

The Influence of Throughput on Thermodynamic Efficiencies of a Thermal Power Plant

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Abstract This study carried out energy and exergy analyses of a thermal power plant in order to evaluate the energetic and exergetic efficiencies and irreversibilities of units, sections and the overall system. It was also, to determine the optimum fuel-air ratio and optimum combustion temperature at different throughputs. The thermal plant consisting of 23 units and 4 sections was simulated using HYSYS simulation software and EXCEL spreadsheet. The EXCEL spreadsheet was used for the energy and exergy analyses. It was found that throughput did not influence the energy efficiencies of the units but the exergy efficiencies. Throughput did not influence the energy and exergy efficiencies of the sections. The overall energetic efficiencies of the plant were 18.17, 19.79, 21.42, and 21.45% and the overall exergetic efficiencies were 10.26, 11.22, 11.58, and 11.61% for throughputs of 50, 75, 100 and 110%, respectively. The overall irreversibilities of the plant increased as the throughput increased. The optimum fuel-to-air ratio which gave the optimum combustion temperature in the furnace was found to be 1:12.6 for all the throughputs which was an improvement over the current practice of 1:19.8. Throughput did not influence the maximum combustion temperature in the furnace.

Keywords Thermal Power Plant, Exergy, Energy, Efficiency, Irreversibility, Units and Sections

1. Introduction

Exergy analysis is a thermodynamic analysis technique based on the first and second laws of thermodynamics which provides an alternative and illuminating means of assessing and comparing processes and systems rationally and meaningfully[7]. Several studies have been carried out by researchers[3, 5, 17] to evaluate the performance of thermal power plants using exergy analysis. Analyses of energy, exergy and exergoeconomics were performed on a natural gas based steam power plant[12]. The comparison of coal-fired and nuclear steam power plants using energy and exergy analyses to identify areas with potential for performance improvement has been investigated[15]. A

thermodynamic analysis of a Rankine cycle reheat steam power plant was carried out to study the energy and exergy efficiencies at different operating conditions of boiler temperature, boiler pressure, mass fraction ratio and work output from the cycle[4]. Exergy and cost balances have been used to study gas-turbine cogeneration system[10]. Thermoeconomic analysis of a coal fired electricity generating station was performed[16]. The exergetic destructions were investigated on a steam generation system[1].

This study undertakes energy and exergy analysis of a natural gas based thermal power plant, located at Egbin, Ikorodu, Lagos State of Nigeria. The objectives of this study are to determine the energetic and exergetic efficiencies and irreversibilities of the 23 plant units, 4 sections and the overall system and to determine the optimum fuel-air ratio and optimum combustion temperature in the furnace at different throughputs (50, 75, 100 and 110% power output).

