LAUTECH Journal of Engineering and Technology 5(1) 2009: 1 – 6

ENERGY AND EXERGY ANALYSES OF A 220MW STEAM POWER PLANT

F.N[1] Osuolale*, A.N[2] Anozie, and A.A.[1] Obisanya

[1] **Department of Chemical Engineering, Ladoke Akintola University of Technology, Ogbomoso**
[2] **Department of Chemical Engineering, Obafemi Awolowo University, Ile-Ife**
***Corresponding author. E-mail:funmikorede@ yahoo.com. Phone no 080-544-591-43**

ABSTRACT

This study presents a thermodynamic analysis of a 220MW thermal plant using its design and operating data. The plant was simulated using HYSYS version 3.2 simulator software. The whole plant was sectionalised into three, each comprising of different units to determine the contribution of each unit to the efficiency and irreversibility of the plant. The maximum exergy loss of 168MW was in the boiler unit. The energetic and exergetic efficiencies were studied for different parameters such as turbine inlet temperature and pressure and fuel flow rate. The overall efficiency of the plant in terms of the first law of thermodynamics (energetic) was 24.1% and the second law analysis (exergetic) was 23.3%.

INTRODUCTION

The increasing awareness that the world's energy resources are limited has caused scientists to take a closer look at energy conversion devices and to develop new techniques to better utilize the existing limited resources. The rate of depletion of fossil fuel reserves has necessitated the operation of power plants in the most efficient manner. During the past two decades, increasing energy prices and environmental impact has brought the energy issues to the forefront and considerable attention has been paid to efficient energy utilization and process improvement studies and programs. In this regard, one essential tool that has been of immeasurable use is exergy analysis (second law of thermodynamic analysis). It has become a key aspect of providing better understanding of the process; quantify sources of inefficiency and distinguish quality of energy used. (Jin *et al*, 1997; Rosen and Dincer, 1997; Dincer and Rosen, 1999, Doldersum, 1998).

Exergy represents the part of energy, which can be converted into maximum useful work. It is used to establish criteria for the performance of engineering devices.(Asada and Boelman,2004). Unlike energy, exergy is not conserved and gets depleted due to irreversibilities in the processes (Sengupta *et al*, 2006). The greater the extent of irreversibilities, the greater the entropy production. Therefore, entropy can be used as a quantitative measure of irreversibilities associated with a process. The performance of engineering systems is degraded by the presence of irreversibilities, and the entropy production is a measure of the magnitudes of the irreversibilities present during that process. It is now becoming a technological challenge to build high performance engineering process that are not only efficient from the quantity of energy view point (the first law of thermodynamics) but also efficient in conserving the quality of energy (second law of thermodynamics) by minimizing the entropy production (Jin *et al*, 1997).

Exergy analysis has been applied to different types of thermal power systems. Ozturk et. al (2006) and Ozgener et. al (2005) did an exergy analysis of geothermal power plant while Suresh et.al(2006) performed theirs on a coal based thermal power plant. Dincer and Al-Muslim (2001) performed a thermodynamic analysis of a rankine cycle reheat steam power plant to study the energy and exergy efficiencies at different operating conditions. Rosen and Dincer (2003a) performed a thermo economic analysis of a power plant and applied it on a coal fired electricity generating station. Uhlenbruck and Lucas (2004) optimise a combined cycle power plant using exergoeconomic. Habib *et al* (1995) provided a procedure for optimization of the first and second reheat pressures in thermal plants based on the energy efficiency and exergy balance. Rosen (2001) compared coal-fired and nuclear steam power plants using energy and exergy analysis to identify areas with potential for performance improvement. Kwon *et al* (2001) and Gaggioli *et al,* (1991) brought a reduction in production cost and fuel consumption cost by utilising exergy in gas turbine cogeneration system and a 22MW thermal plant respectively. Other workers like Caton (2000) and Sahin and Ali (1995) have also made contribution on the exergy destruction of an internal combustion engine and a combined carnot cycle.

