

**A STUDY OF SECTIONS INTERACTION EFFECTS ON THERMODYNAMIC EFFICIENCIES OF A THERMAL POWER PLANT.****<sup>1</sup>P. O. Ayoola\* and <sup>2</sup>A.N. Anozie**

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**Abstract:** This study carried out energy and exergy analyses of a thermal power plant in order to investigate the interaction effects of coupling sections of the plant and overall system. The thermal plant was simulated using HYSYS simulation software and EXCEL spreadsheet was used for the energy and exergy analyses. The sections were grouped into four, namely: Turbine-generator, Condenser, Regenerator and Furnace-boiler Sections. The energetic and exergetic efficiencies and irreversibilities at different throughputs (50, 75, 100 and 110% power outputs) were evaluated for each section and the sections were coupled into sub-systems one after the other until the whole system was coupled. The results showed that the furnace-boiler and the condenser sections have the least exergetic efficiencies of an average of 24.08% and 38.85%, respectively, while the energetic efficiencies of the regenerator and furnace-boiler were the least and were 67.04% and 62.74% on the average, respectively. The overall system energetic and exergetic efficiencies were at an average of 20.21% and 11.17%, respectively. This showed that overall second-law efficiency of the plant was lower than the energy efficiency as was expected. The result of the overall irreversibilities of the plant also increased as the throughput increased.

**Keywords:** Thermal power plant, energy, exergy, efficiency, irreversibility, sections, sub-systems, HYSYS software

**1. Introduction**

Exergy analysis is a thermodynamic analysis technique based on the first and second law of thermodynamics which provides an alternative and illuminating means of assessing and comparing processes and systems rationally and meaningfully [9]. Exergy represents the part of energy, which can be converted into maximum useful work. It was used to establish criteria for the performance of engineering devices [3]. Unlike energy, exergy was not conserved and got depleted due to irreversibilities in the processes [19]. 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 was degraded by the presence of irreversibilities, and the entropy production was a measure of the magnitudes of the irreversibilities present during that process [3]. Several studies had been carried out by researchers [4, 6, 7, and 19] to evaluate the performance of thermal power plants using exergy analysis. Energy, exergy and exergoeconomic analyses were used on a steam power plant using natural gas [14]. The comparison of coal-fired and nuclear steam power plants using energy and exergy analyses to identify areas with potential for performance improvement had been investigated [16]. Analysis of a Rankine cycle was carried out reheat steam power plant to study the energy and exergy efficiencies at different operating conditions with varying boiler temperature, boiler pressure, mass fraction ratio and work output from the cycle [15]. Exergy and cost balances had been used to study gas-turbine cogeneration system [12]. The performance of a thermo-economic analysis of a coal fired electricity generating station was achieved [17] and the investigation of the exergetic destructions of a steam generation system [1].

This study undertook exergy analysis of a natural gas based thermal power plant, located at Egbin, Ikorodu, Lagos State of Nigeria. The objectives of this study were to determine the energetic and exergetic efficiencies and irreversibilities of the four sections and the overall system at different throughputs (50, 75, 100 and 110% power output) and the effects of coupling sections of the thermal plant on thermodynamic efficiencies.

## 2. Plant description

The 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 was 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 was used as cooling water. The water was passed through the condenser to enhance the recovery of water from steam. The recovered 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 was reduced in the supplementary cooling system before finally being discharged back into the lagoon [12]. The process flow diagram of the plant was shown in Figure 1. The thermal plant had 23 units and these were grouped into 4 sections, namely; turbine-generator, condenser, regenerator and boiler-furnace sections as shown in Figure 1.

## 3. Methodology

### 3.1 Simulation

HYSYS (2003) process simulator was used to simulate the plant and process data were obtained from the plant. The Peng-Robinson equation of state was used for the simulation. 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% CO<sub>2</sub>, 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. The HYSYS model of the thermal plant is shown in Figure 2.

### 3.2 Energy and Exergy analyses

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

#### 3.2.1 Energy and Exergy analyses of Sections

##### (A) The turbine-generator section

The energy and exergy of source and sink were calculated by considering all the streams entering and leaving the section.

