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THE INVESTIGATION OF INCREASING OF THE EFFICIENCY IN THE POWER PLANT WITH GAS-SOLID FUELS BY EXERGY ANALYSIS

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Abstract: In this study the energy and exergy analysis have been applied to the power plant in the Iron and Steel Works Co. This plant consist of two parts, which could be described as old and new sections. These components work together as an integrated power plant. In this work, the irreversibility rates and energy losses of each units have been determined separately by energy and exergy analysis. Also, units have been compared by irreversibility rates and some considerable suggestions have been made to improve efficiency. It is suggested to remove three pressure reduction units (PDD1, PDD2, PDD3), have a total irreversibility rate of 6054 kW, from the existing plant and replaced by a turbo-generator (TG4). Calculated results showed that the increments of overall thermal (or first law) efficiency and overall exergy (or second law) efficiency of suggested plant were 2.27 and 2.21 %, respectively.
Keywords: Energy; Exergy; Irreversibility; exergy efficiency; Steam power plant.

GAZ-KATI YAKITLI GÜÇ SANTRALİNDE VERİM ARTIŞININ EKSERJİ ANALİZİ KULLANILARAK İNCELENMESİ

Özet: Bu çalışmada, Demir-Çelik Fabrikasındaki güç santraline enerji ve ekserji analizi uygulanmıştır. Santral, eski ve yeni olmak üzere iki kısımdan oluşmaktadır. Bu kısımlar birbirleriyle entegre olarak çalışmaktadır. Bu çalışmada, her bir ünitenin enerji kayıpları ve tersinmezlikleri enerji ve ekserji analizi uygulanarak belirlenmiştir. Ayrıca, üniteler tersinmezliklerine göre karşılaştırılmış ve verim artırıcı bazı önemli öneriler yapılmıştır. Mevcut santraldeki toplam tersinmezliği 6054 kW olan üç basınç düşürücünün (PDD1, PDD2, PDD3) kaldırılması ve yerine bir turbo-jeneratör (TG4) konulması önerilmiştir. Yapılan hesaplamalar sonucunda, önerilen bu santralin mevcut santrale göre genel (1. Kanun) verim ve genel ekserji verim artışları sırasıyla % 2.27 ve 2.21 olarak belirlenmiştir.
Anahtar kelimeler*:* Enerji; Ekserji; Tersinmezlik; ekserji verimi; Buharlı güç santrali.

NOMENCLATURE

$\bar{c}_p^h$	mean isobaric enthalpy capacity (kJ/kmolK)
$\bar{c}_p^\varepsilon$	mean isobaric exergy capacity (kJ/kmolK)
$\dot{E}$	total exergy rate (kW)
$\dot{E}_d$	irreversibility rate (kW)
$\dot{E}_o$	chemical exergy rate (kW)
$\dot{E}_Q$	rate of heat exergy (kW)
$\dot{E}_{ph}$	physical exergy rate (kW)
h	specific enthalpy (kJ/kg)
$\dot{H}$	enthalpy rate (kW)
$\dot{m}$	mass flow rate (kg/s)
$\dot{n}$	molar flow rate (kmol/s)
P	pressure (kPa)
$\dot{Q}$	heat rate (kW)
$\bar{R}$	universal gas constant (kJ/kmolK)
s	specific entropy (kJ/kgK), mass fraction of S in the coal (-)
T	temperature (K)
$\dot{V}$	volumetric flow rate (m^3/h)
$\dot{W}$	power (kW)
x	mole fraction of gas mixture(-)

Greek letters

$\bar{\varepsilon}$	molar specific exergy (kJ/kmol)
ε	specific exergy (kJ/kg)
η	thermal(or first law) efficiency
ψ	exergy (or second law) efficiency

Subscripts

b	boiler
C	consumption
d	destruction
f	fuel

i	inlet, number of component
in	input
j	exit
k	location
L	loss
m	mixture
o	environmental state, chemical
out	output
ov	overall
p	constant pressure, pump
ph	physical
th	thermal

Superscripts

cw	cooling water
EPP	existing power plant
f	fuel
fw	feed water
g	gas
MPP	modified power plant
P	power
PP	power plant
st	steam
w	water

Abbreviations

B	boiler
Col	collector
FWP	feed water pump
FWT	feed water tank
HPH	high pressure heater
LPH	low pressure heater
P	pump
PDD	pressure drop diffuser
PSC	pressure steam collector
TA	turbo-aspirator
TB	turbo-blower
TG	turbo-generator
TBC	condencer of turbo-blower
TGC	condencer of turbo-generator

INTRODUCTİON

Today, technology is making a fast progress almost in every aspect and parallel to this, there is an increasing need for energy and energy sources are diminishing constantly. Consequently, under these circumstances, to reduce energy losses due to the inefficiencies occurred through conversion processes is as much important as the production process itself.

The general energy supply and environmental situation requires an improved utilization of energy sources. Therefore, the complexity of power-generating units has increased considerably. Plant owners are increasingly demanding a strictly guaranteed performance. This requires thermodynamic calculations of high accuracy. As a result, the expenditure for thermodynamic calculation during design and optimization has grown tremendously (Dincer and Al-Muslim, 2001).
In order to find the energy loss of a plant, energy analyses must be carried out and the quality of energy must be considered in addition to its quantity. Exergy analysis is used for examining the quality of energy. There have been many studies on the exergy analysis, especially after 1990s and there are many researches in the literature.

Recently, exergy analysis has become a key aspect in providing a better understanding of the process, to quantify sources of inefficiency, to distinguish quality of energy (or heat) used (Kopac, 2000; Bejan, 2002; Rosen and Dincer, 2003; Kopac and Zemher, 2004; Cihan et.al., 2006; Kopac and Hilalci, 2007; Rosen and Tag, 2007 and 2008; Brammer and Hessami, 2008; Balli et. al., 2008; Ameri et. al., 2009; Erdem et. al., 2009; Modesto and Nebra, 2009; Ajundi, 2009).

The objective of this paper is to obtain the units with high irreversibility in the system by applying the energy and exergy analysis together to the existing power plant in Iron and Steel Works Co and to made some suggestions for increasing efficiency.

SYSTEM DESCRIPTION AND ASSUMPTIONS MADE

Two schematic of the power plant (existing and modified) systems investigated are illustrated in Figures 1, 2. The existing power plant consists of four steam boilers, three steam turbines with three electrical generators (TG1, TG2, TG3), four turbo-blower (TB1, TB2, TB3, TB4), four pressure dropping diffusers (PDD1, PDD2, PDD3, PDD4), two feed water tanks (FWT1, FWT2), four collectors (col1, col2, col3, PSC), a turbo-pump (TP), two feed water pumps (FWP1, FWP2), seven circulation pumps (P1, P2, P3, P4, P4, P5, P6, P7), two high pressure heaters (HPH1, HPH2), two low pressure heaters (LPH1, LPH2), a turbo-aspirator (TA) and seven condensers (TG1C, TG2C, TG3C, TB1C, TB2C, TB3C, TB4C). The modified power plant consists of four steam boilers, four steam turbines with three electrical generators (TG1, TG2, TG3, TG4), four turbo-blower (TB1, TB2, TB3, TB4), a pressure dropping diffuser (PDD4), two feed water tanks (FWT1, FWT2), three collectors (col1, col2, col3), a turbo-pump (TP), two feed water pumps (FWP1, FWP2), seven circulation pumps (P1, P2, P3, P4, P4, P5, P6, P7), two high pressure heaters (HPH1, HPH2), two low pressure heaters (LPH1, LPH2), a turbo-aspirator (TA), a pressure steam collector and seven condensers (TG1C, TG2C, TG3C, TB1C, TB2C, TB3C, TB4C).

The TG1, TG2, TG3, TG4 electrical generators of steam turbines produced 12500, 12500, 2400, 6404 kW, respectively. The total pumps power used by the power plant system are 478 kW (W_p). The TB1 (turbine-blower), TB2, TB3, TB4, TA (turbine-aspirator) and TP (turbine-pump) steam turbines produced 3105, 1641, 1641, 772, 234 and 128 kW, respectively. PSC produced 13053 kW as a steam (0.85 MPa, 245 ^oC, 16 t/h) for the cook oven plant. The power plant produced 5323 kW (2.5 MPa, 380 ^oC, 6 t/h for the blast furnaces), 24328 kW (0.6 MPa, 280 ^oC, 29 t/h for the general processes), 13053 kW (0.85 MPa, 245 ^oC, 16 t/h for the cook oven plant) as a steam.

The following assumptions were made during this study:

(i) The power plant system operates in a steady-state condition.
(ii) The ideal gas principles are applied to air and combustion gas.
(iii) The combustion reaction is complete.
(iv) The exergies of kinetic and potential are neglected.
(v) The temperature and pressure of dead (environmental) state are 25 ^oC and 101.325 kPa, respectively.
(vi) The operation values of the plant are listed in Table 1.
(vii) The flow rate, the lower heating value, specific exergy and the composition of the fuels are listed in Tables 2, 3.

After combustion reaction, the flow rates and the mole fractions of the combustion gases are listed in Table 4.

EXERGY ANALYSIS OF THE POWER PLANT SYSTEM

Exergy is the amount of work obtained when a piece of matter is brought to a state of thermodynamic equilibrium with the common components of its surroundings by means of reversible processes. This a broad definition of exergy; thermodynamic equilibrium includes not only pressure and temperature but also chemical equilibrium with the substances of the environment.

The exergy balance for such a system in its basic form is essentially the same as for an open system undergoing purely physical processes, and can be written conveniently in the form (Kopac and Hilalci, 2007):

$$\sum_{IN}\dot{E}_i - \sum_{OUT}\dot{E}_j = -\dot{E}_{Q_{in}} + \dot{W}_{out} + \dot{E}_d \qquad (1)$$

where subscripts i and j refer to streams entering and leaving the control region, respectively. The exergy rate of a stream of substance (neglecting the potential and kinetic components) can be written in the form:

$$\dot{E} = \dot{E}_{ph} + \dot{E}_o \qquad (2)$$

where $\dot{E}_{ph}$ and $\dot{E}_o$ refer to physical and chemical exergy rate components, respectively.

Hence, using molar quantities, the LHS of Equation (1) is:

$$\left(\sum_{IN}\dot{n}_i\bar{\varepsilon}_{ph,i} - \sum_{OUT}\dot{n}_j\bar{\varepsilon}_{ph,j}\right) + \left(\sum_{IN}\dot{n}_i\bar{\varepsilon}_{0,i} - \sum_{OUT}\dot{n}_j\bar{\varepsilon}_{0,j}\right) = -\dot{E}_{Q_{in}} + \dot{W}_{out} \qquad (3)$$

allowing the chemical and physical changes in the exergy of the streams of matter to be dealt with separately. Where $\bar{\varepsilon}$, $\dot{E}_{Q_{in}}$, $\dot{W}_{out}$ and $\dot{E}_d$ refer to specific molar exergy, source heat exergy rate, power output and exergy destruction rate (irreversibility rate), respectively.

If the streams consist of pure substances their chemical exergies can be obtained from Kotas's tables (Kotas, 1995).

A simple combustion process is an exothermic chemical reaction; the reactants are usually air and fuel and the products are mainly of a mixture of common environmental substances. A method of calculating the chemical exergy of industrial fuel in solid and gas form are given by Kotas (1995).