In this study, exergy and energy analysis of a 220MW thermal plant was conducted with the aim of determining the efficiency of the plant, locating the source of inefficiency and suggesting ways of improvement.

Description of the Thermal Power Plant

The thermal power plant is a steam turbine power plant comprising of 6 x 220MW independent boiler-turbine units. The units are designed for dual firing using either high power fuel oil (HPFO) and/or Natural gas. The system is of the reheat type with a high-intermediate-low pressure impulse reaction turbine design and a hydrogen cooled generator. Each unit consists of mainly boiler and turbine units. The turbine units, namely the high pressure turbine (HPT), the low pressure turbine (LPT) and the intermediate pressure turbine(IPT) are mounted on a single shaft and coupled with the generator. The condensed steam in the condenser is pumped by the condensate extraction pump (CEP) and passed through the steam air ejector and a gland steam condenser which removes air to establish vacuum in the process before being passed to the condensate polishing plant (CPP). The water from CPP is pumped by condensate booster pumps (CBP), and passed through the drain cooler. The water then passes through Low Pressure regenerating heaters 1, 2 and 3 subsequently. The LP heaters utilizes the extraction steam bled from different stages of the Low Pressure turbine and the drains (drip) from the LP heaters are cascaded backward and the final drip from LP heater 1 is use to heat up the process water.

The water from the LP heater 3 then goes into the deareator which also removes air and serve as an open-type heat exchanger. The pegging steam for dearcator comes from the IP turbine exhaust. The feed water from the deareator is pumped by the boiler feed pump (BFP) and passed through the High Pressure heaters 5 and 6. The extraction steams for the HP heater 5 and 6 are coming from IP turbine and the cold reheat line (CRH) respectively.

The feed water from HP heater 6 passes through the economizer before going into the boiler drum. Steam from the boiler drum then passes through the primary and secondary superheater respectively. Superheated steam at 540^{0}C and 12.5MPa then goes directly into the High Pressure turbine (HP turbine) where it does some work by driving the turbine blade. Lean (exhaust) steam from the HP turbine goes back into the reheater in the furnance by cold Reheat line (CRH) and it is reheated back to 538^{0}C and 12.5MPa before it is passed through the Hot reheat line (HRH) and then back into intermediate pressure turbine (IP turbine) and the exhaust steam of the IP turbine goes directly to the low pressure turbine (LP turbine). The exhaust steam from the LP turbine is thereafter condensed in the condenser using lagoon water as the coolant. A schematic diagram for the 220MW unit is depicted in Figure 4

METHODOLOGY

For the purpose of this study, the plant was divided into three sections. Section one consists of the three turbines and the turbo generator .Section two is made up the constituents of section one plus the pumps and condenser. Section three encompases the whole plant namely the turbines, the generator, the condenser, the pumps and the boiler. The essence of this subdivision is to ascertain the contribution of each unit to the efficiency and or irreversibility of the plant. The sections are highlighted as control volumes 1, 2 and 3 in Figure 4

The whole plant was modelled using HYSYS 3.2 simulation software with capability for generating thermodynamics properties needed for the analysis. A prototype of the model is given in Figure 6.

Theory

In energy-exergy analysis of open systems, the governing equations are that of conservation of mass equation, conservation of energy equation and exergy balance equation. The mass and energy equations are giving respectively as (Al-Muslim et al., 2005)

$$\sum \dot{m}_i = \sum \dot{m}_e \quad (1)$$

$$\sum \dot{B}_i + \dot{Q}_{cv} = \sum \dot{B}_e + \dot{W}_{cv} \quad (2)$$

The mass and energy balance equations (1) and (2) are incorporated into the HYSYS simulation package. Neglecting potential and kinetic exergy, the total flow exergy is expressed, as(Enrico and Wall;2007)

$$\dot{B} = \dot{N}\left[(h-h^0)-T_0(s-s^0)+\sum_j(\mu_j^* - \mu_{0,j})+RT_0\ln\left(\frac{c_j}{c_{0,j}}\right)\right] \quad (3)$$

where the rate of physical exergy is

$$\dot{B}_{ph} = \dot{N}\left[(h-h^0)-T_0(s-s^0)\right] \quad (3a)$$

and the rate of chemical exergy is

$$\dot{B}_{ch} = \dot{N}\left[\sum_j(\mu_j^* - \mu_{0,j})+RT_0\ln\left(\frac{c_j}{c_{0,j}}\right)\right] \quad (3b)$$