The following equations were used.

$$\dot{E}_{in} = \dot{E}_{S3} + \dot{E}_{S5} + \dot{E}_{S15} + \dot{E}_{S16} + \dot{E}_{S27} + \dot{E}_{S28} + \dot{E}_{S29} + \dot{E}_{S30} \quad (1)$$

$$\dot{E}_{out} = \dot{E}_{S7} + \dot{E}_{S8} + \dot{E}_{S17} + \dot{E}_{S18} + \dot{E}_{S31} + \dot{E}_{S32} + \dot{E}_{S33} + \dot{E}_{S34} \quad (2)$$

$$\dot{E}_{source} = \dot{E}_{in} - \dot{E}_{out} \quad (3)$$

$$\dot{E}_{sink} = P_i \quad (4)$$

$$\dot{E}_{xin} = \dot{E}_{xS3} + \dot{E}_{xS5} + \dot{E}_{xS15} + \dot{E}_{xS16} + \dot{E}_{xS27} + \dot{E}_{xS28} + \dot{E}_{xS29} + \dot{E}_{xS30} \quad (5)$$

$$\dot{E}_{xout} = \dot{E}_{xS7} + \dot{E}_{xS8} + \dot{E}_{xS17} + \dot{E}_{xS18} + \dot{E}_{xS31} + \dot{E}_{xS32} + \dot{E}_{xS33} + \dot{E}_{xS34} \quad (6)$$

$$\dot{E}_{xsource} = \dot{E}_{xin} - \dot{E}_{xout} \quad (7)$$

$$\dot{E}_{xsink} = P_i \quad (8)$$

Where:

$P_i$  is the power generated.

#### (B) The condenser section

The energy and exergy of source and sink the condenser were also calculated by considering all the hot and cold streams entering and leaving the section. The equations are:

$$\dot{E}_{source} = \dot{E}_{S39} - \dot{E}_{S42} \quad (9)$$

$$\dot{E}_{sink} = \dot{E}_{S41} - \dot{E}_{S40} \quad (10)$$

$$\dot{E}_{xsource} = \dot{E}_{xS39} - \dot{E}_{xS42} \quad (11)$$

$$\dot{E}_{xsink} = \dot{E}_{xS41} - \dot{E}_{xS40} \quad (12)$$

#### (C) The regenerators section

The regenerative part of the system is the heat exchangers where the heats are recovered back into the system. The energy and exergy of streams were also calculated by considering all the streams entering and leaving the section. The equations are:

$$\dot{E}_{in} = \dot{E}_{S21} + \dot{E}_{S22} + \dot{E}_{S37} + \dot{E}_{S48} + \dot{E}_{S56} + \dot{E}_{S58} + \dot{E}_{S66} \quad (13)$$

$$\dot{E}_{out} = \dot{E}_{S44} + \dot{E}_{S46} + \dot{E}_{S57} + \dot{E}_{S59} + \dot{E}_{S67} + \dot{E}_{S69} + \dot{E}_{S71} \quad (14)$$

$$\dot{E}_{source} = \sum \dot{E}_{in} \quad (15)$$

$$\dot{E}_{sink} = \sum \dot{E}_{out} \quad (16)$$

$$\dot{E}_{xin} = \dot{E}_{xS21} + \dot{E}_{xS22} + \dot{E}_{xS37} + \dot{E}_{xS48} + \dot{E}_{xS56} + \dot{E}_{xS58} + \dot{E}_{xS66} \quad (17)$$

$$\dot{E}_{xout} = \dot{E}_{xS44} + \dot{E}_{xS46} + \dot{E}_{xS57} + \dot{E}_{xS59} + \dot{E}_{xS67} + \dot{E}_{xS69} + \dot{E}_{xS71} \quad (18)$$

$$\dot{E}_{xsource} = \sum \dot{E}_{xin} \quad (19)$$

$$\dot{E}_{xsink} = \sum \dot{E}_{xout} \quad (20)$$

#### (D) The furnace-boiler section

The furnace-boiler section of the thermal plant is the section where energy needed by the plant is generated. The energy and exergy balances are:

$$\dot{E}_{source} = \sum \dot{E}_{in} = \dot{E}_{fuel\ in} + \dot{E}_{air\ input} + \dot{E}_{\Delta H_{rxn}} + \dot{E}_{S71} \quad (21)$$

$$\dot{E}_{sink} = \sum \dot{E}_{out} = \dot{E}_{S1} + \dot{E}_{12} + \dot{E}_{flue\ gas} \quad (22)$$

$$\dot{E}_{xsource} = \sum \dot{E}_{xin} = \dot{E}_{x\ fuel\ in} + \dot{E}_{x\ air\ input} + \dot{E}_{x\ rxn}^{Ch} + \dot{E}_{xS71} \quad (23)$$

$$\dot{E}_{xsink} = \sum \dot{E}_{xout} = \dot{E}_{xS1} + \dot{E}_{x12} + \dot{E}_{x\ flue\ gas} \quad (24)$$

Exergy analysis of thermal plants involves chemical reactions of various kinds including reactions of combustion. It is therefore important that the method of analysis used should offer means of dealing, without undue complication, with the chemical aspects of energy conversion [10]. The chemical exergy of the fuel due to combustion was considered along side with the physical exergy. The enthalpy and entropy values used in calculating the heat of reaction and exergy of chemical reaction were taken from literature [15].

The reaction of methane and oxygen is:



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

$$\bar{e}_{in}^{Chrxn} = \left( \bar{h}_{CH_4} + 2\bar{h}_{O_2} - \bar{h}_{CO_2} - 2\bar{h}_{H_2O} \right) - T_0 \left( \bar{s}_{CH_4} + 2\bar{s}_{O_2} - \bar{s}_{CO_2} - 2\bar{s}_{H_2O} \right) \quad (26)$$

This gives the exergy rate of chemical reaction entering the plant as:

$$\dot{E}_{in}^{Ch} = \dot{m}_{in}^{Ch} \times n_{Ch} \times \bar{e}_{in}^{Chrxn} \quad (27)$$

Where:  $\dot{m}_{in}^{Ch}$  is the mass flow rate of chemical substance at the inlet,

$n_{Ch}$  is the mass fraction of chemical substance.

### 3.3 Energy and Exergy Balances on the Sub-systems and Overall System

For the purpose of studying coupling (interaction) effects among sections, the whole thermal plant was grouped into sub-systems as shown in Figure 1. For full understanding of these balances the HYSYS model of the plant has to be compared with process flow diagram of the plant.

#### (A) The turbine-generator as sub-system 1 (Base Case)

The turbine-generator section was also chosen as the base case sub-system 1. Therefore, the energy and exergy balance equations of plant section 1 given in 3.2.1(A) are applicable here.

#### (B) Coupling of turbine-generator and the condenser (sub-system 2)

The energy and exergy were also calculated by considering all the streams entering and leaving the sub-system. Such as:

$$\dot{E}_{in} = \dot{E}_{S3} + \dot{E}_{S5} + \dot{E}_{S15} + \dot{E}_{S16} + \dot{E}_{S27} + \dot{E}_{S28} + \dot{E}_{S29} + \dot{E}_{S30} + \dot{E}_{S40} \quad (28)$$

$$\dot{E}_{out} = \dot{E}_{S7} + \dot{E}_{S8} + \dot{E}_{S17} + \dot{E}_{S18} + \dot{E}_{S32} + \dot{E}_{S33} + \dot{E}_{S34} + \dot{E}_{S41} + \dot{E}_{S42} \quad (29)$$

$$\dot{E}_{sink} = P_i \quad (30)$$

$$\dot{E}_{source} = \Sigma \dot{E}_{in} - \Sigma \dot{E}_{out} \quad (31)$$

$$\dot{E}x_{in} = \dot{E}x_{S3} + \dot{E}x_{S5} + \dot{E}x_{S15} + \dot{E}x_{S16} + \dot{E}x_{S27} + \dot{E}x_{S28} + \dot{E}x_{S29} + \dot{E}x_{S30} + \dot{E}x_{S40} \quad (32)$$