The most general definition of physical exergy can be expressed in molar form as:

$$\bar{\varepsilon}_{ph} = (\bar{h} - \bar{h}_o) - T_o(\bar{s} - \bar{s}_o) \qquad (4)$$

which can be used with suitable property tables when considering, for example, steam, water, and other liquids and solids. For an ideal gas may be conveniently expressed in terms of the thermal component $\bar{\varepsilon}^{\Delta T}$ and pressure component $\bar{\varepsilon}^{\Delta P}$ as:

$$\bar{\varepsilon}_{ph} = \bar{c}_p^{\varepsilon}(T - T_o) + \bar{R}T_o \ln\frac{P}{P_o} \qquad (5)$$

where $\bar{c}_p^{\varepsilon}$ is mean isobaric exergy capacity of some gases.

It follows from the Gibbs-Dalton rules that the physical exergy of a mixture of n components can be evaluated from:

$$(\bar{\varepsilon}_{ph})_m = \sum_{k=1}^{n} x_k \bar{\varepsilon}_k^{\Delta T} + \bar{R}T_o \ln(\frac{P}{P_o}) \qquad (6)$$

where P is the total pressure of the mixture. Using tabulated values of $\bar{c}_p^{\varepsilon}$, Equation (6) may be written in the alternative form:

$$(\bar{\varepsilon}_{ph})_m = (T - T_o)\sum_{k=1}^{n} x_k \bar{c}_{p,k}^{\varepsilon} + \bar{R}T_o \ln(\frac{P}{P_o}) \qquad (7)$$

where $\bar{c}_p^{\varepsilon}$ is molar mean isobaric exergy capacity.

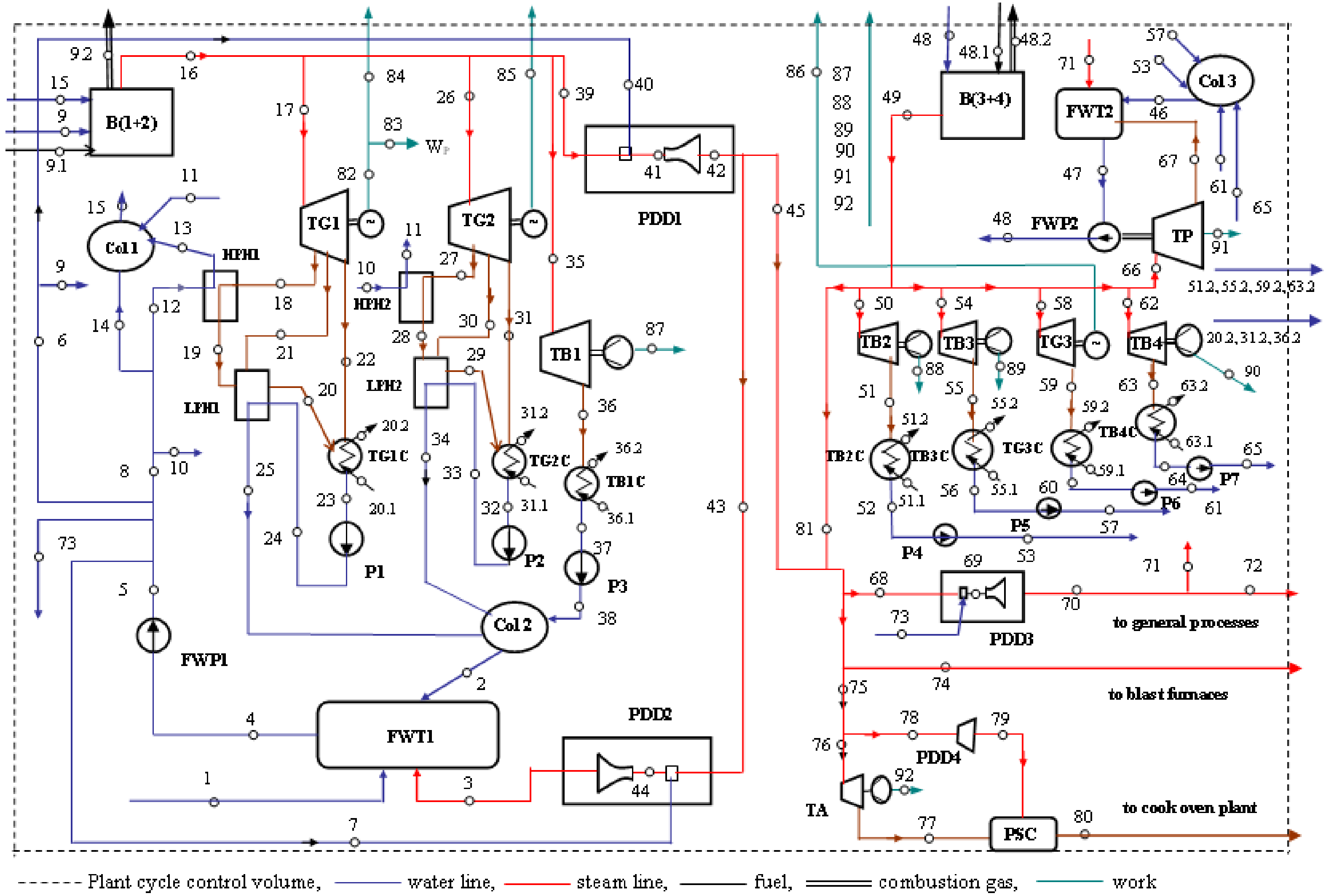
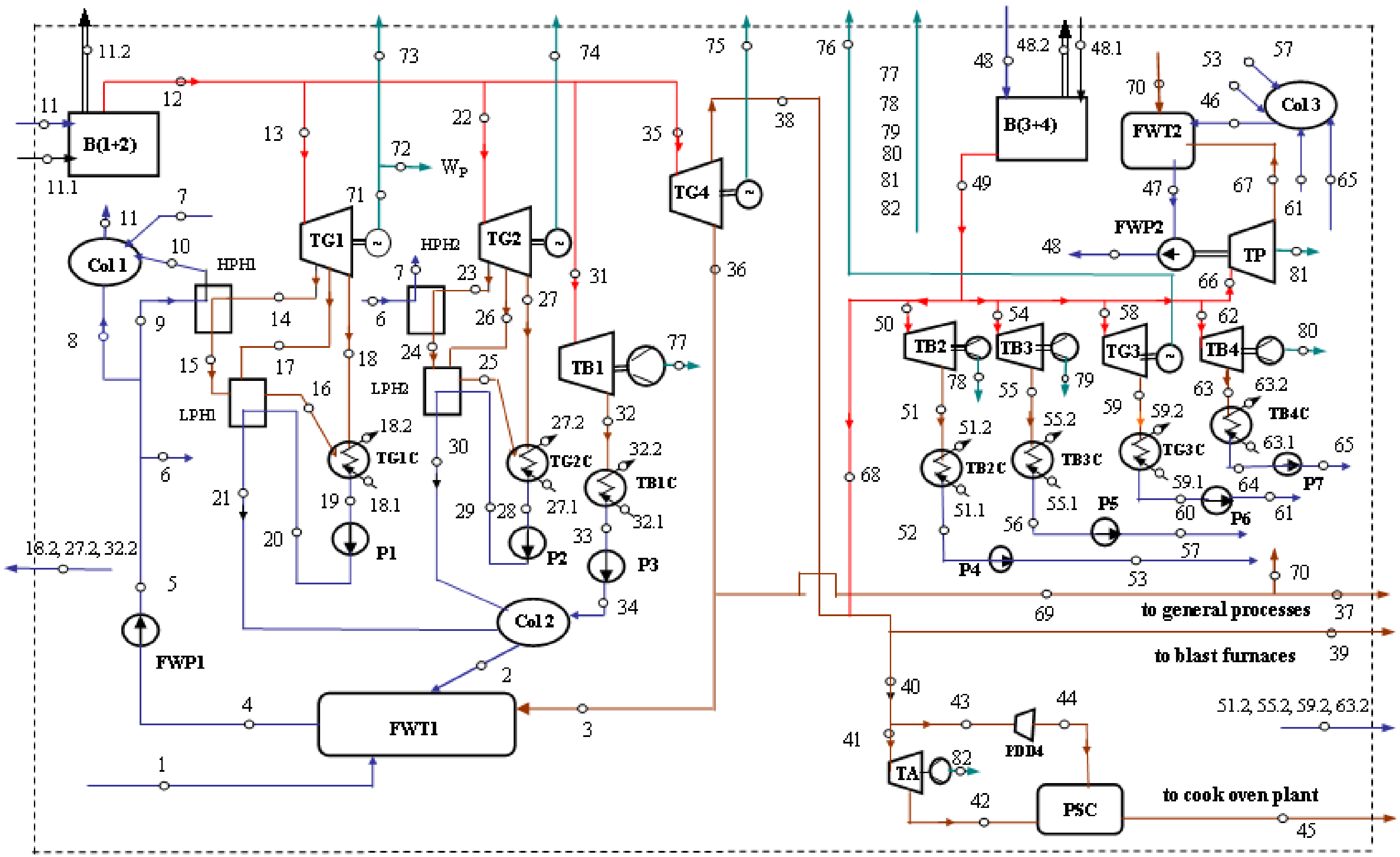


Figure 1. The schematic of the existing power plant system investigated.



- - - - - Plant cycle control volume, ——— water line, ——— steam line, ——— fuel, ═══ combustion gas, ——— work

Figure 2. The schematic of the modified power plant system investigated.

Table 1. Operation values of the existing-modified plant

	existing plant	modified plant
Net power output, kW	34443	**40847**
Total mass flow rate of steam (boiler 1+2), t/h	200	**208**
Output pressure of the boilers (1, 2), MPa	6.6	6.6
Output temperature of the steam in the boiler (1, 2), ^oC	505	505
Inlet temperature of cooling water in the condenser (TG1C, TG2C), ^oC	26	26
Output temperature of cooling water in the condenser (TG1C, TG2C), ^oC	40	40
Mass flow rate of cooling water of the condenser (TG1C, TG2C), t/h	2125	2125
Inlet temperature of cooling water in the condenser (TB1C), ^oC	26	26
Output temperature of cooling water in the condenser (TB1C), ^oC	43	43
Mass flow rate of cooling water of the condenser (TB1C), t/h	468	468
Total mass flow rate of steam (boiler 3+4), t/h	50	50
Output pressure of the boilers (3, 4), MPa	2.6	2.6
Output temperature of the steam in the boiler (3, 4), ^oC	385	385
Inlet temperature of cooling water in the condenser (TB2C, TB3C), ^oC	26	26
Output temperature of cooling water in the condenser (TB2C, TB3C), ^oC	36	36
Mass flow rate of cooling water of the condenser (TB2C, TB3C), t/h	680	680
Inlet temperature of cooling water in the condenser (TG3C), ^oC	26	26
Output temperature of cooling water in the condenser (TG3C), ^oC	35	35
Mass flow rate of cooling water of the condenser (TG3C), t/h	945	945
Inlet temperature of cooling water in the condenser (TB4C), ^oC	26	26
Output temperature of cooling water in the condenser (TB4C), ^oC	29	29
Mass flow rate of cooling water of the condenser (TB4C), t/h	1130	1130
Pressure of combustion products, kPa	106.62	106.62
Temperature of combustion products, ^oC	150	150
Mechanical efficiency, %	95	95
Electrical efficiency, %	98	98