2. Plant Description

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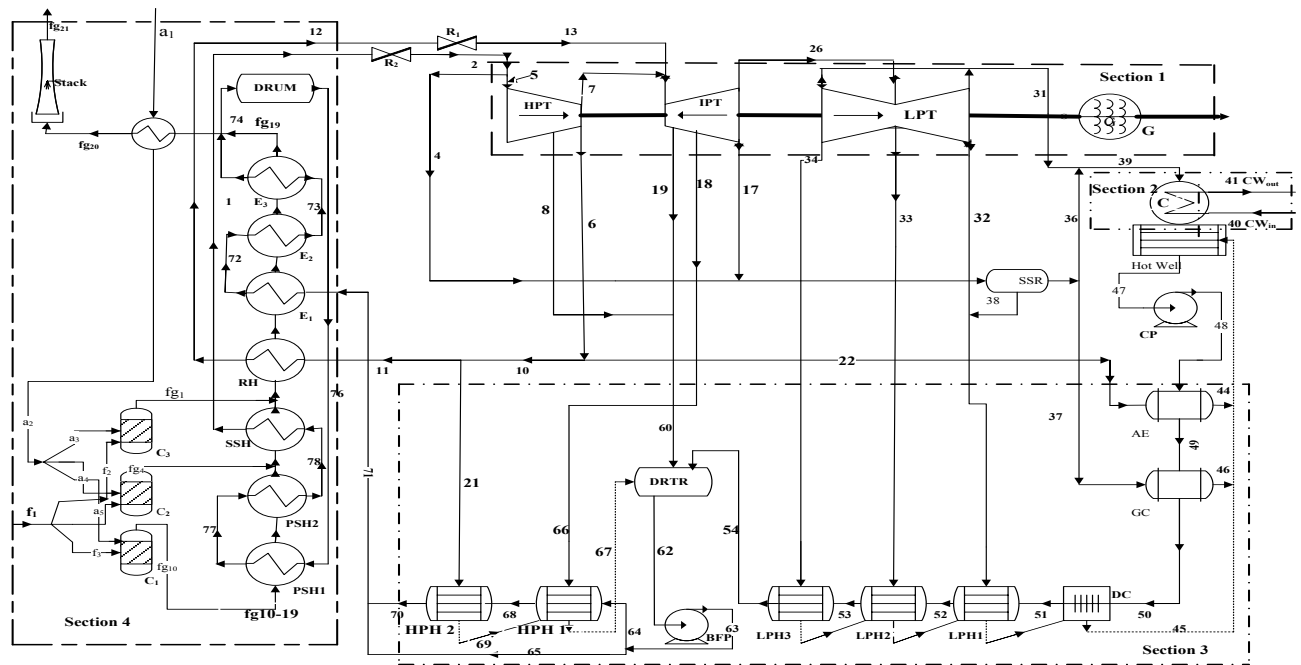


Figure 1. Process flow diagram of the thermal plant showing the units and sections

PSH-Primary Superheater, SSH-Secondary Superheater, RH-Reheater, E-Economizer, AP-Air Preheater, HPT-High Pressure Turbine, IPT- Intermediate Pressure Turbine, LPT- Low Pressure Turbine, C-Condenser, CP-Condenser Pump, AE- Aerator Ejector, GC- Grand Condenser, DC- Drain Cooler, LPH-Low Pressure Heater, DRTR-Deaerator, BFP- Boiler Feed Pump, HPH- High Pressure Heater, C₁, C₂,...Combustors, a₁, a₂,... air streams, 1, 2,... Process streams, f₁, f₂,...Natural Gas, fg₁, fg₂,...flue gas streams

The Egbin thermal power plant burns fossil fuels, which primarily consists of natural gas (NG) and high pour fuel oil (HPFO) as back up, and generates steam which is converted to shaft work in the turbine and to electric power in the generator. The steam generated in the boiler enters the turbine at temperature of about 540°C and pressure of 12.5MPa to spin the turbine blade at a very high speed of 3000 rev/min. There are six turbines units, each capable of generating 220 MW. The water from the lagoon is used as cooling water. The water is passed through the condenser to enhance the condensation of water from steam. The condensed water in the condenser enters the condensate polishing plant for treatment before being sent back to the boiler for re-use. The cooling water which gains temperature from the condenser exits through a discharge channel into the lagoon. The temperature of the effluent water from the powerhouse is reduced in the supplementary cooling system before finally being discharged back into the lagoon[11]. The process flow diagram of the plant is shown in Figure 1.

3. Theory

Two types of exergy of material streams are taken into account, thermo-mechanical (physical) exergy for all streams and chemical exergy associated with the composition of streams with respect to datum environmental species.