$$\dot{E}x_{out} = \dot{E}x_{S7} + \dot{E}x_{S8} + \dot{E}x_{S17} + \dot{E}x_{S18} + \dot{E}x_{S32} + \dot{E}x_{S33} + \dot{E}x_{S34} + \dot{E}x_{S41} + \dot{E}x_{S42} \quad (33)$$

$$\dot{E}_{X_{\sin k}} = P_i \quad (34)$$

$$\dot{E}_{X_{source}} = \Sigma \dot{E}_{X_{in}} - \Sigma \dot{E}_{X_{out}} \quad (35)$$

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### 183 (C) Coupling of turbine-generator, condenser and the regenerators (sub-system 3)

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185 The regenerative part of the system are the heat exchangers where the heats are recovered back into the system. The  
186 efficiencies (energetic and exergetic) were also calculated by considering all the streams entering and leaving the  
187 sub-system. Such as:

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$$\dot{E}_{source} = \Sigma \dot{E}_{in} = \dot{E}_{S2} + \dot{E}_{S13} + \dot{E}_{S40} \quad (36)$$

$$\dot{E}_{\sin k} = \dot{E}_{out} = \dot{E}_{S11} + \dot{E}_{S41} + \dot{E}_{S71} \quad (37)$$

$$\dot{E}_{X_{source}} = \dot{E}_{X_{in}} = \dot{E}_{X_{S2}} + \dot{E}_{X_{S13}} + \dot{E}_{X_{S40}} \quad (38)$$

$$\dot{E}_{X_{\sin k}} = \dot{E}_{X_{out}} = \dot{E}_{X_{S11}} + \dot{E}_{X_{S41}} + \dot{E}_{X_{S42}} \quad (39)$$

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### 195 (D) Coupling of the 4 sections (the overall system)

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197 In calculating the overall efficiency and overall irreversibility of the thermal plant, the streams of material entering  
198 and leaving the entire plant were considered.

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200 The overall energy and exergy balances are:

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$$\dot{E}_{source} = \Sigma \dot{E}_{in} = \dot{E}_{fuel\ in} + \dot{E}_{air\ input} + \dot{E}_{\Delta H} + \dot{E}_{cooling\ water\ in} \quad (40)$$

$$\dot{E}_{\sin k} = \Sigma \dot{E}_{out} = \dot{E}_{flue\ gas} + \dot{E}_{cooling\ water\ in} \quad (41)$$

$$\dot{E}_{X_{source}} = \Sigma \dot{E}_{X_{in}} = \dot{E}_{X_{fuel\ in}} + \dot{E}_{X_{air\ input}} + \dot{E}_{X_{rxn}^{Ch}} + \dot{E}_{X_{cooling\ water\ in}} \quad (42)$$

$$\dot{E}_{\sin k} = \Sigma \dot{E}_{out} = \dot{E}_{flue\ gas} + \dot{E}_{cooling\ water\ in} \quad (43)$$

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208 The total irreversibility of the Thermal Plant by Kotas, (1980):

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$$\dot{I} = \Sigma \dot{E}_{X_{in}} - \Sigma \dot{E}_{X_{out}} \quad (44)$$

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212 The net power generated in the plant  $P_{net}$  was obtained by subtracting the auxiliary power used by the plant such as  
213 power used by the pumps ( $P^{CEP}$ ,  $P^{BEP}$ ), compressors and the furnace-boiler from the total power generated. The  
214 auxiliary power was assumed to be 5% of the total power generated. The relationship is given by:

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$$P_{net} = P_T - P^{Aux} \quad (45)$$

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218 The overall energetic ( $\eta$ ) and exergetic ( $\psi$ ) efficiencies [11, 17] are given by:

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$$\eta = \frac{Net\ power\ generated}{\Sigma \dot{E}_{in} - \Sigma \dot{E}_{out}} \quad (46)$$

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$$\eta = \frac{\text{Net power generated}}{\text{Heat energy generated by the fuel}} \quad (47)$$