Table 2. The values of the fuels and the combustion air in the existing and modified plants (for a single boiler)

	Existing plant		Modified plant			
	Flow rate		Flow rate		Lower heating value	Specific exergy
Fuel	boiler (1,2)	boiler (3,4)	boiler (1,2)	boiler (3,4)		
Coal	6 t/h	----	6 t/h	----	29937 kJ/kg	32272 kJ/kg
Coke gas	0.88 m^3/s	0.88 m^3/s	0.88 m^3/s	0.88 m^3/s	16545 kJ/m^3	17372 kJ/m^3
Blast furnace gas	7.1 m^3/s	3.55 m^3/s	**8.3 m^3/s**	3.55 m^3/s	3109 kJ/m^3	3050 kJ/m^3
Combustion air	80000 m^3/h	32832 m^3/h	**83196 m^3/h**	32832 m^3/h	---	---

Table 3. The compositions of the fuels and air (%)

coal (mass)		coke gas (volumetric)		blast furnace gas (volumetric)	
humidity	12.75	CH_4	22.18	CO	23.12
ash	13.06	CO	6.95	CO_2	18.08
C	60.39	CO_2	3.02	H_2	1.74
H_2	4.00	H_2	57.58	N_2	57.06
S	0.60	C_2H_4	1.46	air (volumetric)	
N_2	1.20	N_2	7.14		
O_2	8.00	O_2	0.36	humidity	0.3
		C_2H_6	0.49	N_2	20.9
		C_2H_2	0.82	O_2	78.8

Table 4. The values of the products of combustion (for a single boiler)

	Product	Existing plant		Modified plant	
		flow rate, $\dot{V}$	mole fraction, x	flow rate, $\dot{V}$	mole fraction, x
		m^3/s	---	m^3/s	---
Boiler 1,2	CO_2	5.1331	0.16770	**5.6174**	**0.1725**
	H_2O	2.1525	0.07034	**2.1755**	**0.0668**
	SO_2	0.0070	0.00023	**0.00647**	**0.0002**
	O_2	0.9180	0.03000	**0.9928**	**0.0305**
	N_2	22.389	0.73170	**23.773**	**0.7300**
Boiler 3,4	CO_2	1.7879	0.13200	1.7879	0.13200
	H_2O	1.0384	0.07660	1.0384	0.07660
	O_2	0.4065	0.03000	0.4065	0.03000
	N_2	10.3163	0.76140	10.3163	0.76140

In the exergy analysis of power plants, exergy of steam is computed at all states and changes in exergy are determined for each major component. Unlike energy, exergy is not conserved but destroyed in the system. In the components of the plant exergy is dissipated during a process because of friction, mixing, combustion, heat transfer, etc. The source of exergy destruction (or irreversibility) in both the boiler and turbine is mainly combustion (chemical reaction), frictional, thermal losses in the flow path (Cihan et. al. 2006), in the heat exchangers of the system (condenser, feed water heater) is due to the large temperature difference between the hot and cold fluid.

The schematic of subcomponents of the investigated power plants and exergy balance equations are given in Tables 5, 6. The exergy destructions ($\dot{E}_d$) occur due to irreversibilities within a component or system. The exergy loses ($\dot{E}_L$) occur when the energy associated with a material or energy stream as stack gas and condenser outlet water is rejected to the environment. The exergy loses for the plants system are given as fallows:

$$\dot{E}_L^{EPP} = \dot{E}_{9.2}^{g} + \dot{E}_{48.2}^{g} + \dot{E}_{20.2}^{w} + \dot{E}_{31.2}^{w} + \dot{E}_{36.2}^{w} + \dot{E}_{51.2}^{w} + \dot{E}_{55.2}^{w} + \dot{E}_{59.2}^{w} + \dot{E}_{63.2}^{w} + \dot{E}_{72}^{st} + \dot{E}_{74}^{st} + \dot{E}_{80}^{st} \quad (8)$$

$$\dot{E}_L^{MPP} = \dot{E}_{11.2}^{g} + \dot{E}_{48.2}^{g} + \dot{E}_{18.2}^{w} + \dot{E}_{27.2}^{w} + \dot{E}_{32.2}^{w} + \dot{E}_{51.2}^{w} + \dot{E}_{55.2}^{w} + \dot{E}_{59.2}^{w} + \dot{E}_{63.2}^{w} + \dot{E}_{37}^{st} + \dot{E}_{39}^{st} + \dot{E}_{45}^{st} \quad (9)$$

The exergy consumption ($\dot{E}_C$) for a system is the sum of the exergy destructions and the exergy loses for the plant system. The exergy consumption ($\dot{E}_C$) is given as follows:

$$\dot{E}_C^{PP} = \dot{E}_L^{PP} + \dot{E}_d^{PP} \quad (10)$$

Neither the existing plant including the PSC steam (state no. 80), the steams (state nos. 72, 74) nor the modified plant including the PSC steam (state no. 45), the steams (state nos. 37, 39) as process steams produced by the systems are not used. In this situation, for the existing plant, the exergy loses consist of the stack gases (state nos. 9.2, 48.2) exergies, steam outlet exergies (state nos. 72, 74, 80) and exergy of condensers outlet (state nos. 20.2, 31.2, 36.2, 51.2, 55.2, 59.2, 63.2). For the modified plant, the exergy loses consist of the stack gases (state nos. 11.2, 48.2) exergies, steam outlet exergies (state nos. 37, 39, 45) and exergy of condensers outlet (state nos. 18.2, 27.2, 32.2, 51.2, 55.2, 59.2, 63.2).

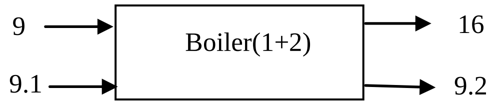
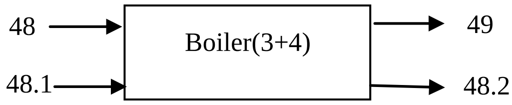
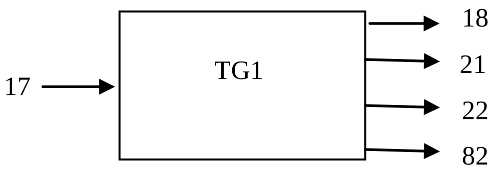
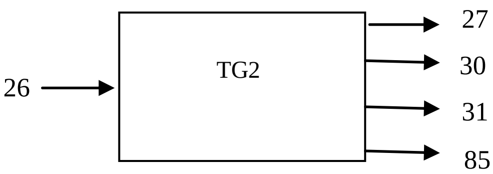
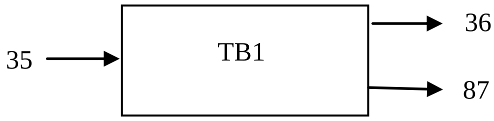
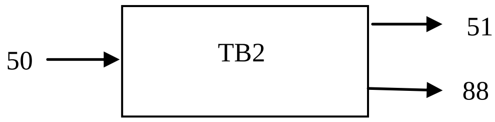
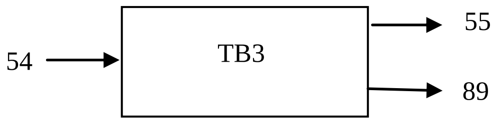
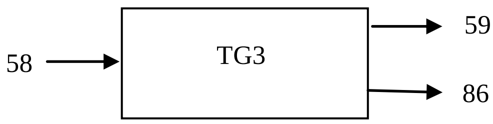
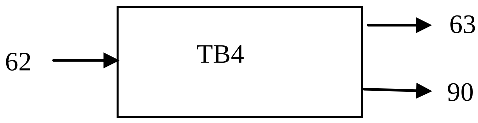
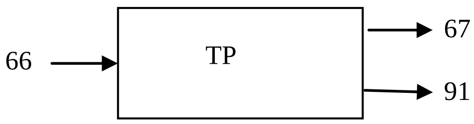
The overall thermal efficiency and the overall exergy efficiency of the plant are calculated from Equations (10, 11)

$$\eta_{ov} = \frac{\dot{W}_{net}}{\dot{H}_f} \quad (10)$$

$$\psi_{ov} = \frac{\dot{W}_{net}}{\dot{E}_f} = 1 - \frac{\dot{E}_d^{PP} + \dot{E}_L^{PP} + \dot{W}_p}{\dot{E}_f} \quad (11)$$

The exergy consumption (E_C) consists of the exergy destruction for the components, exergy loses for the outlet steam exergies, the stack gases exergies and the condensers outlet exergies for the plant

Table 5. Exergy balance equations for the subsystem of the existing plant.

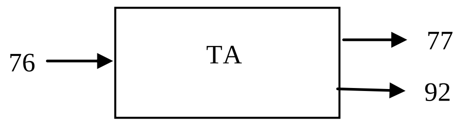
No	Control volume	Exergy balance equations
1		$\dot{E}_{9.1}^{f} + \dot{E}_{9}^{fw} - \dot{E}_{16}^{st} - \dot{E}_{9.2}^{g} = \dot{E}_{d}^{B1+2}$
2		$\dot{E}_{48.1}^{f} + \dot{E}_{48}^{fw} - \dot{E}_{49}^{st} - \dot{E}_{48.2}^{g} = \dot{E}_{d}^{B3+4}$
3		$\dot{E}_{17}^{st} - \dot{E}_{18}^{st} - \dot{E}_{21}^{st} - \dot{E}_{22}^{st} - \dot{E}_{82}^{P} = \dot{E}_{d}^{TG1}$
4		$\dot{E}_{26}^{st} - \dot{E}_{27}^{st} - \dot{E}_{30}^{st} - \dot{E}_{31}^{st} - \dot{E}_{85}^{P} = \dot{E}_{d}^{TG2}$
5		$\dot{E}_{35}^{st} - \dot{E}_{36}^{st} - \dot{E}_{87}^{P} = \dot{E}_{d}^{TB1}$
6		$\dot{E}_{50}^{st} - \dot{E}_{51}^{st} - \dot{E}_{88}^{P} = \dot{E}_{d}^{TB2}$
7		$\dot{E}_{54}^{st} - \dot{E}_{55}^{st} - \dot{E}_{89}^{P} = \dot{E}_{d}^{TB3}$
8		$\dot{E}_{58}^{st} - \dot{E}_{59}^{st} - \dot{E}_{86}^{P} = \dot{E}_{d}^{TG3}$
9		$\dot{E}_{62}^{st} - \dot{E}_{63}^{st} - \dot{E}_{90}^{P} = \dot{E}_{d}^{TB4}$
10		$\dot{E}_{66}^{st} - \dot{E}_{67}^{st} - \dot{E}_{91}^{P} = \dot{E}_{d}^{TP}$

.