The heat exergy is given as

$$B_h = \sum_j\left(1-\frac{T_0}{T_j}\right)\dot{Q}_{cv} \quad (4)$$

System Analysis

In the exergetic analysis of a system, careful consideration must be made in the choice of the reference environment. This is because the exergy of a system is zero when in equilibrium with its reference environment (Dincer and Rosen 2003 b). For this analysis, reference temperature of 25^{0}C and pressure of 101.325kPa were used.

For the first section, only the physical exergy is applicable. The exergy in and out were calculated and the efficiency is given as

$$\eta = \frac{Exergy\ sink}{Exergy\ source} = \frac{G}{\sum B_{in} - \sum B_{out}} \quad (5)$$

Where: G = the generator output

$\sum \dot{B}_{in} =$ *total exergy into turbines*

$\sum \dot{B}_{out} =$ *total exergy out of turbines*

The efficiency of the second section was also calculated using equation 5. In calculating the exergy of the condenser equation 4 was used while equation 3a was used in calculating the exergy of streams. The total exergy in and out were calculated. The efficiency of this section is giving as the ratio of difference in inlet and outlet exergy to the net work generated. For the third subdivision, here,

$\sum \dot{B}_{in} = B_{fuel} + B_{air} + B_{stream\ in}$

$\sum \dot{B}_{out} = B_{flue\ gas} + B_{stream\ out}$

Equation 3 was used in calculation of flue gas exergy with the following assumptions

(i) The fuel which is natural gas is assumed to be only methane
(ii) Excess air of about 20% is required in the boiler
(iii) There is complete combustion, hence the gas in the flue gas contain only oxygen, nitrogen, water vapour and carbon(IV) oxide
(iv) The air is assumed to be dry that is, the air is considered to enter the system after passing through the gas-air heater
(v) Air is assumed to enter at 25^0C and 1 atm
(vi) Fuel is assumed to enter at room temperature
(vii) Auxiliary power consumption is not taken into account.

The third subdivision gives the overall efficiency of the whole plant while the other subdivisions give insight into the contribution of individual unit to the exergetic efficiency and irreversibility of the plant.

RESULTS AND DISCUSSION

The set of thermodynamic parameters obtained for the operating conditions of the thermal plant at 100% full load capacity is given in Table 1. The corresponding exergy of each stream were also presented. The operating temperature and pressure of the high power steam into the turbine are 538^0C and 12.5MPa respectively. At these conditions the efficiency of each subdivision given in Figure1 shows that the first subdivision has the highest efficiency. The turbines which are the main constituent of this division can therefore be said to be appreciably efficient. A reduction in the exergetic and energetic efficiency is noticed for the second division. This may be as a result of the power rating of the condensate extraction pump and condensate booster pump in transporting and converting lean steam to sub cooled water for the boiler. The third division with the highest irreversibility contributes majorly to the inefficiency of the plant. The boiler is found to be the major inclusion in the third division and hence can be said to significantly increase the inefficiency of the whole plant. This is in line with the works of Suresh et.al; (2006) and Sengupta et.al.(2006). The combustion and heat transfer at a high temperature difference contribute grossly to the irreversibility of this unit. A major improvement of this unit will positively impact the whole thermal plant.

