the first law of thermodynamics and only quantifies the flow of energy in processes rather than qualifying it and hence giving a fictitious efficiency of processes. Unlike energy, exergy is not conserved; it rather combines the laws of conservation of mass and energy with the second law of thermodynamics. Efficiency calculations based on the second law can be applied to any complex process including complex chemical processes, thermal engine or electrical devices whereas energetic efficiency can not readily be applied to complex systems in which the desired input and output are some combination of work and heat.

(Dincer, 2002) reported that the impacts of energy on the environment and the achievement of energy efficiency of processes are better addressed by the concept of exergy. In addition, because of the role of exergy in determining energy efficiency of processes and environmental impacts of energy, 14 and as energy policy is increasingly playing an important role in sustainability issues, it is pertinent to include exergy in energy policy making.

The concept of exergy is not only limited to energy in its implications but has implications in terms of economy and the environment.

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Economic Implications of Exergy

Exergoeconomic analysis is the second law based economic analysis and it uses exergy to apportion the production cost to different parts of the production routes by combining thermodynamics with accounting to achieve optimum design (Rivero et al 2004).

While exergy analysis will answer the question of magnitude and location of thermodynamics inefficiency in processes as well as means of reducing this inefficiency and economic analysis will answer for cost of equipments and required total investments, exergoeconomic analysis answers the questions of the cost of thermodynamics inefficiency in processes and measures of improving the cost effectiveness of the overall process (Tsatsaronis, 2007).

Exergoeconomic analysis optimizes the quantity as well as the quality of energy in processes. Methodologies for optimizing processes using exergoeconomics are evolving and should soon gain widespread application (Zhang et. al, 2000). Exergoeconomics considers how the capital cost of one part of the system affects the other parts and hence optimizing the total cost of the system (Gong and Wall, 1997),It provides cost based information while suggesting potential for improvement in processes. Decision for replacing a particular unit in a system are better substantiated by using exergoeconomics (Kaushik et al, 2001) Exergoeconomics has been applied in the design of energy efficient systems(Bonnet et. al,2005) and in the retrofitting of existing processes (Chen et. al,2000).

Environmental Implications

The magnitude of the exergy of a system depends on the departure of the state of the system from that of the environment and thus a way of measuring the effects and the work that an effluent can have on the environment (Rivero, 2002). This is because the exergy of a system is zero when it is in equilibrium with its reference environment. Exergy therefore relates the impacts of energy usage by a system to the environmental degradation resulting from that system (Demirel,2004). Quite a number of environmental issues have been linked to the production, transformation and usage of energy. Dincer (1998) identified eleven major areas of environmental concerns in which energy plays a very significant role. This include water pollution, maritime pollution, land use and sitting impact, radiation and radioactivity, solid waste disposal, hazardous air pollutants, ambient air quality, acid deposition, stratospheric ozone depletion and global climate change.

Exergy loss is in terms of waste exergy emission to the environment and internal exergy consumption. Increase exergy efficiency reduces exergy loss and hence reduction in waste released to the environment. Increase exergetic efficiency also leads to reduction in the requirement for new facility for the production, transformation and distribution of various energy forms and the attendants' impacts that such facilities would have on the environment. Exergy provides an effective measure of the potential of a substance to impact the environment (Dincer,2002, Rosen,1999, Rosen and Dincer,2001).

Reduction in environmental pollution and efficient usage of energy are good pointers to sustainable development of which exergy is the main crux. The continual use of finite natural resources will ultimately lead to the depletion of these natural resources in addition to the pollution of the environment. A solution to this problem brings the concept of sustainable development which is defined as "a development that ensures the needs of the present society without compromising the ability of future generation to meet their own needs"(Cornelissen,1997). An important aspect of sustainable development is the minimization of irreversibilities caused by the use of non-renewables. Exergy analysis is a concept that brings this about and hence can be seen as the main link between energy and the environment and energy and sustainable development.

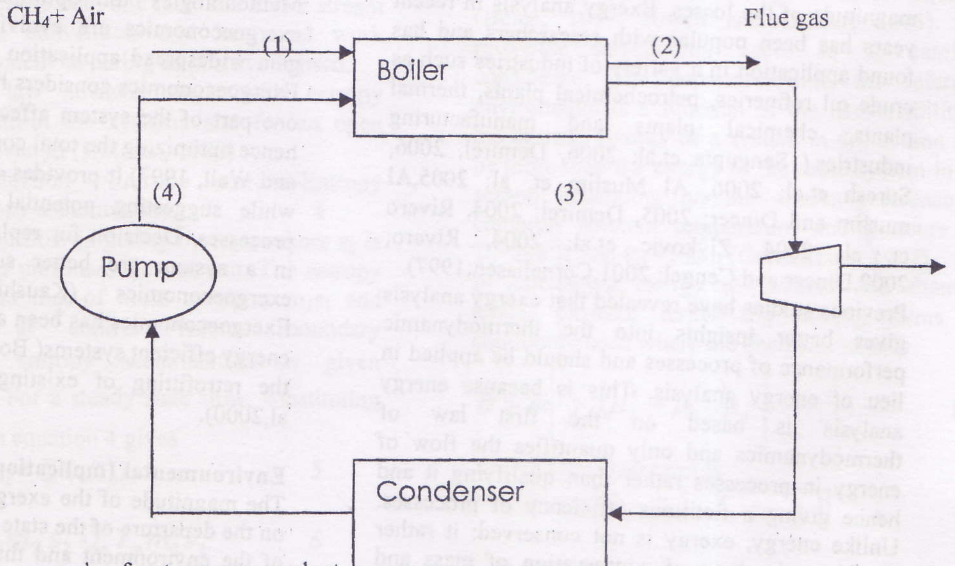

Figure 2: Power cycle of a steam power plant

ILLUSTRATIVE EXAMPLE

Description

Steam is generated in a boiler and is fed to a turbine. Exhaust from the turbine enters a condenser at 10kPa where it is condensed to saturated liquid which is then pumped to a boiler. The system consists of four units with a net output of 80,000kW

(a) The Boiler: The steam generated in the boiler is from complete combustion of methane to oxygen. The flue gas leaving the furnace is at temperature of 187^{0}C. The steam is generated at a rate of 83.59kg/s and at a pressure of 8800kPa and a temperature of 500^{0}C

(b) The Turbine: The high pressure steam generated in the boiler is used to power the turbine. The net power output of the turbine is 80,000kW with adiabatic efficiency of 0.75.Low pressure steam exit the turbine to the condenser at 10kPa.