Table 5. *Continued.*

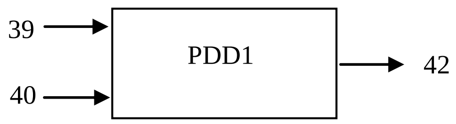
No	Control volume	Exergy balance equations

11



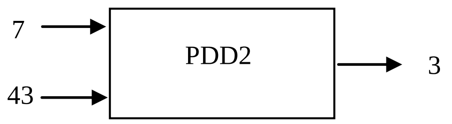
$$\dot{E}^{st}_{76} - \dot{E}^{st}_{77} - \dot{E}^{P}_{92} = \dot{E}^{TA}_{d}$$

12



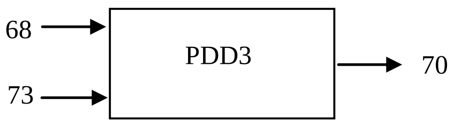
$$\dot{E}^{st}_{39} + \dot{E}^{fw}_{40} - \dot{E}^{st}_{42} = \dot{E}^{PDD1}_{d}$$

13



$$\dot{E}^{st}_{43} + \dot{E}^{fw}_{7} - \dot{E}^{st}_{3} = \dot{E}^{PDD2}_{d}$$

14

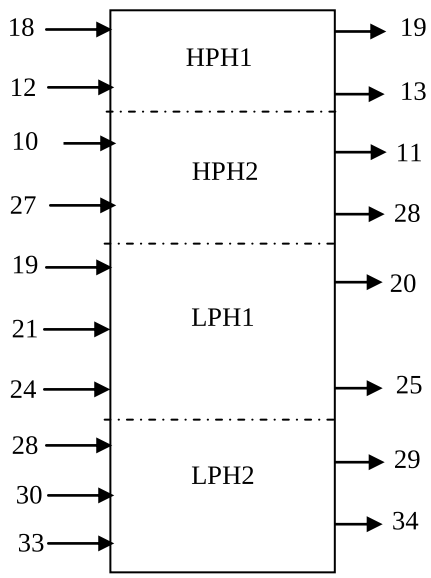


$$\dot{E}^{st}_{68} + \dot{E}^{fw}_{73} - \dot{E}^{st}_{70} = \dot{E}^{PDD3}_{d}$$

15

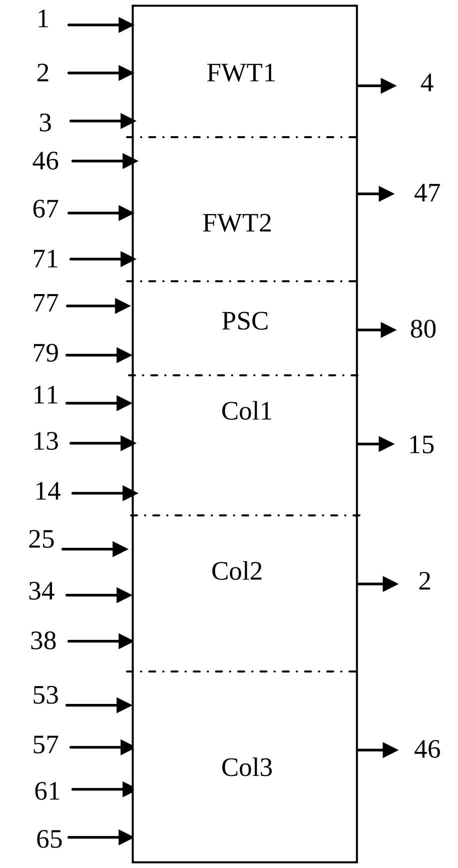
$$\dot{E}^{st}_{78} - \dot{E}^{st}_{79} = \dot{E}^{PDD4}_{d}$$

16



$$\begin{pmatrix} \dot{E}^{fw}_{12} + \dot{E}^{st}_{18} - \dot{E}^{fw}_{13} - \dot{E}^{st}_{19} \\ + \dot{E}^{fw}_{10} + \dot{E}^{st}_{27} - \dot{E}^{fw}_{11} - \dot{E}^{st}_{28} \\ + \dot{E}^{st}_{19} + \dot{E}^{st}_{21} + \dot{E}^{fw}_{24} - \dot{E}^{st}_{20} - \dot{E}^{fw}_{25} \\ + \dot{E}^{st}_{28} + \dot{E}^{st}_{30} + \dot{E}^{fw}_{33} - \dot{E}^{st}_{29} - \dot{E}^{fw}_{34} \end{pmatrix} = \begin{pmatrix} \dot{E}^{HPH1}_{d} \\ + \dot{E}^{HPH2}_{d} \\ + \dot{E}^{LPH1}_{d} \\ + \dot{E}^{LPH2}_{d} \end{pmatrix}$$

Table 5. *Continued.*

<table>
<tr><th>No</th><th>Control volume</th><th>Exergy balance equations</th></tr>
<tr><td>17</td><td>


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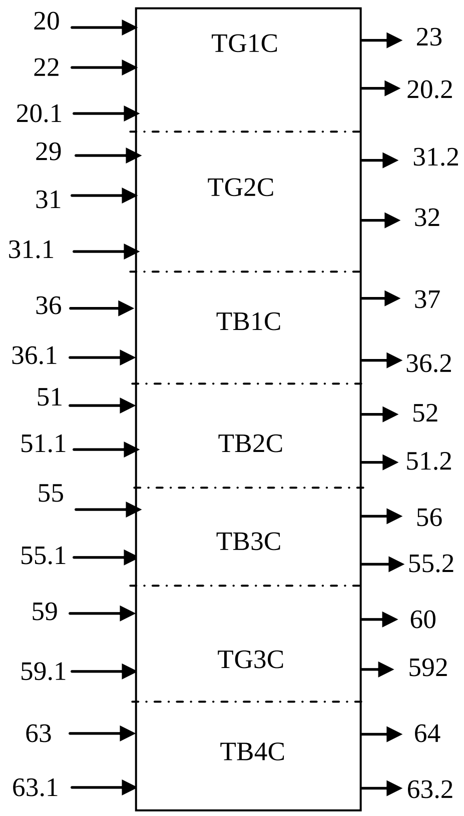
$$\begin{pmatrix} \dot{E}_{1}^{fw}+\dot{E}_{2}^{fw}+\dot{E}_{3}^{st}-\dot{E}_{4}^{fw} \\ +\dot{E}_{46}^{fw}+\dot{E}_{67}^{st}+\dot{E}_{71}^{st}-\dot{E}_{47}^{fw} \\ +\dot{E}_{77}^{st}+\dot{E}_{79}^{st}-\dot{E}_{80}^{st} \\ +\dot{E}_{11}^{fw}+\dot{E}_{13}^{fw}+\dot{E}_{14}^{fw}-\dot{E}_{15}^{fw} \\ +\dot{E}_{25}^{fw}+\dot{E}_{34}^{fw}+\dot{E}_{38}^{fw}-\dot{E}_{2}^{fw} \\ +\dot{E}_{53}^{fw}+\dot{E}_{57}^{fw}+\dot{E}_{61}^{fw}+\dot{E}_{65}^{fw}-\dot{E}_{46}^{fw} \end{pmatrix} = \begin{pmatrix} \dot{E}_{d}^{FWT1} \\ +\dot{E}_{d}^{FWT2} \\ +\dot{E}_{d}^{PSC} \\ +\dot{E}_{d}^{Col1} \\ +\dot{E}_{d}^{Col2} \\ +\dot{E}_{d}^{Col3} \end{pmatrix}$$

</td></tr>
<tr><td>18</td><td>


</td><td>

$$\begin{pmatrix} \dot{E}_{20}^{st}+\dot{E}_{22}^{st}+\dot{E}_{20.1}^{cw}-\dot{E}_{23}^{fw}-\dot{E}_{20.2}^{cw} \\ +\dot{E}_{29}^{st}+\dot{E}_{31}^{st}+\dot{E}_{31.1}^{cw}-\dot{E}_{32}^{fw}-\dot{E}_{31.2}^{cw} \\ +\dot{E}_{36}^{st}+\dot{E}_{36.1}^{cw}-\dot{E}_{37}^{fw}-\dot{E}_{36.2}^{cw} \\ +\dot{E}_{51}^{st}+\dot{E}_{51.1}^{cw}-\dot{E}_{52}^{fw}-\dot{E}_{51.2}^{cw} \\ +\dot{E}_{55}^{st}+\dot{E}_{55.1}^{cw}-\dot{E}_{56}^{fw}-\dot{E}_{55.2}^{cw} \\ +\dot{E}_{59}^{st}+\dot{E}_{59.1}^{cw}-\dot{E}_{60}^{fw}-\dot{E}_{59.2}^{cw} \\ +\dot{E}_{63}^{st}+\dot{E}_{63.1}^{cw}-\dot{E}_{64}^{fw}-\dot{E}_{63.2}^{cw} \end{pmatrix} = \begin{pmatrix} \dot{E}_{d}^{TG1C} \\ +\dot{E}_{d}^{TG2C} \\ +\dot{E}_{d}^{TB1C} \\ +\dot{E}_{d}^{TB2C} \\ +\dot{E}_{d}^{TB3C} \\ +\dot{E}_{d}^{TG3C} \\ +\dot{E}_{d}^{TB4C} \end{pmatrix}$$