The overall efficiency of the plant is considerably low. A detailed parametric study of the plant was also conducted in order to reveal the best operating conditions that will give the highest overall efficiency of the plant. Parameters considered were turbine inlet temperature and pressure, and fuel flow rate. In Figure 2 the variation of overall efficiency and the turbine inlet temperature are shown. Within the limit of 430^0C and 600^0C, the optimum temperature is 530^0C. There is a noticed decrease in the efficiency above and below this temperature. This is confirming the fact that there is an optimum value for operating which design and operating engineers must always target. Exergy analysis can aid in achieving this target for a new design or retrofitting an existing design. Figure 3 shows the variation of turbine inlet pressure and their respective efficiencies. The highest efficiency here is also for the operating pressure of 12.5 MPa. The turbine temperature however has much more significant effect on the efficiency as compared to the turbine pressure. This is because the operation of the plant is as a result of temperature difference. Playing around with this parameter might bring a trade off that will improve the efficiency of the plant and reduce its irreversibility. The effect of fuel flowrate on the overall exergetic and energetic efficiency is presented in Figure 4. The operating fuel flow rate of the plant has an exergetic efficiency of 23.7%. Reduction in the value of this flow rate increases the efficiency of the plant to 24%. Gaggioli *et al,* (1991) got a similar result. The increase in the efficiency as a result of reduction in the flow rate may be explained from the point that exergy analysis is not limited to energy transfer in processes but it is as well influenced by mass transfer.

For each of the parametric study, the energetic efficiency is higher than exergetic efficiency. This is revealing the fact that energy analysis conceals room for improvement of processes. Exergy analysis is therefore best suited for analysing process efficiency.

CONCLUSION

The energy and exergy analysis of the thermal plant was conducted. The overall efficiency of the plant was 23%. This is grossly inadequate and measures of improving this should be looked into. The boiler was found to greatly contribute to the inefficiency of the plant. Efforts at improving the efficiency of the plant can then be concentrated on this unit. The parametric study considered in improving the efficiency though increased it but at a minimal level. Major overhauling of the plant can possibly better improve its efficiency. This improvement will reduce environmental pollution as a result of unutilised fuel and lengthen the usage life of our finite resources. In the design of new thermal plant, exergy analysis should be incorporated at the design stage in lieu of energy analysis to detect inefficient processes and location of irreversibilities in such processes.

Table 1: Parameters at different points of the HYSYS simulation results

STREAM	Specific Enthalpy (kJ/kg)	Specific Entropy (kJ/kgC)	Flowrate (kg/hr)	Shifted specific Enthalpy (kJ/kg)	Change in Enthalpy (ΔH)	Change in Entropy (ΔS)	Total Exergy of stream (kJ/hr)
1	-12500	9.262	647504	3500	3342	6.28	2116334449
2	-12500	9.262	11107	3500	3342	6.28	36302674.2
3	-12500	9.262	634762	3500	3342	6.28	2074687859
6	-12830	9.449	634762	3170	3012	6.47	1862248887
7	-12560	9.288	11107	3440	3282	6.31	35629034.6
12	-12820	9.45	579724	3180	3022	6.47	1706562525
17	-12390	10.01	29942	3610	3452	7.03	100597635
18	-12390	10.01	560889	3610	3452	7.03	1884446818
19	-12590	10.11	29942	3410	3252	7.13	94534379.5
20	-12800	10.25	560889	3200	3042	7.27	1651116994
26	-12800	10.25	22332	3200	3042	7.27	65739825
27	-12800	10.25	20953	3200	3042	7.27	61680393.8
28	-12800	10.25	34739	3200	3042	7.27	102262931
29	-12800	10.25	459191	3200	3042	7.27	1351743506
30	-12950	10.35	22332	3050	2892	7.37	62334195
31	-13100	10.48	20953	2900	2742	7.49	55274014
32	-13240	10.67	34739	2760	2602	7.68	86613011.8
37	-13530	11.11	460231	2470	2312	8.12	1008941410
39	-15910	2.749	460231	90	-67.364	-.23	9791414.53
40	-15820	3.053	32590000	180	22.635	.0718	3378768250
41	-15790	3.162	32590000	210	52.635	.180	4267660500
15	-12390	10.01	579724	3610	3452	7.0289	1947727709
66	-15050	5.041	627504	950	7922	2.0599	517047608
33	-13530	11.1	459191	2470	2313	8.118	1006776268
62	-15230	4.655	20000	770	612	1.673	13072500
Air	-0.2836	5.397	903937.6	15999.7164	12	0.75	1.4341E+10
FLUE GAS	-2236	6.531	947929.4	13764	1	.001	1.2893E+10