Physical exergy of stream

The total rate of exergy in a stream is obtained from its specific value as:

$$\dot{E}x_i = \dot{m}_i e_i \quad (1)$$

The specific physical exergy of the stream was evaluated from the following equation:

$$e_i = (h_i - h_o) - T_o (s_i - s_o) = \Delta h - T_o \Delta s \quad (2)$$

The energy rate of a stream was obtained from its specific value as:

$$\dot{E}x = \dot{m}_i (h - h_o) \quad (3)$$

where h and s are the molar enthalpy and entropy, respectively, of the flowing matter, expressed in functional relationship as:

$$h_o = h(T_o, P_o) \text{ and } s_o = s(T_o, P_o)$$

Chemical exergy of streams

For a mixture of gases, the molar chemical exergy can be expressed as:

$$\varepsilon_{mix}^{Ch} = \sum x_i \varepsilon_i^{Ch} + RT_o x_i \ln x_i \quad (4)$$

where x_i is its mole fraction in the mixture and the molar chemical exergies of the individual gases, ε_i^{Ch} are given in literature[13, 18].

Exergy of chemical reaction:

The combustion reaction of methane and oxygen is



The specific exergy of chemical reaction (kJ/kg) can be written as:

$$\bar{e}_{in}^{Chrxn} = \left(\bar{h}_{CH_4} + 2\bar{h}_{O_2} - \bar{h}_{CO_2} - 2\bar{h}_{H_2O} \right) - T_o \left(\bar{s}_{CH_4} + 2\bar{s}_{O_2} - \bar{s}_{CO_2} - 2\bar{s}_{H_2O} \right) \quad (6)$$

This gives the exergy rate of combustion in the plant as;

$$\dot{E}x_{in}^{Ch} = \dot{m}_{in}^{Ch} * \bar{e}_{in}^{Chrxn} \quad (7)$$

where;

\dot{m}_{in}^{Ch} is the mass flow rate of chemical substance at the inlet.

Energetic and Exergetic efficiencies; and Irreversibility

The equations used in calculating the energetic and exergetic efficiencies of equipment units are given by:

$$\eta = \frac{\dot{E}x_{sink}}{\dot{E}x_{source}} \quad (8)$$

$$\psi = \frac{\dot{E}x_{sink}}{\dot{E}x_{source}} \quad (9)$$

The irreversibility of the unit is given by:

$$\dot{I} = \dot{E}x_{source} - \dot{E}x_{sink} \quad (10)$$

The overall energetic (η) and exergetic (ψ) efficiencies by [6, 9] are:

$$\eta = \frac{\text{Power generated}}{\sum \dot{E}x_{in} - \sum \dot{E}x_{out}} \quad (11)$$

$$\eta = \frac{\text{Power generated}}{\text{Heat energy generated by the fuel}} \quad (12)$$

and

$$\psi = \frac{\text{Power generated}}{\sum \dot{E}x_{in} - \sum \dot{E}x_{out}} \quad (13)$$

$$\psi = \frac{\text{Power generated}}{\text{Heat exergy generated by the fuel}} \quad (14)$$

But it must be pointed out that the heat energy or exergy from the combustion reaction must be accounted as an input in the denomination of equations for overall energy and exergy efficiencies given above.

The overall irreversibility of the thermal plant is given by:

$$\dot{I} = \sum \dot{E}x_{in} - \sum \dot{E}x_{out} \quad (15)$$

4. Methodology

Simulation

HYSYS (2003) process simulator was used to simulate the plant. The two major equipment in the plant were the turbines and the heat exchangers. The expander was used to simulate the turbine. The Peng-Robinson equation of state was used for the simulation. The thermal plant had 23 units and these were grouped into 4 sections, namely;

turbine-generator, condenser, regenerators and boiler-furnace sections as shown in Figure 1. In this analysis, the following assumptions were made: the natural gas burnt in the combustor was assumed to be 87.3% methane, 6.3% ethane, 2.7% propane, 1.5% butane, 0.5% pentane, 0.2% heptanes, 1% CO₂, 0.7% nitrogen; the compressed air used in the combustor was standard air; unaccounted heat loss from the system due to radiation and convection was neglected; fuel undergoes complete combustion.

Process data were obtained from the plant and thermodynamic properties were obtained from the HYSYS environment once the process was fully converged.