</td></tr>
</table>

Table 5. *Continued.*

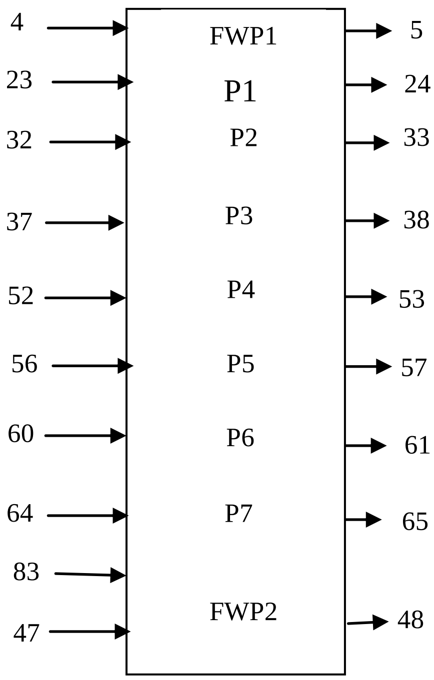
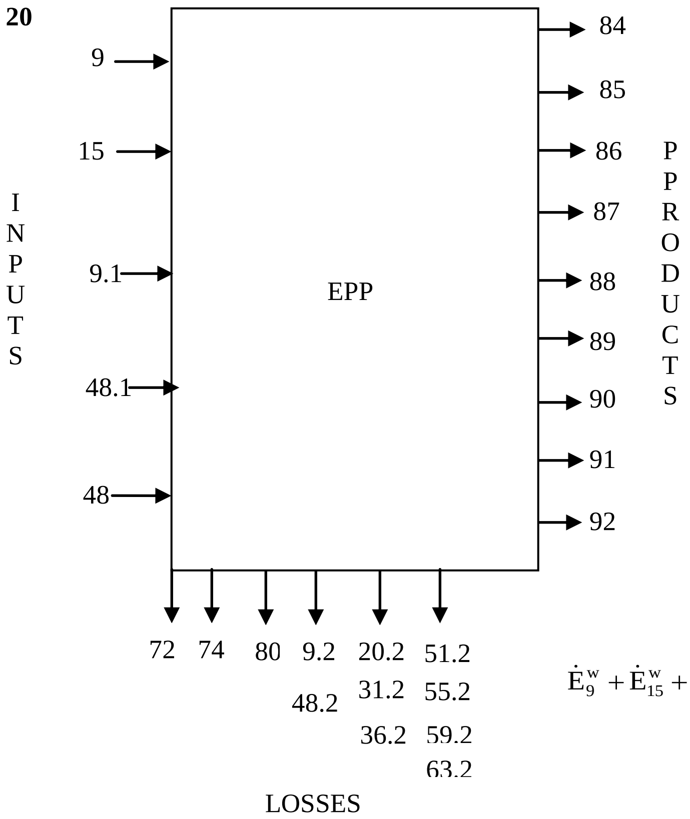
No	Control volume	Exergy balance equations
19		$\begin{pmatrix}\dot{E}_4^{fw}+\dot{E}_{23}^{fw}+\dot{E}_{32}^{fw}\\ +\dot{E}_{37}^{fw}+\dot{E}_{52}^{fw}+\dot{E}_{56}^{fw}\\ +\dot{E}_{60}^{fw}+\dot{E}_{64}^{fw}+\dot{E}_{47}^{fw}\\ +\dot{E}_{83}^{p}-\dot{E}_{5}^{fw}-\dot{E}_{24}^{fw}\\ -\dot{E}_{33}^{fw}-\dot{E}_{38}^{fw}-\dot{E}_{53}^{fw}\\ -\dot{E}_{57}^{fw}-\dot{E}_{61}^{fw}-\dot{E}_{65}^{fw}\\ -\dot{E}_{48}^{fw}\end{pmatrix}=\begin{pmatrix}\dot{E}_d^{FWP1}+\dot{E}_d^{P1}\\ +\dot{E}_d^{P2}+\dot{E}_d^{P3}\\ +\dot{E}_d^{P4}+\dot{E}_d^{P5}\\ +\dot{E}_d^{P6}+\dot{E}_d^{P7}\\ +\dot{E}_d^{FWP2}\end{pmatrix}$
20		$\begin{pmatrix}\dot{E}_{72}^{st}+\dot{E}_{74}^{st}+\dot{E}_{80}^{st}\\ +\dot{E}_{9.2}^{g}+\dot{E}_{48.2}^{g}+\dot{E}_{20.2}^{w}\\ +\dot{E}_{31.2}^{w}+\dot{E}_{36.2}^{w}+\dot{E}_{51.2}^{w}\\ +\dot{E}_{55.2}^{w}+\dot{E}_{59.2}^{w}+\dot{E}_{63.2}^{w}\end{pmatrix}=\dot{E}_L^{EPP}$ $\begin{pmatrix}\dot{E}_{84}^{P}+\dot{E}_{85}^{P}+\dot{E}_{86}^{P}+\dot{E}_{87}^{P}\\ +\dot{E}_{88}^{P}+\dot{E}_{89}^{P}+\dot{E}_{90}^{P}+\dot{E}_{91}^{P}\\ +\dot{E}_{92}^{P}\end{pmatrix}=\dot{E}_P^{EPP}$ $\dot{E}_9^{w}+\dot{E}_{15}^{w}+\dot{E}_{48}^{w}+\dot{E}_{9.1}^{f}+\dot{E}_{48.1}^{f}-\dot{E}_L^{EPP}-\dot{E}_P^{EPP}=\dot{E}_d^{EPP}$ $\dot{E}_L^{EPP}+\dot{E}_d^{EPP}=\dot{E}_C^{EPP}$

Table 6. Exergy balance equations for the subsystem of the modified plant.

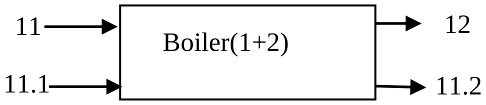
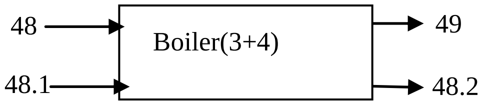
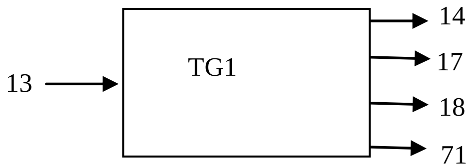
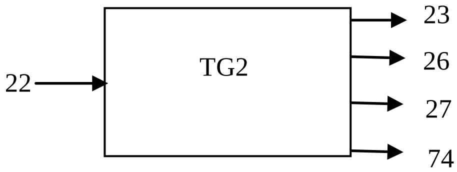
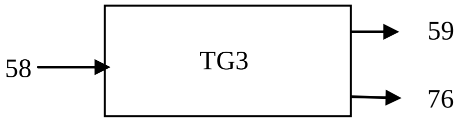
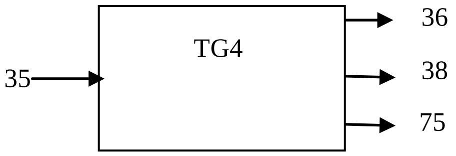
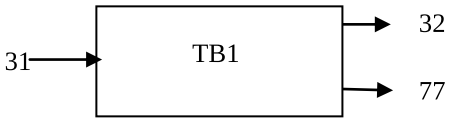
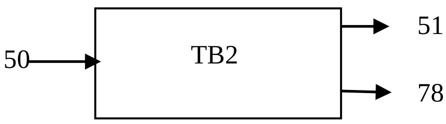
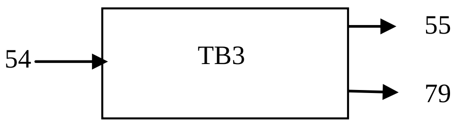
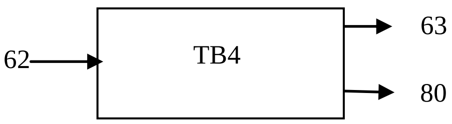
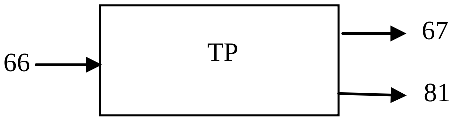
No	Control volume	Exergy balance equations
1		$\dot{E}^{f}_{11.1} + \dot{E}^{fw}_{11} - \dot{E}^{st}_{12} - \dot{E}^{g}_{11.2} = \dot{E}^{B1+2}_{d}$
2		$\dot{E}^{f}_{48.1} + \dot{E}^{fw}_{48} - \dot{E}^{st}_{49} - \dot{E}^{g}_{48.2} = \dot{E}^{B3+4}_{d}$
3		$\dot{E}^{st}_{13} - \dot{E}^{st}_{14} - \dot{E}^{st}_{17} - \dot{E}^{st}_{18} - \dot{E}^{P}_{71} = \dot{E}^{TG1}_{d}$
4		$\dot{E}^{st}_{22} - \dot{E}^{st}_{23} - \dot{E}^{st}_{26} - \dot{E}^{st}_{27} - \dot{E}^{P}_{74} = \dot{E}^{TG2}_{d}$
5		$\dot{E}^{st}_{58} - \dot{E}^{st}_{59} - \dot{E}^{P}_{76} = \dot{E}^{TG3}_{d}$
6		$\dot{E}^{st}_{35} - \dot{E}^{st}_{36} - \dot{E}^{st}_{38} - \dot{E}^{P}_{75} = \dot{E}^{TG4}_{d}$
7		$\dot{E}^{st}_{31} - \dot{E}^{st}_{32} - \dot{E}^{P}_{77} = \dot{E}^{TB1}_{d}$
8		$\dot{E}^{st}_{50} - \dot{E}^{st}_{51} - \dot{E}^{P}_{78} = \dot{E}^{TB2}_{d}$
9		$\dot{E}^{st}_{54} - \dot{E}^{st}_{55} - \dot{E}^{P}_{79} = \dot{E}^{TB3}_{d}$
10		$\dot{E}^{st}_{62} - \dot{E}^{st}_{63} - \dot{E}^{P}_{80} = \dot{E}^{TB4}_{d}$
11		$\dot{E}^{st}_{66} - \dot{E}^{st}_{67} - \dot{E}^{P}_{81} = \dot{E}^{TP}_{d}$

Table 6. *Continued.*

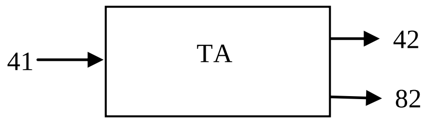
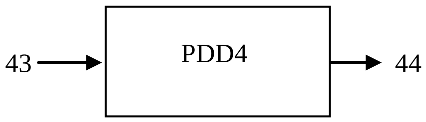
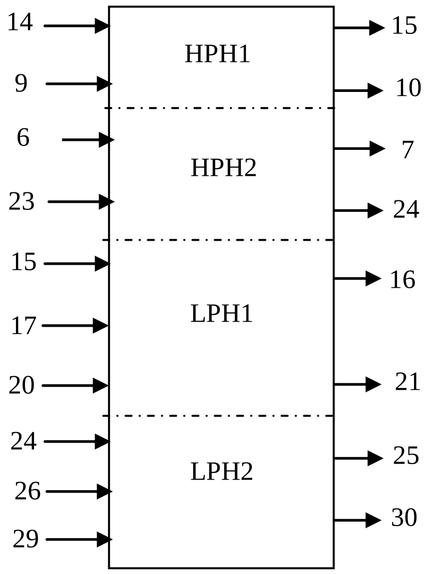
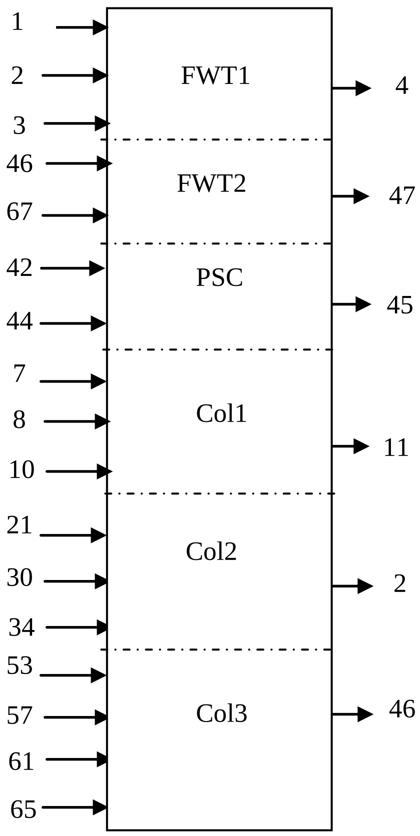
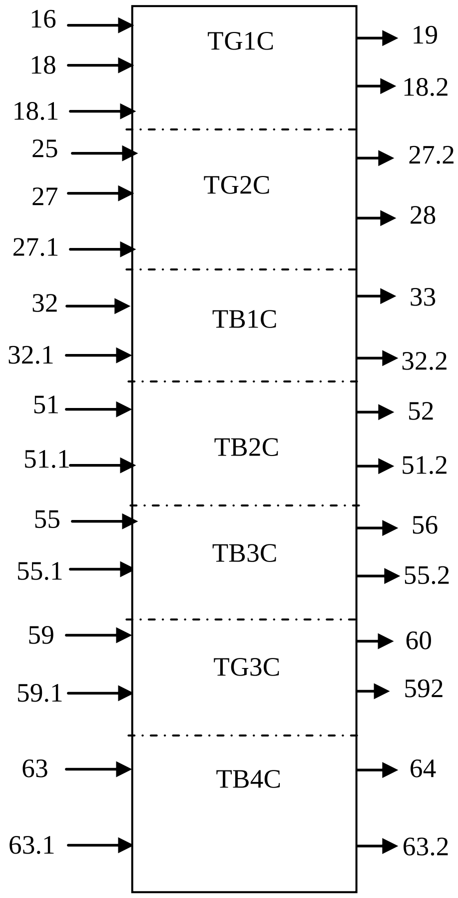
No	Control volume	Exergy balance equations
12		$\dot{E}^{st}_{41} - \dot{E}^{st}_{42} - \dot{E}^{P}_{82} = \dot{E}^{TA}_{d}$
13		$\dot{E}^{fw}_{43} - \dot{E}^{st}_{44} = \dot{E}^{PDD4}_{d}$
14		$\begin{pmatrix} \dot{E}^{fw}_{9} + \dot{E}^{st}_{14} - \dot{E}^{fw}_{10} - \dot{E}^{st}_{15} \\ + \dot{E}^{fw}_{6} + \dot{E}^{st}_{23} - \dot{E}^{fw}_{7} - \dot{E}^{st}_{24} \\ + \dot{E}^{st}_{15} + \dot{E}^{st}_{17} + \dot{E}^{fw}_{20} - \dot{E}^{st}_{16} - \dot{E}^{fw}_{21} \\ + \dot{E}^{st}_{24} + \dot{E}^{st}_{26} + \dot{E}^{fw}_{29} - \dot{E}^{st}_{25} - \dot{E}^{fw}_{30} \end{pmatrix} = \begin{pmatrix} \dot{E}^{HPH1}_{d} \\ + \dot{E}^{HPH2}_{d} \\ + \dot{E}^{LPH1}_{d} \\ + \dot{E}^{LPH2}_{d} \end{pmatrix}$
15		$\begin{pmatrix} \dot{E}^{fw}_{1} + \dot{E}^{fw}_{2} + \dot{E}^{st}_{3} - \dot{E}^{fw}_{4} \\ + \dot{E}^{fw}_{46} + \dot{E}^{st}_{67} - \dot{E}^{fw}_{47} \\ + \dot{E}^{st}_{42} + \dot{E}^{st}_{44} - \dot{E}^{st}_{45} \\ + \dot{E}^{fw}_{7} + \dot{E}^{fw}_{8} + \dot{E}^{fw}_{10} - \dot{E}^{fw}_{11} \\ + \dot{E}^{fw}_{21} + \dot{E}^{fw}_{30} + \dot{E}^{fw}_{34} - \dot{E}^{fw}_{2} \\ + \dot{E}^{fw}_{53} + \dot{E}^{fw}_{57} + \dot{E}^{fw}_{61} + \dot{E}^{fw}_{65} - \dot{E}^{fw}_{46} \end{pmatrix} = \begin{pmatrix} \dot{E}^{FWT1}_{d} \\ + \dot{E}^{FWT2}_{d} \\ + \dot{E}^{PSC}_{d} \\ + \dot{E}^{Col1}_{d} \\ + \dot{E}^{Col2}_{d} \\ + \dot{E}^{Col3}_{d} \end{pmatrix}$