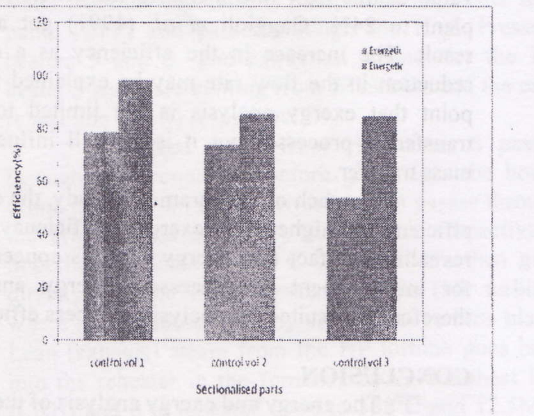

Figure 1: Exergetic and energetic efficiencies of the subdivision.

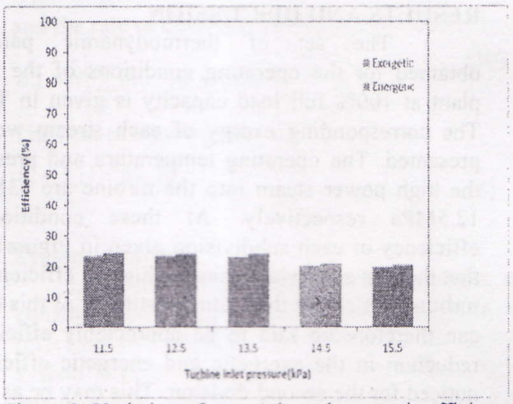

Figure 3: Variation of exergetic and energetic efficiency with turbine inlet pressure

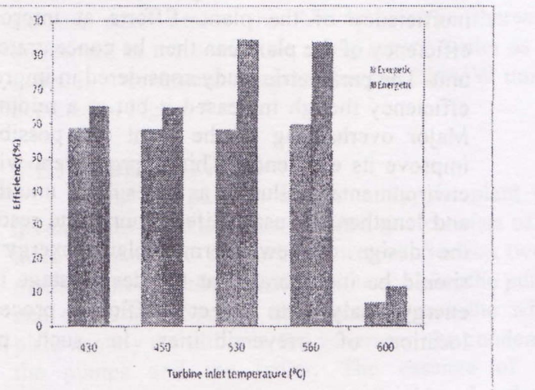

Figure 2: Variation of exergetic and energetic efficiency with turbine inlet temperature