Energy and Exergy analyses

The exergy and energy calculations were done using EXCEL spreadsheet after extracting the thermodynamics data from the HYSYS simulations environment. These were calculated using the formulae given in the theory section applied to each unit, section and overall process of the thermal plant.

5. Results and Discussion

5.1. Units Energetic and Exergetic Efficiencies

The units energetic and exergetic efficiencies are shown in Table 1. The units energetic efficiencies are mostly 100% because of the assumption of no heat losses that was made in the simulations. The exergetic efficiencies are between 23.23–90.7% for the furnace-boiler section and between 6.63 – 86.12% for the turbine-generator, condenser and regenerator sections, for all the throughputs. However, as throughput is changed, the operating parameters also change and unit exergetic efficiencies are sensitive to process parameters. The second-law efficiency helped to identify the units that are operating inefficiently. Units with very low exergetic efficiencies are those where the exergy of sink is very low compared to exergy of source such as in the condenser.

5.2. Sections Energetic and Exergetic Efficiencies and Irreversibilities

The sections energetic and exergetic efficiencies at different throughputs are shown in Tables 2. The sections energetic efficiencies were between 99.81–99.98% for the turbine-generator section, 99.98–100% for the condenser section, 63.31–77.41% for the regenerator section, and 62.08–63.24% for the furnace-boiler section. The sections exergetic efficiencies were between 80.01–82.94% for the turbine-generator section, 22.23–26.61% for the condenser section, 38.72–46.95% for the regenerators section, and 37.65–40.24% for the furnace-boiler section, for all the throughputs. The reduction in the values of the efficiencies in the sections as compared to the units, was due to the build-up of irreversibilities in the units to the sections. Irreversibilities of the sections showed that the boiler-furnace section of the thermal plant was extremely very high, as shown in Figure 2,

compared to other sections within the plant. This was caused by the increase in irreversibilities as heat transfer through a finite temperature difference, chemical reactions, friction, and mixing in the boiler-furnace section of the thermal plant increased.

Table 1. The Energetic and Exergetic Efficiencies of Units in the Sections of the Thermal Plant at Different Throughputs

Unit Name	110% Throughput		100% Throughput		75% Throughput		50% Throughput	
	Energetic Efficiency (%)	Exergetic Efficiency (%)	Energetic Efficiency (%)	Exergetic Efficiency (%)	Energetic Efficiency (%)	Exergetic Efficiency (%)	Energetic Efficiency (%)	Exergetic Efficiency (%)
Boiler Section								
Air Pre-Heater	100	58.41	100	37.29	100	23.23	100	31.35
Combustor 1	100	36.33	100	36.13	100	46.02	100	44.37
Combustor 2	100	36.33	100	36.13	100	46.02	100	44.37
Combustor 3	100	36.33	100	36.13	100	46.02	100	44.37
Pry. Superheater 1	100	54.83	100	54.74	100	53.77	100	52.93
Pry. Superheater 2	63.45	36.16	57.3	32.1	69.67	38.56	60.67	32.23
Sec. Superheater	88.98	50.71	90.24	62.45	89.26	60.84	89.2	61.51
Reheater	100	64.23	100	77.12	100	64.45	100	54.6
Economizer 1	100	32.18	100	52.49	100	46.76	100	50.69
Economizer 2	100	51.23	100	86.22	100	54.46	100	75.09
Economizer 3	100	78.13	100	90.54	100	90.69	100	59.8
Turbine-generator section								
High P. T	100	86.12	100	85.83	100	85.25	99.99	84.82
Intermediate P. T	100	85.39	100	85.41	100	84.99	99.42	84.43
Low P. T	100	78.33	100	78.07	100	77.9	100	77.34
Condenser section								
Condenser	99.97	22.73	99.98	23.35	99.99	24.23	100	26.61
Regenerator Section								
Air Ejection	99.99	7.01	99.27	7.57	100	7.75	100	7.99
Gland condenser	100	8.89	100	10.15	100	6.63	80.77	13.78
Drain Cooler	99.61	50.24	99.88	34.45	100	46.53	100	32.01
Low P. Heater 1	100	12.33	100	7.86	100	12.55	100	6.31
Low P. Heater 2	100	57.1	99.96	20.96	100	50.59	100	14.48
Low P. Heater 3	99.99	22.54	99.98	13.67	100	12.55	100	12.77
High P. Heater 1	100	36.44	100	35.71	100	49.24	100	39.2
High P. Heater 2	100	49.32	93.38	45.42	100	47.78	100	29.3