Table 6. *Continued.*

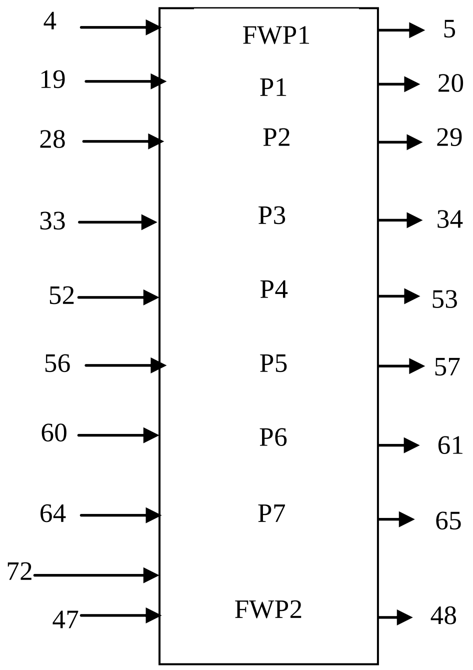
No	Control volume	Exergy balance equations

16



$$\left(\begin{array}{l} \dot{E}^{st}_{16}+\dot{E}^{st}_{18}+\dot{E}^{cw}_{18.1}-\dot{E}^{fw}_{19}-\dot{E}^{cw}_{18.2} \\ +\dot{E}^{st}_{25}+\dot{E}^{st}_{27}+\dot{E}^{cw}_{27.1}-\dot{E}^{fw}_{28}-\dot{E}^{cw}_{27.2} \\ +\dot{E}^{st}_{32}+\dot{E}^{cw}_{32.1}-\dot{E}^{fw}_{33}-\dot{E}^{cw}_{32.2} \\ +\dot{E}^{st}_{51}+\dot{E}^{cw}_{51.1}-\dot{E}^{fw}_{52}-\dot{E}^{cw}_{51.2} \\ +\dot{E}^{st}_{55}+\dot{E}^{cw}_{55.1}-\dot{E}^{fw}_{56}-\dot{E}^{cw}_{55.2} \\ +\dot{E}^{st}_{59}+\dot{E}^{cw}_{59.1}-\dot{E}^{fw}_{60}-\dot{E}^{cw}_{59.2} \\ +\dot{E}^{st}_{63}+\dot{E}^{cw}_{63.1}-\dot{E}^{fw}_{64}-\dot{E}^{cw}_{63.2} \end{array}\right)=\left(\begin{array}{l} \dot{E}^{TG1C}_{d} \\ +\dot{E}^{TG2C}_{d} \\ +\dot{E}^{TB1C}_{d} \\ +\dot{E}^{TB2C}_{d} \\ +\dot{E}^{TB3C}_{d} \\ +\dot{E}^{TG3C}_{d} \\ +\dot{E}^{TB4C}_{d} \end{array}\right)$$

17

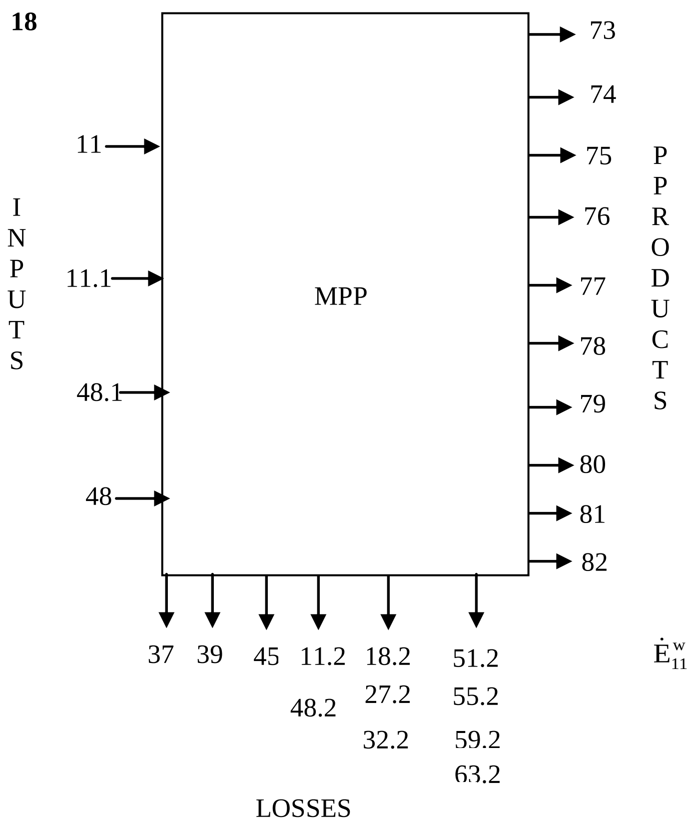


$$\left(\begin{array}{l} \dot{E}^{fw}_{4}+\dot{E}^{fw}_{19}+\dot{E}^{fw}_{28} \\ +\dot{E}^{fw}_{33}+\dot{E}^{fw}_{52}+\dot{E}^{fw}_{56} \\ +\dot{E}^{fw}_{60}+\dot{E}^{fw}_{64}+\dot{E}^{fw}_{47} \\ -\dot{E}^{fw}_{5}-\dot{E}^{fw}_{20}-\dot{E}^{fw}_{29} \\ -\dot{E}^{fw}_{34}-\dot{E}^{fw}_{53}-\dot{E}^{fw}_{57} \\ -\dot{E}^{fw}_{61}-\dot{E}^{fw}_{65}-\dot{E}^{fw}_{48} \\ +\dot{E}^{p}_{72} \end{array}\right)=\left(\begin{array}{l} \dot{E}^{FWP1}_{d}+\dot{E}^{P1}_{d} \\ +\dot{E}^{P2}_{d}+\dot{E}^{P3}_{d} \\ +\dot{E}^{P4}_{d}+\dot{E}^{P5}_{d} \\ +\dot{E}^{P6}_{d}+\dot{E}^{P7}_{d} \\ +\dot{E}^{FWP2}_{d} \end{array}\right)$$

Table 6. *Continued.*

No	Control volume	Exergy balance equations

18



$$\begin{pmatrix} \dot{E}^{st}_{37}+\dot{E}^{st}_{39}+\dot{E}^{st}_{45} \\ +\dot{E}^{g}_{11.2}+\dot{E}^{g}_{48.2}+\dot{E}^{w}_{18.2} \\ +\dot{E}^{w}_{27.2}+\dot{E}^{w}_{32.2}+\dot{E}^{w}_{51.2} \\ +\dot{E}^{w}_{55.2}+\dot{E}^{w}_{59.2}+\dot{E}^{w}_{63.2} \end{pmatrix} = \dot{E}^{MPP}_{L}$$

$$\begin{pmatrix} \dot{E}^{P}_{73}+\dot{E}^{P}_{74}+\dot{E}^{P}_{75}+\dot{E}^{P}_{76} \\ +\dot{E}^{P}_{77}+\dot{E}^{P}_{78}+\dot{E}^{P}_{79}+\dot{E}^{P}_{80} \\ +\dot{E}^{P}_{81}+\dot{E}^{P}_{82} \end{pmatrix} = \dot{E}^{MPP}_{P}$$

$$\dot{E}^{w}_{11}+\dot{E}^{w}_{48}+\dot{E}^{f}_{11.1}+\dot{E}^{f}_{48.1}-\dot{E}^{MPP}_{L}-\dot{E}^{MPP}_{P}=\dot{E}^{MPP}_{d}$$

$$\dot{E}^{MPP}_{L}+\dot{E}^{MPP}_{d}=\dot{E}^{MPP}_{C}$$

RESULTS AND DISCUSSION

Using the data given in Table 1 and the thermodynamic basic equations, the measurement and unmeasurement data (temperature, pressure, total enthalpy rate, total exergy rate) are calculated. Temperature, pressure, mass flow rate, total enthalpy and total exergy rate for the plants system streams are given in Tables 7, 8 in accordance with their state numbers as specified in Figures 1, 2. Using the values given in Tables 7, 8 and the exergy balance equation illustrated in Tables 5, 6, the energy lost and the exergy destruction (or the irreversibility) are calculated for each component and the plant system. Using the values given in Tables 2, 3 and 4 and the method of calculating the chemical exergy of industrial fuel in solid and gas form given by Kotas (1995), the fuel energy, the fuel exergy, the stack gas energy and the stack gas exergy are calculated. This results are given in Tables 9 and 10. According to Table 9,

- The total heats of fuel for the existing plant and modified plant are determined to be 224250 and 231712 kW, respectively.
- The heat lost of the boilers, the turbines, the pressure drop units, the feed water tanks and collectors, the heaters, the condensers and the pipes for the existing plant are calculated as 35061, 2219, 1132, 915, 178, 607 and 44814 kW, respectively.
- The heat lost of the boilers, the turbines, the pressure drop units, the feed water tanks and collectors, the heaters, the condensers and the pipes for the modified plant are calculated as 36110, 2694, 318, 1092, 178, 607 and 46188 kW, respectively.
- The energies of the outlet steams and the outlet water of the condensers for the existing plant and modified plant are calculated 42704 and 107877 kW, respectively.
- The net powers of the existing plant and modified plant are obtained 34443 and 40847 kW, respectively.
- The overall thermal efficiencies of the existing plant and modified plant are determined to be 15.36% with 34443 kW as electrical and mechanical products and 17.63% with 40847 kW as electrical and mechanical products, respectively. The energy consumptions in the existing plant system and modified plant system are found to be 235507 and 237767 kW, respectively.
- The highest energy consumption between the components of the plants systems has the outlet water of condensers with 107877 kW.