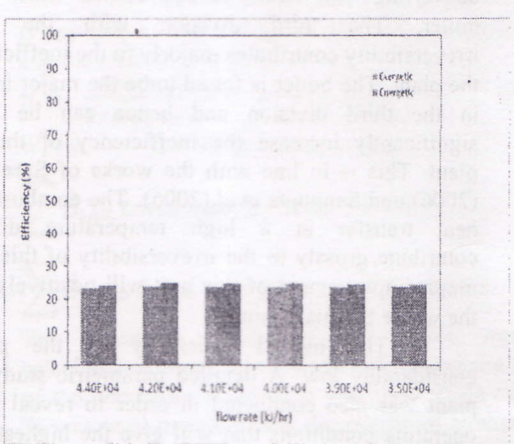

Figure 4: Variation of exergetic and energetic efficiency with fuel flow rate

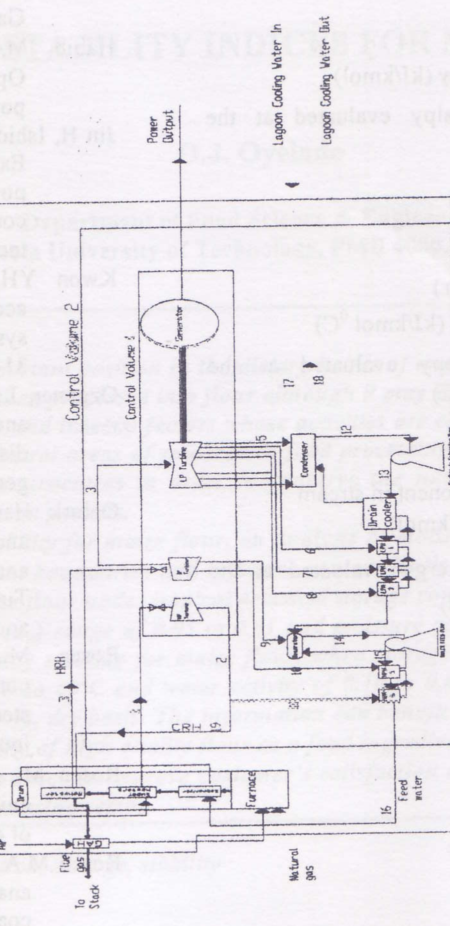

FIG 4 Schematic Diagram of the 210 MW, Egbin Thermal Station (one of the six units)

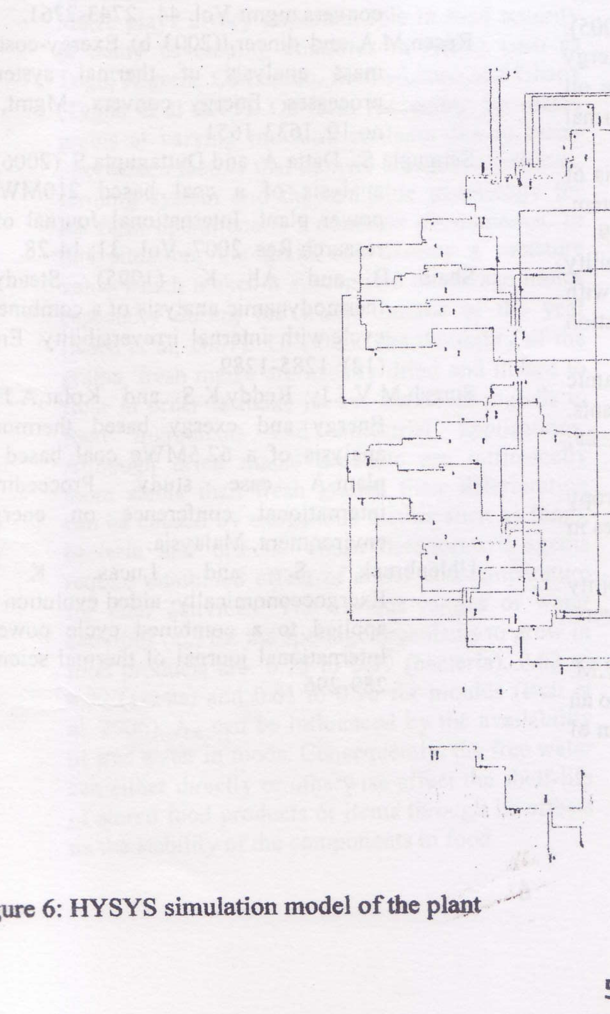

Figure 6: HYSYS simulation model of the plant

NOMENCLATURE

$\dot{B}$ exergy rate (kJ/hr)

h specific molal enthalpy (kJ/kmol)

h^0 specific molal enthalpy evaluated at the restricted dead state (kJ/kmol)

$\dot{m}$ mass flow rate (kJ/hr)

$\dot{N}$ molar flow rate

Q heat transfer rate (kJ/hr)

s specific molal entropy (kJ/kmol ^{0}C)

s^0 specific molal entropy evaluated at the restricted dead state (kJ/kmol ^{0}C)

T temperature (K)

W 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)

Subscripts

ch chemical

cv control volume

e exit

i inlet

j number count

ph physical

o ambient condition

REFERENCES

Al-Muslim; H., Dincer, I. and Zubair, S. M. (2005). Effect of reference state on exergy efficiencies of one- and two-stage crude oil distillation plants. Int. Journ. of Thermal Sciences, 44, 65-73.