Tables 2. The Energetic and Exergetic Efficiencies of Sections and Overall System at Different Throughputs

Throughputs	Turbine-generator		Condenser		Regenerator		Furnace-boiler		Overall System	
	Energetic efficiencies	Exergetic efficiencies	Energetic efficiencies	Exergetic efficiencies	Energetic efficiencies	Exergetic efficiencies	Energetic efficiencies	Exergetic efficiencies	Energetic efficiencies	Exergetic efficiencies
	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
50%	99.85	82.01	100	26.61	63.64	38.72	62.08	39.64	18.17	10.26
75%	99.81	80.01	99.99	24.23	63.81	40.51	62.55	40.24	19.79	11.22
100%	99.83	82.72	99.98	23.25	63.31	44.01	63.24	37.65	21.42	11.58
110%	99.98	82.94	99.97	22.23	77.41	46.95	63.17	37.85	21.45	11.61

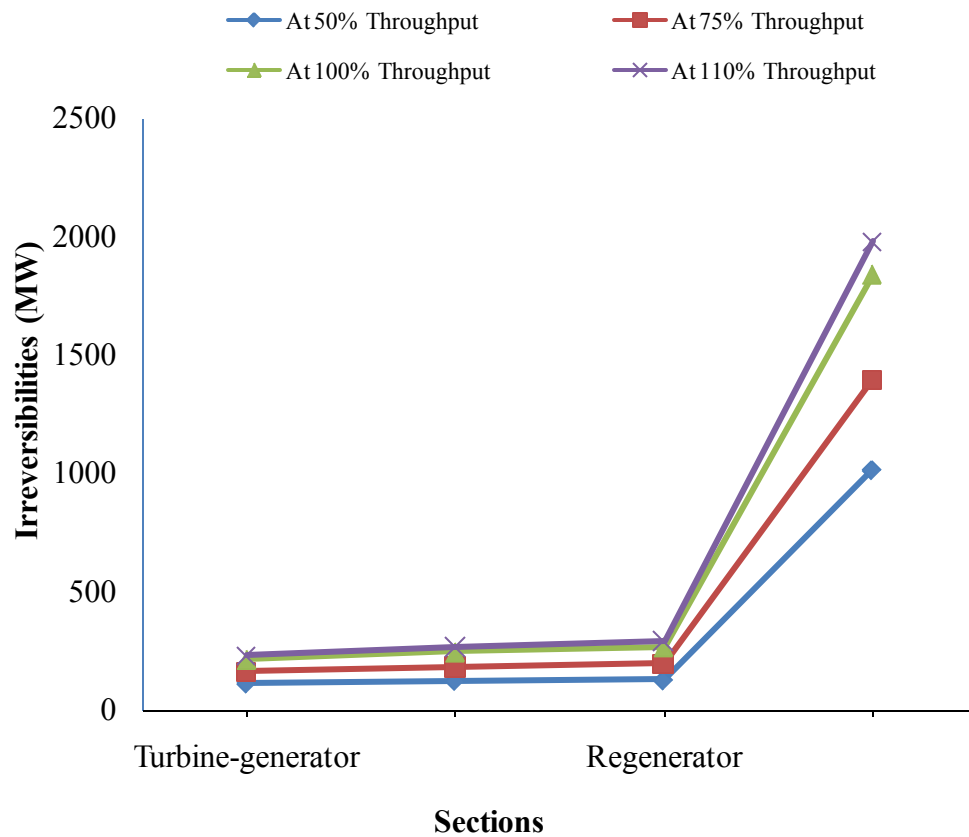


Figure 2. Variation of the irreversibilities of the sections of the thermal plant