According to Table 10,

- The total exergies of fuel for the existing plant and modified plant are determined to be 233688 and 241008 kW, respectively.
- The irreversibilities of the boilers, the turbines, the pressure drop units, the feed water tanks and collectors, the heaters, the condensers and the pipes for the existing plant are calculated as 148284, 25207, 6537, 3167, 813, 3747 and 3371 kW, respectively.
- The irreversibilities of the boilers, the turbines, the pressure drop units, the feed water tanks and collectors, the heaters, the condensers and the pipes for the modified plant are calculated as 152136, 27088, 483, 3231, 813, 3747 and 4681 kW, respectively.
- The exergies of the outlet steams and the outlet water of the condensers for the existing plant and modified plant are calculated 12545 and 2796 kW, respectively.
- The overall exergy efficiencies of the existing plant and modified plant are determined to be 14.74% with 34443 kW as electrical and mechanical products and 16.95% with 40847 kW as electrical and mechanical products, respectively. The exergy consumptions in the existing plant system and modified plant system are found to be 206465 and 207519 kW, respectively.
- The highest exergy consumptions between the components of the existing plant and the modified plant have the boilers with 148284 and 152136 kW, respectively. The percentage ratios to the fuel exergy of the exergy consumptions of the boilers of the existing plant and the modified plant are calculated 63.45% and 63.12%, respectively.
- The increments of the overall thermal efficiency and the overall rational efficiency in the modified plant are determined to be 2.27 and 2.21%, respectively.

CONCLUSIONS

This study presents a comprehensive energy and exergy analyses of the existing and modified plants. The investigation of the irreversibilities of components and the overall efficiency of the existing power plant. During the evaluation of performance of a power plant, exergy analysis has shown a better insight for the losses (irreversibilities) in electric power generation. The overall performance should be based on the second-law (or overall exergy) efficiency rather than the first law (or overall thermal) efficiency. Energy analysis misleads the determining the inefficiencies (irreversibilities) in the system.

Some concluding remarks drawn from the results of the present study may be listed as follows:

- The overall thermal efficiencies of the existing plant and modified plant are determined to be 15.36% with 34443 kW as electrical and mechanical products and 17.63% with 40847 kW as electrical and mechanical products, respectively. The energy consumptions in the existing plant system and modified plant system are found to be 235507 and 237767 kW, respectively.
- The highest energy consumption between the components of the plants systems has the outlet water of condensers with 107877 kW.

- The overall exergy efficiencies of the existing plant and modified plant are determined to be 14.74% with 34443 kW as electrical and mechanical products and 16.95% with 40847 kW as electrical and mechanical products, respectively. The exergy consumptions in the existing plant system and modified plant system are found to be 206465 and 207519 kW, respectively.

- The highest exergy consumptions between the components of the existing plant and the modified plant have the boilers with 148284 and 152136 kW, respectively. The percentage ratios to the fuel exergy of the exergy consumptions of the boilers of the existing plant and the modified plant are calculated 63.45% and 63.12%, respectively. The increments of the overall thermal efficiency and the overall exergy efficiency in the modified plant are determined to be 2.27 and 2.21%, respectively. These values in the efficiencies are very important for a power plant. This thermodynamic analysis technique provides more meaningful efficiencies than the energy analysis, and pinpoints the locations and causes of inefficiencies more accurately. The procedures given in this paper for the exergy analysis of the power plant could be applied to the different thermal applications for optimization and design purposes.

Table 7. Thermodynamic values of state points referred to Fig. 1 for the existing (or actual) power plant.

State Point	Pres. P MPa	Temp. T, °C	Flov Rate $\dot{m}$, t/h	Enthalpy h, kJ/kg	Entropy s, kJ/kgK	Total Enthalpy $\dot{H}$, kW	Exergy e, kJ/kg	Total Exergy $\dot{E}$, kW
0	0.100	25	-----	104.93	0.3672	------	0.00	0
1	1.100	25	51	105.90	0.3671	1500	1.00	14
2	1.100	95	134	397.50	1.2460	14796	30.69	1142
3	1.000	300	23	3051.00	7.1230	19493	932.84	5960
4	0.600	146	208	614.46	1.8009	35502	82.29	4754
5	9.100	146	208	620.50	1.7918	35851	91.04	5260
6	9.100	146	15	620.50	1.7918	2585	91.04	379
7	5.100	146	1	617.96	1.7961	172	87.22	24
8	9.100	146	190	620.50	1.7918	32749	91.04	4805
9	9.100	146	10	620.50	1.7918	1724	91.04	253
10	9.100	146	70	620.50	1.7918	12065	91.04	1770
11	9.100	177	70	754.24	2.0996	14666	133.05	2587
12	9.100	146	70	620.50	1.7918	12065	91.04	1770
13	9.100	177	70	754.24	2.0996	14666	133.05	2587
14	9.100	146	50	620.50	1.7918	8618	91.04	1264
15	9.100	168	190	715.13	2.0119	37743	120.08	6338
16	6.600	505	200	3427.00	6.8450	190389	1391.69	77316
17	6.600	505	60	3427.00	6.8450	57117	1391.69	23195
18	1.120	330	4	3112.00	7.1760	3458	978.05	1087
19	1.120	178	4	754.50	2.1200	838	127.24	141
20	0.198	115	8	482.50	1.4730	1072	48.04	107
20.1	0.155	26	2125	109.2	0.3813	64458	0.07	40
20.2	0.155	40	2125	167.7	0.5724	98990	1.62	956
21	0.198	160	4	2789.00	7.3320	3099	608.56	676
22	0.005	60	52	2612.00	8.5550	37729	67.11	969
23	0.098	60	60	251.20	0.8310	4187	8.06	134
24	1.200	60	60	252.10	0.8304	4202	9.14	152
25	1.200	100	60	419.80	1.3060	6997	35.11	585
26	6.600	505	60	3427.00	6.8450	57117	1391.69	23195
27	1.120	330	4	3112.00	7.1760	3458	978.05	1087
28	1.120	178	4	754.50	2.1200	838	127.24	141
29	0.198	115	8	482.50	1.4730	1072	48.04	107
30	0.198	160	4	2789.00	7.3320	3099	608.56	676
31	0.005	60	52	2612.00	8.5550	37729	67.11	969
31.1	0.155	26	2125	109.2	0.3813	64458	0.07	40
31.2	0.155	40	2125	167.7	0.5724	98990	1.62	956
32	0.098	60	60	251.20	0.8310	4187	8.06	134
33	1.200	60	60	252.10	0.8304	4202	9.14	152
34	1.200	100	60	419.80	1.3060	6997	35.11	585
35	6.600	505	14	3427.00	6.8450	13327	1391.69	5412
36	0.005	50	14	2594.00	8.4970	10088	66.39	258
36.1	0.16	26	468	109.2	0.3813	14196	0.07	9
36.2	0.16	43	468	180.2	0.6122	23426	2.26	294
37	0.088	50	14	209.40	0.7037	814	4.19	16
38	1.200	50	14	210.30	0.7032	818	5.24	20
39	6.600	505	66	3427.00	6.8450	62828	1391.69	25514
40	9.100	147	5	624.70	1.8020	868	92.20	128
41	6.600	388	71	3134.00	6.4360	61809	1220.57	24072
42	2.600	388	71	3211.00	6.9540	63328	1143.20	22547

Table 7. Continued.

State Point	Pres. P, MPa	Temp. T, °C	Flov Rate $\dot{m}$, t/h	Enthalpy h, kJ/kg	Entropy s, kJ/kgK	Total Enthalpy $\dot{H}$, kW	Exergy e, kJ/kg	Total Exergy $\dot{E}$, kW
43	2.600	388	22	3211.00	6.9540	19623	1143.20	6986
44	2.600	305	23	3018.00	6.6430	19282	1042.88	6663
45	2.600	385	49	3204.00	6.9440	43610	1139.18	15506
46	0.250	40	45	167.80	0.5723	2098	1.75	22
47	0.300	106	50	444.50	1.3740	6174	39.54	549
48	6.100	106	50	448.80	1.3690	6233	45.33	630
49	2.600	385	50	3204.00	6.9440	44500	1139.18	15822
50	2.500	385	12	3206.00	6.9640	10687	1135.22	3784
51	0.005	47	12	2588.00	8.4800	8627	65.46	218
51.1	0.15	26	680	109.2	0.3813	20627	0.07	13
51.2	0.15	36	680	151.0	0.5187	28522	0.92	174
52	0.091	45	12	188.50	0.6385	628	2.72	9
53	0.370	45	12	188.70	0.6384	629	2.95	10
54	2.500	385	12	3206.00	6.9640	10687	1135.22	3784
55	0.005	47	12	2588.00	8.4800	8627	65.46	218
55.1	0.15	26	680	109.2	0.3813	20627	0.07	13
55.2	0.15	36	680	151.0	0.5187	28522	0.92	174
56	0.091	45	12	188.50	0.6385	628	2.72	9
57	0.370	45	12	188.70	0.6384	629	2.95	10
58	2.500	380	15	3194.00	6.9470	13308	1128.29	4701
59	0.005	50	15	2594.00	8.4970	10808	66.39	277
59.1	0.15	26	945	109.2	0.3813	28665	0.07	18
59.2	0.15	35	945	146.8	0.5052	38535	0.75	196
60	0.088	47	15	196.80	0.6647	820	3.22	13
61	0.400	47	15	197.10	0.6646	821	3.54	15
62	2.500	385	6	3206.00	6.9640	5343	1135.22	1892
63	0.005	45	6	2584.00	8.4680	4307	65.03	108
63.1	0.145	26	1130	109.2	0.3813	34277	0.07	21
63.2	0.145	29	1130	121.7	0.4230	38200	0.14	44
64	0.091	43	6	180.10	0.6122	300	2.16	4
65	0.370	43	6	180.40	0.6121	301	2.49	4
66	2.500	380	3	3194.00	6.9470	2662	1128.29	940
67	0.500	280	3	3023.00	7.3860	2519	826.47	689
68	2.600	385	29	3204.00	6.9440	25810	1139.18	9177
69	2.600	280	31	2956.00	6.5330	25454	1013.66	8729
70	0.600	280	31	3020.00	7.2980	26006	849.69	7317
71	0.600	280	2	3020.00	7.2980	1678	849.69	472
72	0.600	280	29	3020.00	7.2980	24328	849.69	6845
73	5.100	146	2	617.96	1.7961	346	87.22	49
74	2.500	380	6	3194.00	6.9470	5323	1128.29	1880
75	2.300	340	16	3108.00	6.8470	13813	1072.09	4765
76	2.300	340	7	3108.00	6.8470	6043	1072.09	2085
77	0.850	220	7	2882.00	6.8780	5604	836.85	1627
78	2.300	340	9	3108.00	6.8470	7770	1072.09	2680
79	0.850	265	9	2981.00	7.0690	7453	878.93	2197
80	0.850	245	16	2937.00	6.9870	13053	859.37	3819
81	2.500	385	2	3206.00	6.9640	1781	1135.22	631

