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Thermal Power Plant Performance Analysis by Estimating Boiler Efficiency via Indirect Method: A Case Study

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Abstract
In this paper, a coal (lignite) fired thermal power plant having capacity of 160 MW is taken into consideration and the impact of condenser pressure, moisture content of lignite, excess air coefficient, the efficiency of turbine pressure and heater numbers on power plant thermal efficiency is investigated. It is aimed to determine the performance losses of each equipment by means of thermodynamics and economic analysis. In this scope, it is expected that the power plant operator will be able to evaluate the reduction potential of equipment performance losses and ensure more effective use of the power plants by correctly planning the maintenance and rehabilitation needs and time. In the calculations, the boiler efficiency was determined with EN 12952-15 standard (indirect method) since this method has higher accuracy in coal-fired boilers. It is seen that the condenser pressure and excess air coefficient increments have no significant impact on power plant efficiency compared to moisture content of lignite, excess air coefficient, efficiency of turbine pressure and heater numbers. The significant effect is observed for fuel moisture content which rises from 22% to 47% and the power plant efficiency falls from 40% to 28%. The variation of the power plant thermal efficiency in case of failure of heaters is investigated and the power plant efficiency has decreased from 40.17% to 36.09% when the pre-heaters are no longer in to be in use because of any reason. In addition, revenue losses are estimated for each main equipment efficiency reduction for better use of power plant capacities and electricity lowering production costs.

1. Introduction

The energy needs of the world are increasing rapidly with the development of population and technology. One of these increasing needs can be stated as electrical energy and attention is directed to energy conversion plants. Among energy conversion plants, thermal power plants are commonly used to generate electricity all over the world and the energy produced in thermal power plants is related to the performance of the power plant. It is also known that about eighty percent of the world's power generation is provided by fossil fuels, with the other 20% depending on other types of energy sources such as nuclear energy or renewable energy sources, etc. [1],[2]. Since the decrease in the performance of each equipment constituting the power plant affects the thermal efficiency and power generation, it increases the unit electricity production cost and causes a decrease in the revenues of the power plant [3]. Thus, many different parameters are used to determine the performance of thermal power plants. It is important to determine the parameters affecting the energetic performance of a power plant since it is directly related with generated electricity. The performance of power plants is very critical since it is directly related to operating and electricity production costs. Among the other different types of power plants, coal-fired ones have advantages such as reliability and low-cost fuel. There are several papers in the literature that

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discuss the performances of coal-fired thermal power plants [4-16] and some of them are summarized as follows:

See and Coelli [9] investigated the technical efficiency levels of Malaysian thermal power plants and the extent to which various factors influence these plants' efficiency levels. Over eight years from 1998 to 2005, they used Stochastic Frontier Analysis (SFA) methods on plant-level data. Their empirical findings show that plant size and fuel type have a significant influence on technical efficiency levels, whereas plant age and peaking plant type have no statistically significant influence on Malaysian thermal power plant technical efficiencies.

Ahmadi and Toghraie [10] investigated the steam cycle of the Shahid Montazeri Power Plant in Isfahan, which has a capacity of 200 MW per unit. Analyses are carried out using EES (Engineering Equation Solver) software. The results of the energy analyses indicated that the condenser accounts for 69.8% of the total lost energy in the cycle, while exergy analysis identifies the boiler as the main equipment wasting exergy, accounting for 85.66% of the total exergy entering the cycle.

Oman et al. [11] investigated the effects of coal composition on the power plant in their study. In energy conversion, a significant heat loss occurs due to flue gas. In the study of electricity generating plants, they focused on the coal grinding and flue gas cleaning process. At 150°C flue gas temperature, when the excess air coefficient is increased by 10%, the total heat loss increases by 8% due to the heat dissipated by the flue gas, and an increase of 28% occurs when the excess air coefficient is increased by 50%. The findings of measurements and experiments on two power plant units were given in another study done by Oman et al. [11]. The processed coal is lignite, which has lower heating values between 9 and 10 MJ/kg, as well as ash and moisture concentrations of roughly 20% and 38%, respectively. The effect of lignite composition on heating value, boiler loss, boiler-specific steam generation, self-consumption of electricity, power consumption for coal grinding and flue gas desulphurization was explored.

Ganapathy et al. [12] calculated energy and exergy first law efficiency (energy efficiency) and the second law efficiency (exergy efficiency) of the 50MWe unit of lignite fired steam power plant at Thermal Power Station-I. The analyses show that 39% of the maximum energy losses occur in the condenser and 42.73% of the maximum exergy losses occur in the combustor.