Table 3. Fuel and Air Flow rates and Steam Generated at Different Throughputs

Throughputs (%)	Fuel flow rate(kg/hr)	Air Flow rate (kg/hr)	Steam Generated (kg/h)	Power outputs (MW)
50%	24,470	307,500	335,512	110
75%	34,360	432,000	467,450	165
100%	45,570	572,760	647,504	220
110%	50,127	630,000	712,254	242

5.3. The Overall System Energetic and Exergetic Efficiencies and Total Irreversibility

Also in Table 2, it can easily be observed that the energetic and exergetic efficiencies of the overall system for all throughputs were very low compared to the units and sections energetic and exergetic efficiencies. The overall energetic efficiencies of the plant were 18.17, 19.79, 21.42, and 21.45% for throughputs of 50, 75, 100 and 110%, respectively. The overall exergetic efficiencies were 10.26, 11.22, 11.58, and 11.61% for throughputs of 50, 75, 100 and 110%, respectively, and showed that overall second-law efficiency of the plant was lower than the energy efficiency

as was expected. It was observed that throughput did not significantly improve energy and exergy efficiency of the thermal power plant. As shown in Figure 3, the overall irreversibilities at different throughputs showed that irreversibilities increased as the throughputs increased. The results compared to the coal-based thermal plant showed that the energy and exergy efficiencies were 32% and 28%, respectively. These were higher in values due to differences in methods of calculating the efficiencies[19]. The energy and exergy analyses showed further that thermal plants must be complimented with economic analysis to optimize the operation of the plant.