And

$$\psi = \frac{\text{Net power generated}}{\sum \dot{E}_{x_{in}} - \sum \dot{E}_{x_{out}}} \quad (48)$$

$$\psi = \frac{\text{Net power generated}}{\text{Heat exergy generated by the fuel}} \quad (49)$$

## 4. Results and Discussion

### 4.1 Sections Energetic and Exergetic Efficiencies

The results of sections of the thermal plant on stand alone basis are presented in Tables 1. It was observed that the sections energetic efficiencies for all the throughputs were approximately an average of 100% for the turbine-generator and the condenser sections, 67% for the regenerators section, and 63% for the furnace-boiler section. The sections exergetic efficiencies for all the throughputs were an average of 81.5% for the turbine-generator section, 24% for the condenser section, 43% for the regenerators section, and 39% for the furnace-boiler section. The results showed that the furnace-boiler and the condenser sections have the least exergetic efficiencies while the energetic efficiencies of the regenerators and furnace-boiler were the least. The low exergetic efficiencies in the furnace-boiler and condenser sections were as a result of the rate of chemical reaction taking place in the furnace-boiler section and the heat lost to cooling water in the condenser section of the thermal plant.

### 4.2 Coupled Sections (Sub-Systems) and Overall System Energetic and Exergetic Efficiencies

The results of energetic and exergetic efficiencies of coupling the sections are presented in Tables 2 - 4. For the coupling of turbine-generator and condenser as a sub-system shown in Table 2, the energetic efficiencies were 100% for all the throughputs but the average exergetic efficiencies were 72.3%. This showed that coupling of turbine-generator and condenser had no effect on the energetic efficiency but had effect on the exergetic efficiency. For the coupling of turbine-generator, condenser and regenerators as a sub-system shown in Table 3, the energetic efficiencies dropped to an average value of 78% for all the throughputs and the exergetic efficiency also dropped to an average value of 64.3% for all the throughputs. This showed that coupling of regenerators to turbine-generator and condenser had appreciable effect on both energetic and exergetic efficiencies of the sub-system. It was also observed that as the sections were coupled together, the energetic and exergetic efficiencies of the coupled sub-systems dropped and that throughput did not have much effect on the efficiencies of the coupled sub-systems.

For the overall system (coupling of turbine-generator, condenser, regenerator and furnace-boiler), shown in Table 4, both energetic and exergetic efficiencies dropped sharply to an average of 20.2% and 11.7% for all the throughputs, respectively. This showed that the closed loop topology of the thermal plant made the highest contribution in determining the overall process efficiencies. The results further showed that the overall second-law efficiency of the plant was lower than the overall energy efficiency as was expected. The results of a coal-based thermal plant analysis [20] showed that the energy and exergy efficiencies were 32% and 28%, respectively, and are higher in values compared to the results from this study due to the formulae used in calculating the efficiencies. The overall energetic and exergetic efficiencies at different throughputs showed further that thermal plants must be complimented with economic analysis to optimize the operation of the plant.

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| Throughputs | Turbine-generator          |                            | Condenser                  |                            | Regenerators               |                            | Furnace-boiler             |                            |
|-------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|
|             | 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                      |
| 75%         | 99.81                      | 80.01                      | 99.99                      | 24.23                      | 63.81                      | 40.51                      | 62.55                      | 40.24                      |
| 100%        | 99.83                      | 82.72                      | 99.98                      | 23.25                      | 63.31                      | 44.01                      | 63.24                      | 37.65                      |
| 110%        | 99.98                      | 82.94                      | 99.97                      | 22.23                      | 77.41                      | 46.95                      | 63.17                      | 37.85                      |

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**Table 1: The Energetic and Exergetic Efficiencies of the Turbine-generator, Condenser, Regenerators and Furnace-boiler Sections.**

**Table 2: Energetic and Exergetic Efficiencies of the Turbine-generator and Condenser Sub-system**

| Throughputs | Energetic Efficiencies (%) | Exergetic Efficiencies (%) |
|-------------|----------------------------|----------------------------|
| At 50%      | 100                        | 74.61                      |
| At 75%      | 100                        | 70.01                      |
| At 100%     | 100                        | 72.31                      |
| At 110%     | 100                        | 71.45                      |