Asada,H. and Boelman,E.S (2004) Exergy analysis of a low temperature radiant heating system. Building serv.eng.res.technol.25,3 197-209

Caton J. A. (2000) On the destruction of availability (exergy) due to combustion processes with specific application to internal-combustion engines. Energy 25: 1097-1117.

Dincer I and Al-Muslim H. (2001): Thermodynamic analysis of reheat cycle stream power plants. International Journal of energy research, 25: 727- 739.

Dincer I. and Cengel Y. A. (2001) Energy, Entropy and Exergy Concepts and their roles in thermal Engineering. Entropy, 3; 116-149

Doldersum, A (1998) Exergy analysis proves viability of process modifications. Eneryg convers. Mgmt 39, no16-18, 1781-1789

Gaggioli R.A, Sama A.D, Qians, Al-Sayed Y.M. (1991). Integration of a new process into an existing site: a case study in the application of exergy analysis. Journal of Engineering for Gas turbines and power 113: 170-180

Habib MA, said SAM, AL-Zaharna I. (1995). Optimization of reheat Pressures in thermal power plants. Energy 20(6): 555-565.

Jin H, Ishida M, Kobayashi M, Nunokawa M. (1997): Exergy evaluation of two current advanced power plants; supercritical steam turbine and combine cycle. Journal of energy resources technology 119: 250-256.

Kwon YH, Kwak HY, Oh SD. (2001): Exergy economic analysis of gas turbine cogeneration system. Exergy international Journal 1 (1): 31-40

Ozgener, L; Hepbasli, A; and Dincer, I(2005) Energy and exergy assessment of Salihli geothermal district heating system proceeding world geothermal conference

Ozturk, Harun Kemal, Atalay, Oner, Yilanci, Ahmet and Hepbasli, Arif(2006)'Energy and exergy analysis of Kizildere geothermal power plant, Turkey. Energy Sources, part A: utilization and environmental effects, 28:15, 1415-1424.

Rosen M.A. (2001): Energy and Exergy-base comparison of coal-fired and nuclear steam power plant. Exergy international journal, Vol. 1 (3), 180-192.

Rosen M. A and Dincer I. (1997): On exergy and environmental impact. International Journal of energy research 21: 643-654.

Rosen M.A and Dincer I. (2003 a) Thermoeconomic analysis of power plants; an application to coal-fired electrical generating station. Energy convers mgmt Vol. 44. 2743-2761.

Rosen,M.A and dincer,I(2003 b) Exergy-cost-energy-mass analysis of thermal systems and processes. Energy convers. Mgmt, vol.44, no.10, 1633-1651

Sengupta S., Datta A. and Duttagupta S. (2006) Exergy analysis of a coal based 210MW thermal power plant. International Journal of energy research Res. 2007: Vol. 31: 14-28.

Shain B and Ali K. (1995): Steady State thermodynamic analysis of a combined carnot cycle with internal irreversibility. Energy 20 (12): 1285-1289.

Suresh,M.V.J.J; Reddy,K.S and Kolar,A.J (2006) Energy and exergy based thermodynamic analysis of a 62.5MWe coal based thermal plant-A case study. Proceedings of international conference on energy and environment, Malaysia.

Uhlenbruck, S. and Lucas, K (2004) Exergoeconomically- aided evolution strategy applied to a combined cycle power plant. International journal of thermal sciences. 43, 289-296