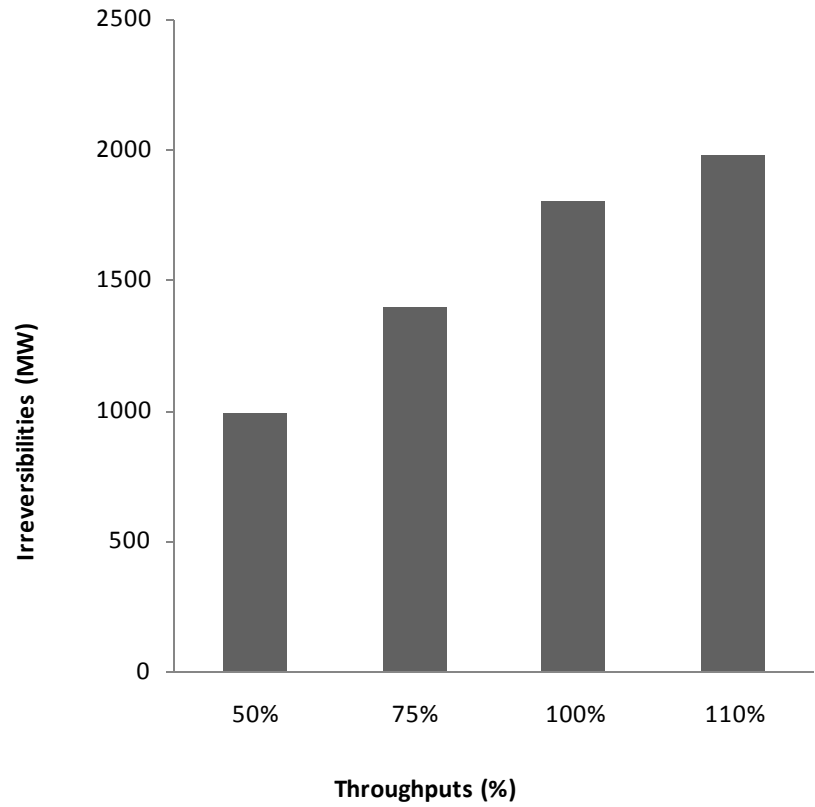


Figure 3. The overall irreversibilities at different throughputs

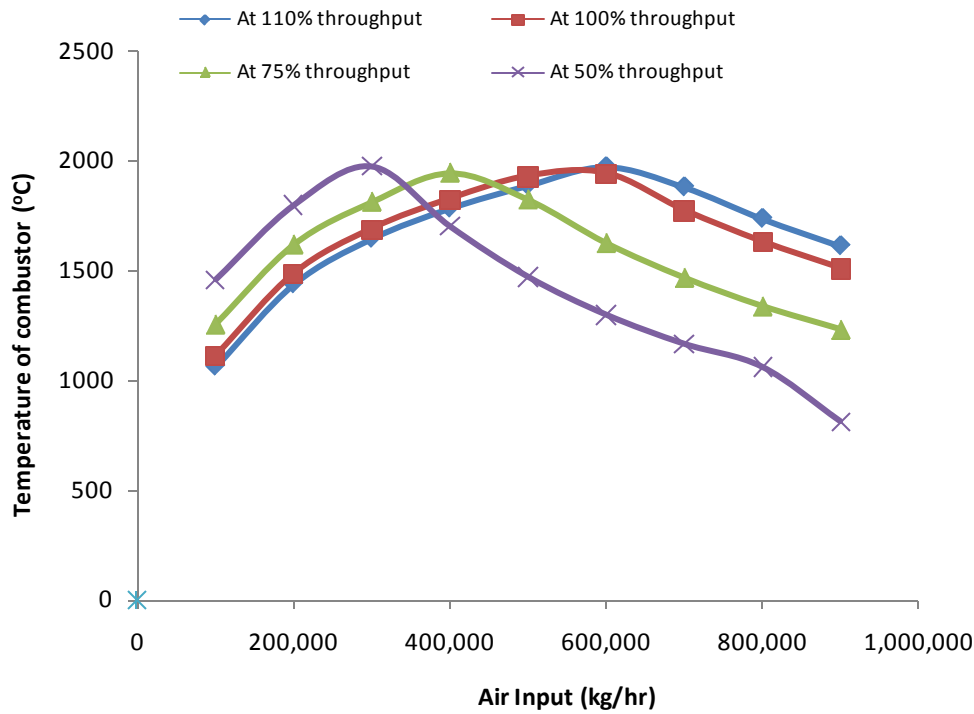


Figure 4. Variation of combustion temperature with air flowrate at constant fuel to air ratio for different throughputs

5.4. The Fuel-Air Ratio

The fuel and air flow rates for the throughputs are shown in Table 3. From Table 3, the fuel to air ratio was about 1:12.6 for all the throughputs compared to the present operating ratio of 1:19.8. Excess air results in incomplete combustion, increased air pollutants emissions and fuel wastage. The total power output generated in the plant was proportional to the total fuel flow rate and the mass flow rate of the steam produced.

The variations of combustion temperature in the furnace with air flow rates at constant fuel rates for different throughputs are shown in Figure 4. It was observed in Figure 4 that the maximum combustion temperature was about the same for all the throughputs and this was the reason why the overall energetic and exergetic efficiencies do not vary much with throughputs. The air input into the combustor can be used directly in controlling the combustion temperature rather than the indirect method of using the combustion temperature to control the air flow rate as was done in the plant, which would have reduced the time to reach steady state operation.

6. Conclusions

In this work, energetic and exergetic analyses were performed on Egbin thermal power plant. It was found that the units exergetic efficiencies were sensitive to plant throughputs but the sections and overall energetic and exergetic efficiencies were not sensitive to variations in plant throughput. The reason for this behaviour was attributed to the fact that the maximum combustion temperatures in the furnace were about the same for all the throughputs. The overall exergetic efficiency was lower than the overall energetic efficiency as was expected because of proper accounting of different types of process exergies of material, heat and work in the plant.

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