Geete and Khandwawala [13],[14] presented a thermodynamic analysis to investigate the effect of back pressure and inlet temperature on the power and heat rate of the power plant. They considered a thermal power plant having capacity of 120 MW. They proposed power and heat rate correction curves for various condenser back pressures (in the range of 0.068-0.142 bar) and inlet temperatures (in the range of 507.78-567.78°C). They stated that the prediction of correction curves can be useful for thermal power plant design.

Vosough et al. [15] examined the energy and exergy analysis of the ideal preheated Rankine cycle and determined the largest energy losses in the cycle. After determining that the energy losses are predominantly in the condenser, they estimated the impact of condenser pressure on the performance of the cycle. It was observed that the maximum efficiency and output power decrease as the condenser pressure increases. In addition, they pointed out that the boiler is the primary source of irreversibility.

Huang et al. [16] researched the performance of a pressurized fluidized bed combustion power plant operated with ten different coal types. They aimed to investigate the effect of ash content, moisture content, sulfur content and calorific value of coal on overall efficiency. They concluded the ash content is the most effective parameter among them since the overall efficiency increased by 2.3% with the increment of ash content up to 40%.

The direct and indirect methods can be used in the calculation of boiler efficiency. While direct efficiency calculations do not provide any information about specific losses and their amounts, the indirect method allows to determine which equipment has low or high-capacity loss. In addition, the measurement errors do not have significant effect on efficiency in this method. In this study, Çan Thermal Power Plant, which is operated with lignite, was taken into consideration. The effect of condenser pressure, moisture content of lignite, excess air coefficient, efficiency of turbine pressure and heaters on power plant thermal efficiency and revenue loss were estimated by using Engineering Equation Solver Software [17]. For this purpose, the performance losses of each equipment were examined by means of thermodynamics and economic analysis. In the calculations, the boiler efficiency was determined with EN 12952-15 standard (indirect method) [18] since this method has higher accuracy in coal-fired boilers. The heat losses in the boiler (the losses due to flue gas, unburned CO, enthalpy and unburned combustibles in slag/flue dust and radiation /convection) were calculated according to this standard. In addition, the effect of these losses on the total efficiency of the power plant was calculated and the income loss caused by this in the power plant was determined. It is expected that this research will be useful for the evaluation of the reduction potential of equipment performance losses and more effective use of the power plants.

2. Plant Description

Çan Thermal Power Plant, which is located in the town of Çan in Çanakkale, Türkiye, was considered in the current study. It is a coal (lignite) fired thermal power plant having capacity of 160 MW. The details of the thermal power plant's main equipment (such as boiler, generator, turbine, cooling system) are given in Table 1 [19]. The types, capacities and efficiencies of equipments can be seen in this table. Also, the schematic representation of Çan Thermal Power Plant is given in Figure 1. It can be classified as an ideal reheat–regenerative rankine cycle having one open feed water, six closed feed water heaters.

Steam enters the high pressure turbine at 17.2 MPa and 540°C and is condensed in the condenser at a pressure of 8.5 kPa. Some steam is extracted from the turbine at 4 MPa for the closed feedwater heater (K2) and the remaining steam is reheated at the same pressure to 540°C. There are 4 low pressure heaters, 2 high pressure heaters and one open feedwater heater to heat feedwater with extracted steam which is obtained from low, intermediate and high pressure turbines. The temperature of the steam is increased by passing through the preheaters and it enters the boiler at a temperature of 244.9 °C. The steam temperature, which was 330.5 °C at the exit from the high-pressure turbine, ix increased to 540 °C by applying the reheating process. The technical specification of Çan Thermal Power) are given in Table 2 [20].

The content of lignite used in the Çan Thermal Power Plant is given as follows: The percentages of ash, moisture, constant carbon, total sulfur and oxygen are 32%, 22%, 58%, 4.5% and 3%, respectively.

3. Calculation Method

Condenser pressure, boiler efficiency, turbine contamination and the use of preheaters significantly affect the efficiency of a thermal power plant. The performance of the thermal power plant considered in the study was evaluated with these parameters and the calculation procedure is given as follows:

Table 1. The details of the thermal power plant main equipment

Boiler	Coal	Turbine
Type Fluidized bed Lignite fired Capacity 128.6 kg/s vapour Efficiency 92%	Heating Value (Design) 2600± 10% kcal/kg (32% ash and 22% moisture) Heating Value (Revised) 2900± %10 kcal/kg (30% ash and 22% moisture) Stock Area Capacity 200.000 ton Capacity of Coal Belt Conveyors 166.7 kg/s	Type 3 Pressure stage Capacity 160 MW Rotation speed 3600 rpm Efficiency 45% General efficiency 42%
Generator	**Cooling System**	**Ash**
Type Synchronize Power 177 MVA Voltage 15 kV Cooling type Air cooling	Type Heller System Capacity 15800 m^3/hour	Ash-slag amount 22.2 kg/s Ash Stock Area 800000 m^2