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**Table 3: Energetic and Exergetic Efficiencies of the Turbine-generator, Condenser and the Regenerators Sub-system**

| Throughputs | Energetic Efficiencies (%) | Exergetic Efficiencies (%) |
|-------------|----------------------------|----------------------------|
| At 50%      | 79.59                      | 66.22                      |
| At 75%      | 79.46                      | 65.51                      |

|         |       |       |
|---------|-------|-------|
| At 100% | 76.86 | 63.30 |
| At 110% | 75.92 | 61.97 |

**Table 4: Energetic and Exergetic Efficiencies of the Whole Thermal Plant**

| Throughputs | Energetic Efficiencies (%) | Exergetic Efficiencies (%) |
|-------------|----------------------------|----------------------------|
| At 50%      | 18.17                      | 10.26                      |
| At 75%      | 19.79                      | 11.22                      |
| At 100%     | 21.42                      | 11.58                      |
| At 110%     | 21.45                      | 11.61                      |

#### 4.3 The Relevance of the Irreversibilities on the Thermal Plant

Table 5 shows the irreversibilities at different throughputs in the sections of the thermal plant. The trend showed that the irreversibilities depend on the fuel input, that is, the higher the fuel input the higher the irreversibilities. The exergy of destruction in the plant which brought about the useful energy in the furnace-boiler was used to heat up the massive tonnes of water to steam of required temperature and pressure and this resulted in high irreversibilities within the plant. It was also observed that about 85.6% of the total irreversibilities occurred at the furnace-boiler section of the thermal plant for all the throughputs and this brought about a great reduction in the energetic and exergetic efficiencies of the overall thermal plant as shown in Table 4. The increase in irreversibilities was caused as a result of heat transfer through a finite temperature difference, chemical reactions, friction, and mixing in the boiler-furnace section of the thermal plant.

Table 6 shows the irreversibilities of the coupled sub-systems and the overall thermal plant. The overall thermal plant irreversibilities have reduced values as shown in Table 6, because great amount of heat generated at the furnace-boiler was absorbed within the plant.

**Table 5: The Irreversibilities of the Sections**

| Through-put | Turbine-generator | Condenser | Regenerators | Furnace-Boiler |
|-------------|-------------------|-----------|--------------|----------------|
| 50%         | 116               | 127       | 129          | 1018           |
| 75%         | 168               | 188       | 201          | 1397           |

|      |     |     |     |      |
|------|-----|-----|-----|------|
| 100% | 219 | 250 | 272 | 1840 |
| 110% | 233 | 270 | 296 | 1980 |

**Table 6: The Irreversibilities of the Coupled Sub-systems and the Overall Thermal Plant**

| Through-put | Turbine-generator | Turbine-generator & Condenser | Turbine-generator, Condenser & Regenerators | Overall System |
|-------------|-------------------|-------------------------------|---------------------------------------------|----------------|
| 50%         | 116               | 127                           | 157                                         | 187            |
| 75%         | 168               | 188                           | 233                                         | 239            |
| 100%        | 219               | 250                           | 322                                         | 351            |
| 110%        | 233               | 270                           | 352                                         | 381            |

## 5. Conclusions

In this work, the energetic and exergetic analyses were performed on a thermal power plant to study sections, sub-systems and overall system efficiencies and irreversibilities at various throughputs. It was found that the sub-systems energetic and exergetic efficiencies were sensitive to plant throughputs but the overall thermal plant energetic and exergetic efficiencies were not sensitive to changes in plant throughput. 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 and the irreversibilities of the thermal plant increased as the throughputs increased.