(c) The Condenser: Cooling water at 25^{0}C condenses the steam exhausted from the turbine to 45.8^{0}C.

(d) The Pump: The condensed steam is pumped to the boiler. The pump is powered by an electrical supply and has an adiabatic efficiency of 0.75.

Exergy Analysis

Table 1 gives the property of the working fluid at each point of the process while the results of the rst and second law efficiency and irreversibility calculations for each of the unit is given in Table 2.

Table 1: Result of the Exergy Analysis

Point	*State of Steam*	*Temperature (^0C)*	*Pressure (kPa)*	*Enthalpy (kJ/kg)*	*Entropy (kJ/kgK)*	*Exergy (kJ/kg)*
1	Subcooled water	45.83	10	203.4	0.6580	7.2173
2	Superheated steam	500	8600	3391.6	6.6858	1398.228
3	Wet steam	45.8	10	2432.2	7.6728	144.83
4	Saturated water	45.8	10	191.8	0.6493	-1.78

Table 2: Results of the 1st and 2nd law Efficiency

Unit	ΔB_{source} *(MW)*	ΔB_{sink} *(MW)*	*Irreversibility (MW*	η *(%)*	ψ *(%)*
Boiler	292.94	117.89	175.05	40.24	92.23
Turbine	106.23	80.99	25.24	76.24	91.88
Pump	0.98	0.76	0.22	77.55	100

DISCUSSION OF RESULTS

Exergy and Energy

The overall exergy efficiency of the plant as the ratio of net work input from the methane combustion to the net work output on the turbine was 27.3% while the corresponding energy efficiency was 31.33%.

The exergy efficiency of the boiler was evaluated as a ratio of difference in outlet and inlet exergy to the net work generated from the combustion process and was found to be 40.24% while the energy efficiency was 92.83%. The high difference implies that most of the energy input into the boiler was transferred to the generated steam while the exergy input into the boiler were consumed by the combustion and heat transfer process. This further highlight the fact that energy analysis gives a fictitious efficiency and exergy analysis should rather be used to have better insight of a process

In the turbine, the exergy efficiency was 76.24% and the energy efficiency was 91.88%. The efficiency was calculated as the ratio of work output of the turbine to the ratio of the change in inlet and exit exergy of the turbine.

The condenser cooling water enters at 25^{0}C and leaves at 30^{0}C. The change is minimal and hence approximately zero.

The energy efficiency of the pump was 100% implying that as much energy as entered the pump was as much ejected while the exergy efficiency of the pump was 77.55%. About 23% of the exergy was consumed in the pump.

Exergy and Economics

The exergoeconomic balance for each of the unit was written. The exergy of each input stream was multiplied by its corresponding exergy cost and any other cost that may be applicable for the input stream and then equated to the exergy of the output stream multiplied by its corresponding exergy cost. The results of the exergoeconomic analysis reveal the costs of the exergy losses and the exergoeconomic improvement potential of the system. (Kaushik et al, 2001). The costs considered include the transformation costs which are the cost of the fuel gas, electricity, cooling water, high pressure steam, and low pressure steam; operation costs and capital costs. For the boiler unit, 48% of the inlet stream cost was unaccounted for in the outlet stream and that of the pump is about 9%. This high loss can be avoided by increasing the exergetic efficiencies of the units.

Exergy and the Environment

The flue gas from the combustion of methane will be released into the atmosphere. This waste exergy emitted from the plant is posing a threat to the environment. Increase in efficiency of the plant from the present 31% to about 100% will reduce the emission from the combustion process and would have made the process a thermodynamically ideal one.

Also methane used in the combustion process is being degraded. This finite resource should therefore be optimally utilised by increasing its efficiency

CONCLUSION

The exergy related implications iterated can assist in attaining sustainable development by pinpointing the location of losses in processes and providing insights into the attainable efficiency of the process. The improved efficiency maximises energy usage, reduces environmental impacts and ultimately pays off in terms of economics. Exergy is here seen as a key part in energy, economics and environmental policies making.

NOMENCLATURE

B	exergy rate (kJ/hr)
h	specific molal enthalpy (kJ/kmol)
H	Total enthalpy (kJ/hr)
I	irreversibility rate (kJ/hr)
u'	internal energy (kJ/kmol)
v	volumetric flow (m^3/s)
v_2	velocity
m	mass flow rate (kJ/hr)
Q	heat transfer rate (kJ/hr)
s	specific molal entropy (kJ/kmol ^{0}C)
S	Total entropy (kJ/hr ^{0}C)
T	temperature (K)
Ws	work rate (kJ/hr)
x	mole fraction of component in stream
μ	chemical potential (kJ/kmol)
μ^*	standard chemical exergy evaluated at the unrestricted dead state (kJ/kmol)
ψ	energy efficiency
η	exergy efficiency

Subscripts

1	inlet
2	exit
j	number count
o	ambient condition

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