The boiler efficiency is determined by using indirect method obtained from EN 12952-15 Standard (Water-tube boilers and auxiliary installations - Part 15: Acceptance tests) [18]. In this standard, the following equation is used for estimation of boiler efficiency as follows:

$$\eta_B = 1 - \frac{\dot{Q}_{L,tot}}{\dot{Q}_{Z,tot}} = 1 - \frac{\dot{Q}_{L,tot}}{\dot{Q}_Z + \dot{Q}_{ZF}} \tag{1}$$

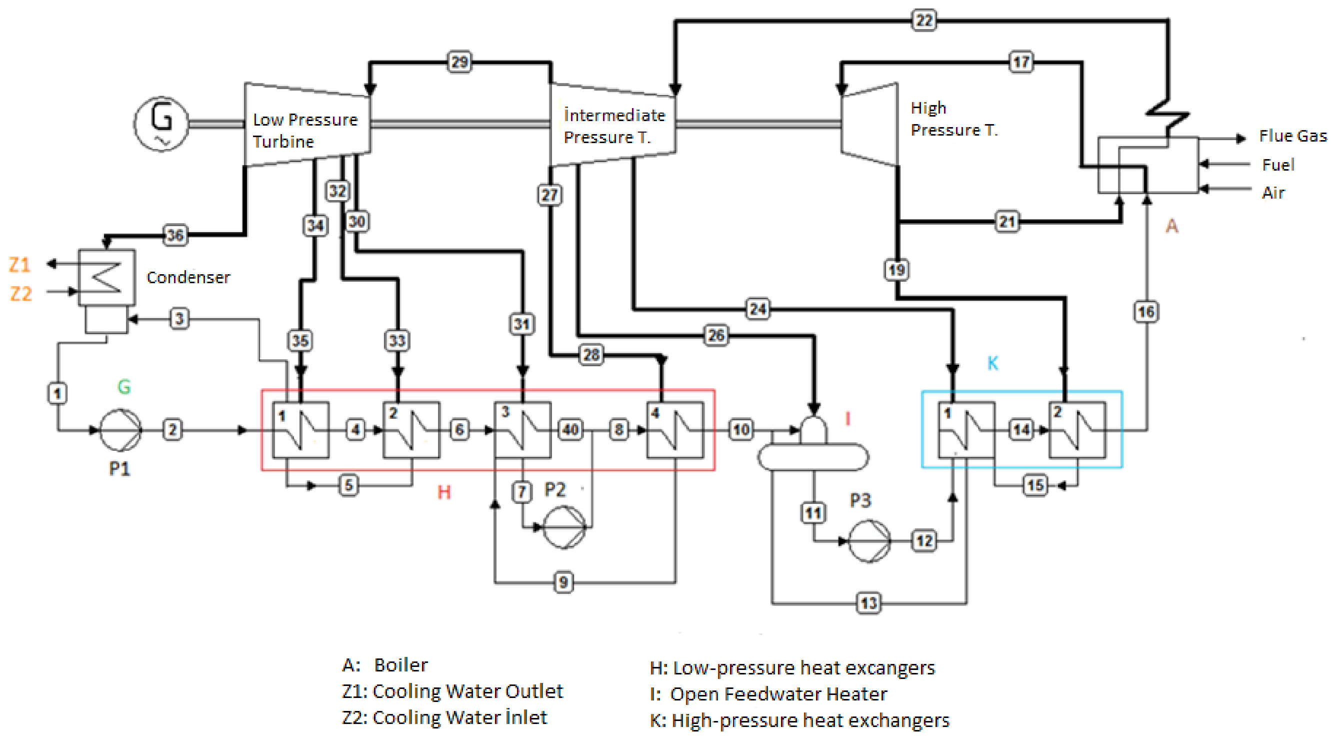


Figure 1. The schematic representation of Çan Thermal Power Plant [20]

The total heat input ($\dot{Q}_{Z,tot}$)is calculated as the sum of the heat credits ($\dot{Q}_{Z}$) and the heat input $\dot{Q}_{ZF}$), which is proportional to the flow rate of the burned fuel. The heat credit includes the amount of heat excluding chemical heat, coal mill power, circulating gas fan power, circulation pump power and powers of other drive motors. Moreover, if it is possible to measure atomizing steam flow the atomizing steam heat can be added to heat credits.