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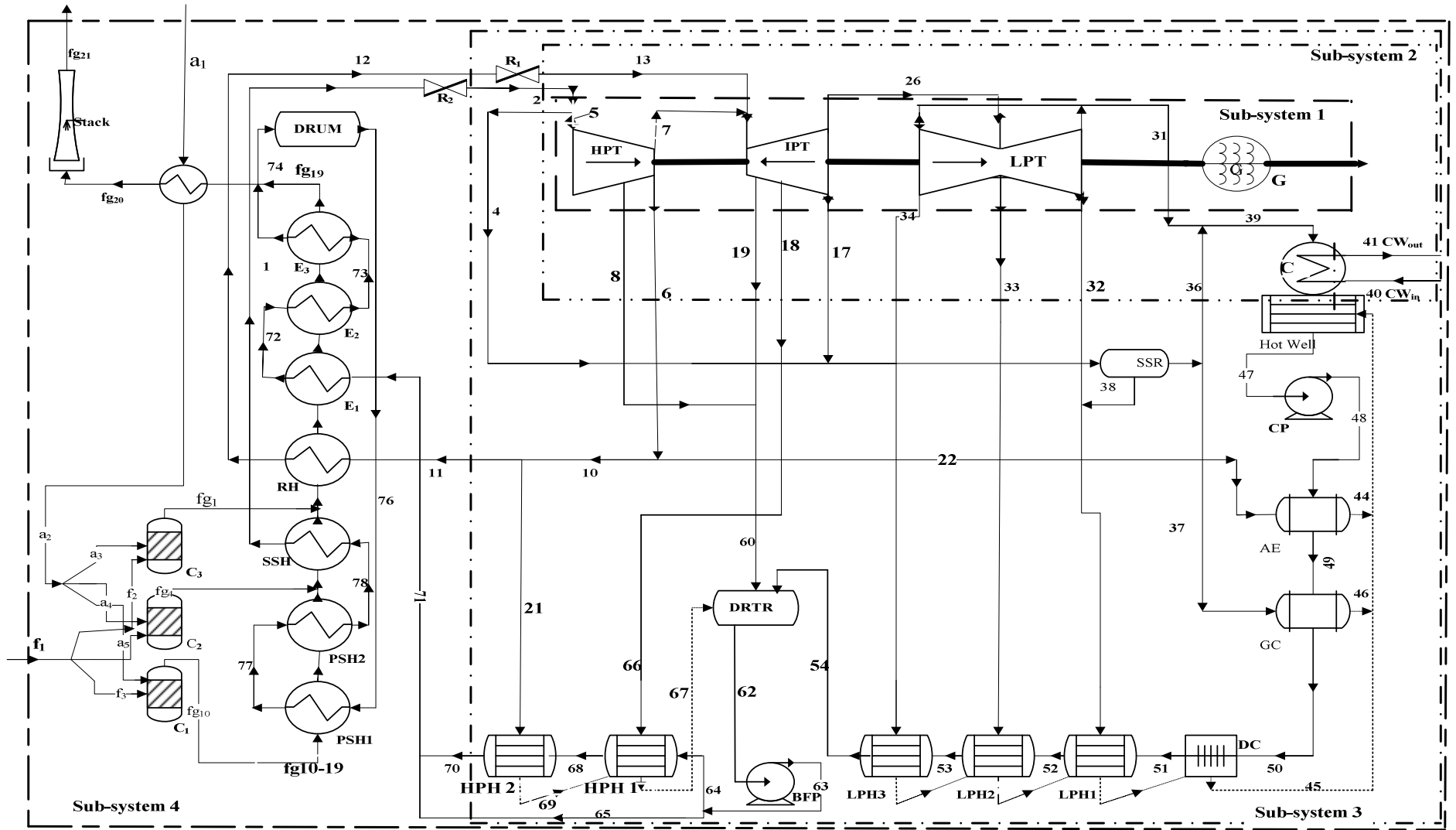


**Figure 1: Process flow diagram of the plant showing the subsystems and overall system**

Sub-system 1: - - - - - Sub-system 2 — · — · -Subsystem 3 - · - · - Sub-system 4/Overall system — — — — —

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, C<sub>1</sub>, C<sub>2</sub>,...Combustors, a<sub>1</sub>, a<sub>2</sub>,... air streams, 1, 2,... Process streams, f<sub>1</sub>, f<sub>2</sub>,...Natural Gas, fg<sub>1</sub>, fg<sub>2</sub>,...flue gas streams.