Table 8 Thermodynamic values of state points referred to Fig. 2 for the modified power plant

State Point	Pressure P, MPa	Temp. T, °C	Flow Rate m, kg/s	Enthalpy h, kJ/kg	Entropy s, kJ/kg.K	Total Enthalpy H, kW	Exergy e, kJ/kg	Total Exergy E, kW
0	0.100	25	---	104.93	0.3672	0	0.00	0
1	1.100	25	51	105.90	0.3671	1500	1.00	14
2	1.100	95	134	397.50	1.2460	14796	30.69	1142
3	1.000	300	23	3051.00	7.1230	19493	932.84	5960
4	0.600	146	208	614.46	1.8009	35502	82.29	4754
5	9.100	146	208	620.5	1.7918	35851	91.04	5260
6	9.100	146	70	620.5	1.7918	12065	91.04	1770
7	9.100	177	70	754.24	2.0996	14666	133	2587
8	9.100	146	68	620.5	1.7918	11721	91.04	1720
9	9.100	146	70	620.5	1.7918	12065	91.04	1770
10	9.100	177	70	754.24	2.0996	14666	133	2587
11	9.100	165	208	703.88	1.9863	40669	116.46	6729
12	6.600	505	208	3427.00	6.8450	198004	1391.69	80409
13	6.600	505	60	3427.00	6.8450	57117	1391.69	23195
14	1.120	330	4	3112.00	7.1760	3458	978.05	1087
15	1.120	178	4	754.50	2.1200	838	127.24	141
16	0.198	115	8	482.50	1.4730	1072	48.04	107
17	0.198	160	4	2789.00	7.3320	3099	608.56	676
18	0.005	60	52	2612.00	8.5550	37729	67.11	969
18.1	0.155	26	2125	109.2	0.3813	64458	0.07	40
18.2	0.155	40	2125	167.7	0.5724	98990	1.62	956
19	0.098	60	60	251.20	0.8310	4187	8.06	134
20	1.200	60	60	252.10	0.8304	4202	9.14	152
21	1.200	100	60	419.80	1.3060	6997	35.11	585
22	6.600	505	60	3427.00	6.8450	57117	1391.69	23195
23	1.120	330	4	3112.00	7.1760	3458	978.05	1087
24	1.120	178	4	754.50	2.1200	838	127.24	141
25	0.198	115	8	482.50	1.4730	1072	48.04	107
26	0.198	160	4	2789.00	7.3320	3099	608.56	676
27	0.005	60	52	2612.00	8.5550	37729	67.11	969
27.1	0.155	26	2125	109.2	0.3813	64458	0.07	40
27.2	0.155	40	2125	167.7	0.5724	98990	1.62	956
28	0.098	60	60	251.20	0.8310	4187	8.06	134
29	1.200	60	60	252.10	0.8304	4202	9.14	152
30	1.200	100	60	419.80	1.3060	6997	35.11	585
31	6.600	505	14	3427.00	6.8450	13327	1391.69	5412
32	0.005	50	14	2594.00	8.4970	10088	66.39	258
32.1	0.16	26	468	109.2	0.3813	14196	0.07	9
32.2	0.16	43	468	180.2	0.6122	23426	2.26	294
33	0.088	50	14	209.40	0.7037	814	4.19	16
34	1.200	50	14	210.30	0.7032	818	5.24	20
35	6.600	505	74	3427.00	6.8450	70444	1391.69	28607

Table 8. *Continued.*

36	1.000	300	54	3051.00	7.1230	45765	932.84	13993
37	0.600	280	29	3020.00	7.2980	24328	849.69	6845
38	2.600	385	20	3204.00	6.9440	17800	1139.18	6329
39	2.500	380	6	3194.00	6.9470	5323	1128.29	1880
40	2.300	340	16	3108.00	6.8470	13813	1072.09	4765
41	2.300	340	7	3108.00	6.8470	6043	1072.09	2085
42	0.850	220	7	2882.00	6.8780	5604	836.85	1627
43	2.300	340	9	3108.00	6.8470	7770	1072.09	2680
44	0.850	265	9	2981.00	7.0690	7453	878.93	2197
45	0.850	245	16	2937.00	6.9870	13053	859.37	3819
46	0.250	40	45	167.80	0.5723	2098	1.75	22
47	0.300	106	50	444.50	1.3740	6174	39.54	549
48	6.100	106	50	448.80	1.3690	6233	45.33	630
49	2.600	385	50	3204.00	6.9440	44500	1139.18	15822
50	2.500	385	12	3206.00	6.9640	10687	1135.22	3784
51	0.005	47	12	2588.00	8.4800	8627	65.46	218
51.1	0.15	26	680	109.2	0.3813	20627	0.07	13
51.2	0.15	36	680	151.0	0.5187	28522	0.92	174
52	0.091	45	12	188.50	0.6385	628	2.72	9
53	0.370	45	12	188.70	0.6384	629	2.95	10
54	2.500	385	12	3206.00	6.9640	10687	1135.22	3784
55	0.005	47	12	2588.00	8.4800	8627	65.46	218
55.1	0.15	26	680	109.2	0.3813	20627	0.07	13
55.2	0.15	36	680	151.0	0.5187	28522	0.92	174
56	0.091	45	12	188.50	0.6385	628	2.72	9
57	0.370	45	12	188.70	0.6384	629	2.95	10
58	2.500	380	15	3194.00	6.9470	13308	1128.29	4701
59	0.005	50	15	2594.00	8.4970	10808	66.39	277
59.1	0.15	26	945	109.2	0.3813	28665	0.07	18
59.2	0.15	35	945	146.8	0.5052	38535	0.75	196
60	0.088	47	15	196.80	0.6647	820	3.22	13
61	0.400	47	15	197.10	0.6646	821	3.54	15
62	2.500	385	6	3206.00	6.9640	5343	1135.22	1892
63	0.005	45	6	2584.00	8.4680	4307	65.03	108
63.1	0.145	26	1130	109.2	0.3813	34277	0.07	21
63.2	0.145	29	1130	121.7	0.4230	38200	0.14	44
64	0.091	43	6	180.10	0.6122	300	2.16	4
65	0.370	43	6	180.40	0.6121	301	2.49	4
66	2.500	380	3	3194.00	6.9470	2662	1128.29	940
67	0.500	280	3	3023.00	7.3860	2519	826.47	689
68	2.500	385	2	3206.00	6.9640	1781	1135.22	631
69	0.600	280	31	3020.00	7.2980	26006	849.69	7317
70	0.600	280	2	3020.00	7.2980	1678	849.69	472

Table 9. Energy balance of the existing and modified plants and percentage ratios to the fuel energy and energy efficiencies of the plants

		Existing Plant				Modified Plant			
		Input		Output		Input		Output	
		kW	%	kW	%	kW	%	kW	%
Energy of the fuel for four boilers		**224250**	**100.00**			**231712**	**100.00**		
Energy of the feed water come back to boilers		**45700**	**20.38**			**46902**	**20.24**		
Energy lost of the boilers	stack gas			10462	4.67			10948	4.72
	heat lost			24599	10.97			25162	10.86
	total			**35061**	**15.63**			**36110**	**15.58**
Heat lost of the turbines	TG1			331	0.15			331	0.14
	TG2			331	0.15			331	0.14
	TB1			134	0.06			134	0.06
	TB2			419	0.19			419	0.18
	TB3			419	0.19			419	0.18
	TG3			100	0.04			100	0.04
	TB4			265	0.12			265	0.11
	TP			15	0.01			15	0.01
	TA			205	0.09			205	0.09
	TG4			--	--			475	0.20
	total			**2219**	**0.99**			**2694**	**1.16**
Heat lost of the reduction units	PDD1			362	**0.16**				
	PDD2			302	**0.13**				
	PDD3			151	**0.07**				
	PDD4			318	**0.14**			318	0.14
	total			**1132**	**0.50**			**318**	**0.14**
Heat lost of feed water tanks and collectors				**915**	**0.41**			**1092**	**0.47**
Heat lost of heaters				**178**	**0.08**			**178**	**0.08**
Heat lost of condencers				**607**	**0.27**			**607**	**0.26**
Heat lost of pipes				**44814**	**19.98**			**46188**	**19.93**
Energy of steam to outher processes				**42704**	**19.04**			**42704**	**18.4 3**
Heat of outlet water of condenser				**107877**	**48.11**			**107877**	**46.56**
Net power				**34443**	**15.36**			**40847**	**17.63**
Total		**269950**	**120.38**	**269950**	**120.38**	**278614**	**120.24**	**278614**	**120.24**
Overall thermal efficiency, ($\eta_{g, \%}$)		**15.36**				**17.63**			

Table 10. Exergy balance of the existing and modified plants and percentage ratios to the fuel exergy and exergy efficiencies of the plants

		Existing Plant				Modified Plant			
		Input		Output		Input		Output	
		kW	%	kW	%	kW	%	kW	%
Exergy of the fuel for four boilers		**233688**	**100.00**			**241008**	**100.00**		
Exergy of the feed water come back to boilers		**7220**	**3.09**			**7358**	**3.05**		
Irreversibilities of the boilers	stack gas			9226	3.94			9762	4.05
	combustion and heat lost			139058	59.51			142374	59.07
	total			**148284**	**63.45**			**152136**	**63.12**
Irreversibilities of the turbines	TG1			7963	3.41			7963	3.30
	TG2			7963	3.41			7963	3.30
	TB1			2049	0.88			2049	0.85
	TB2			1925	0.82			1925	0.80
	TB3			1925	0.82			1925	0.80
	TG3			2025	0.87			2025	0.84
	TB4			1012	0.44			1012	0.42
	TP			124	0.05			124	0.05
	TA			223	0.10			223	0.09
	TG4							1881	0.78
	total			**25207**	**10.79**			**27088**	**11.24**
Irreversibilities of the pressure drop units	PDD1			3094	1.32				
	PDD2			1051	0.45				
	PDD3			1909	0.82				
	PDD4			483	0.21			483	0.20
	total			**6537**	**2.80**			**483**	**0.20**
Irreversibilities of feed water tanks and collectors				**3167**	**1.36**			**3231**	**1.34**
Irreversibilities of heaters				**813**	**0.35**			**813**	**0.34**
Irreversibilities of condencers				**3747**	**1.60**			**3747**	**1.55**
Irreversibilities of pipes				**3371**	**1.44**			**4681**	**1.94**
Exergy of steam to outher processes				**12545**	**5.37**			**12545**	**5.21**
Exergy of outlet water of condenser				**2796**	**1.20**			**2796**	**1.16**
Net power exergy				**34443**	**14.74**			**40847**	**16.95**
Total		**240908**	**103.09**	**240908**	**103.09**	**248366**	**103.05**	**248366**	**103.05**
Overall rational efficiency, (ψ_{ov}, %)		**14.74**				**16.95**			

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