$$\dot{Q}_Z = P_M + P_{UG} + P + \dot{Q}_{SAE} + \dot{m}_{AS}\, h_{AS} \qquad (2)$$

$$\dot{Q}_{SAE} = \dot{m}_{SAE}\,(h_{SAE1} - h_{SAE2}) \qquad (3)$$

The heat input proportional to the burning fuel includes the heat obtained from fuel (chemical heat), the injected steam and in the combustion air and it is calculated as follows:

$$\dot{Q}_{ZF} = \dot{m}_F \left[\frac{H_{F,ref} + h_F}{1 - l_U}\right] + \mu_{AS} h_{AS} + J_A \qquad (4)$$

$$l_U = \frac{\gamma_{ash}\,(1-v)}{1-\gamma_{ash}-\gamma_{H2O}}\;\frac{\dot{m}_{SL}\,u_{SL} + \dot{m}_{FA}\,u_{FA}}{\dot{m}_{SL}\,(1-u_{SL}) + \dot{m}_{FA}\,(1-u_{FA})} \qquad (5)$$

$$J_A = \dot{\mu}_A\, c_{pA}\,(T_A - T_r) \qquad (6)$$

Total heat loss in the boiler contains the losses due to flue gas ($\dot{Q}_G$), unburned CO ($\dot{Q}_{CO}$), enthalpy and unburned combustibles in slag ($\dot{Q}_{SL}$) and flue dust ($\dot{Q}_{FA}$) and radiation and convection ($\dot{Q}_{RC}$). The following equation is used to determine total heat loss as follows:

$$\dot{Q}_{L,tot} = \dot{Q}_G + \dot{Q}_{CO} + \dot{Q}_{SL} + \dot{Q}_{FA} + \dot{Q}_{RC} \qquad (7)$$

Flue gas losses can be determined by using the equation below if flue gas mass flow can be measured directly:

$$\dot{Q}_G = \dot{m}_G c_{p,G}(T_G - T_r) \qquad (8)$$

$$c_{p,G} = \frac{c_{p,TG}\,.\,T_G - c_{p,Tr}.\,T_r}{T_G - T_r} \qquad (9)$$

Unburned CO loss is estimated as follows:

$$\dot{Q}_{CO} = \dot{m}_F \dot{V}_{Gd} Y_{COd} H_{COn} \qquad (10)$$

$$V_{Gd} = V_{God}\frac{Y_{O2d}}{Y_{O2ad} - Y_{O2d}} \qquad (11)$$

$$V_{God} = -0.06018\gamma_F + 0.25437H^* \qquad (12)$$

$$H^* = H + 2.4425\gamma_{H2O} \qquad (13)$$

Slag and flue dusts are not taken into account if they contain very little unburned combustible materials.

$$\dot{Q}_{SL} = \dot{m}[\, c_{SL}\,(T_{SL} - T_r) + \, u_{SL}\, H_{UU}] = \dot{m}_{SL}\, h_{SL} \quad (14)$$

$$\dot{Q}_{FA} = \dot{m}[\, c_{FA}\,(T_G - T_r) + \, u_{FA}\, H_{UU}] = \dot{m}_{FA}\, h_{FA} \quad (15)$$

Since it is difficult to measure heat losses due to convection and radiation, empirical values are used for specification of them and it is calculated by using the following equation:

$$\dot{Q}_{RC} = C\dot{Q}_N^{0,7} \quad (16)$$

C value is equal to 0.0113, 0.0220 and 0.0315 for fuel-oil and natural gas boilers, hard coal boilers and lignite and fluidized bed boilers, respectively.

While calculating the useful heat output, the masses entering and leaving the boiler as in the TS EN 12952-15 standard are taken as basis. The useful heat output is estimated by using the following equation:

$$\dot{Q}_N = \dot{m}_{ST}(h_{ST} - h_{FW}) + \dot{m}_{SS}(h_{FW} - h_{SS}) + \dot{m}_{RHI1}(h_{RHI2} - h_{RHI1}) + \dot{m}_{SRI}(h_{RHI2} - h_{SRI}) + \dot{m}_{RHII1}(h_{RHII2} - h_{RHII1}) + \dot{m}_{SRII}(h_{RHII2} - h_{SRII}) + \dot{m}_{BD}(h_{BD} - h_{FW}) + \dot{m}_{SA}(h_{SA} - h) \quad (17)$$

In this study, the efficiency of thermal plant is estimated as follows:

$$\eta_{th} = \frac{\dot{w}_{net}}{\dot{q}_{in}} = 1 - \frac{\dot{q}_{out}}{\dot{q}_{in}} \quad (18)$$