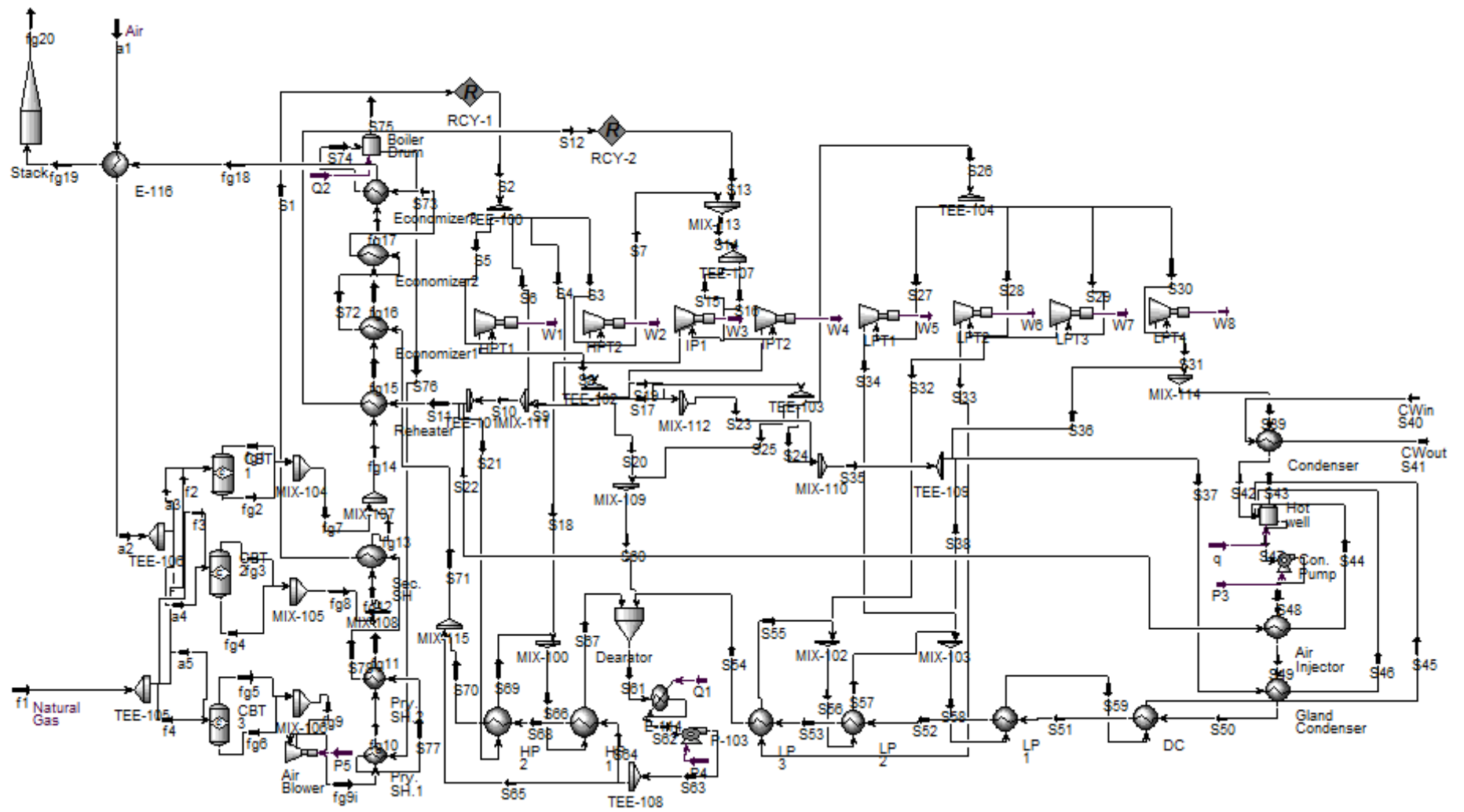


Figure 2: HYSYS model of the thermal plant