One of the most effective parameters in calculating the cost of unit electricity production in thermal power plants is the fuel cost. Specific fuel consumption, which is defined as the amount of fuel required for a unit of energy, is calculated as follows:

$$b_e = \frac{3600}{\eta_t H_u} \quad (19)$$

Table 2. The technical specification of Çan Thermal Power [20]

Number	m (kg/s)	P (kPa)	T (C)	h (kJ/kg)
1	94.33	8.5	42.5	178
2	94.33	N/A	45.3	189.7
3	2.562	25.8	51.3	214.8
4	94.33	N/A	58.09	243.2
5	2.431	50.4	68.7	287.6
6	94.33	N/A	70.68	295.9
7	13.51	185.8	117.9	494.9
8	107.8	N/A	111.6	468.3
9	6.497	505.8	122.2	513.3
10	107.8	N/A	146.7	618.2
11	129.1	1008	176.4	747.5
12	129.1	20600	N/A	769.5
13	15.94	2098	191.8	816
14	129.1	N/A	N/A	908.3
15	9.45	3961	223.8	961.5
16	129.1	N/A	244.9	1061
17	129.5	17200	540	3397
18	129.5	4036	330.5	3043
20	9.45	3955	329.7	3041
21	120.1	4036	330.5	3041
22	120.1	3713	540	3540
24	6.488	2097	454.2	3366
26	5.313	1008	354.8	3167
27	6.497	521.4	269.7	3000
28	6.497	505.7	269.7	3001
29	100.4	521.4	267.6	2997
31	6.86	185.8	168.5	2807
33	2.139	52.56	84.6	2651
34	1.87	27.02	67	2621
35	1.87	25.9	65.8	2619
36	89.4	8.5	N/A	2399

Table 3. The work input of the pump, work output of turbines, heat inlet of the boiler and thermal efficiency of the power plant

$\dot{W}_{pump}$ (kW)	$\dot{W}_{LPT}$ (kW)	$\dot{W}_{MPT}$ (kW)	$\dot{W}_{HPT}$ (kW)	$\dot{W}_{T}$ (kW)	$\dot{Q}_{in}$ (kW)	η_{th}
4.302	56.495	61.885	45.781	164.161	362.368	0.401

The unit energy fuel cost is obtained by multiplying the specific fuel consumption and the fuel price as follows [21]:

$$c_f = Fb_e \tag{20}$$

Revenue of the plant with unit power is determined as follows:

$$c_N = \dot{W}_{net}F_e \tag{21}$$

Revenue losses in the power plant due to variable parameters are the difference between unit energy fuel cost and the income generated by the plant with unit power and it is estimated as follows:

$$RL = c_f - c_N \tag{22}$$

4. Results and Discussion

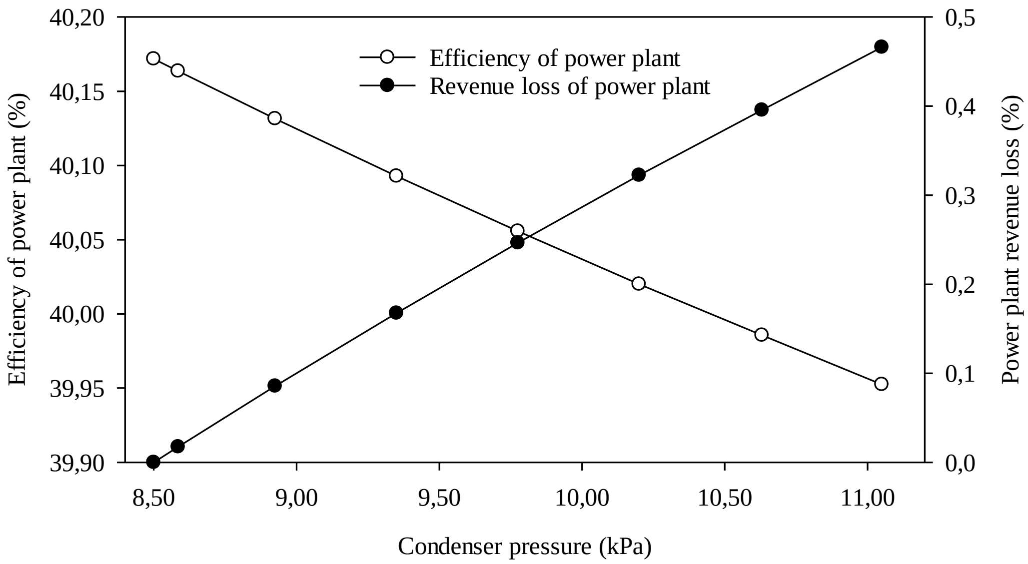
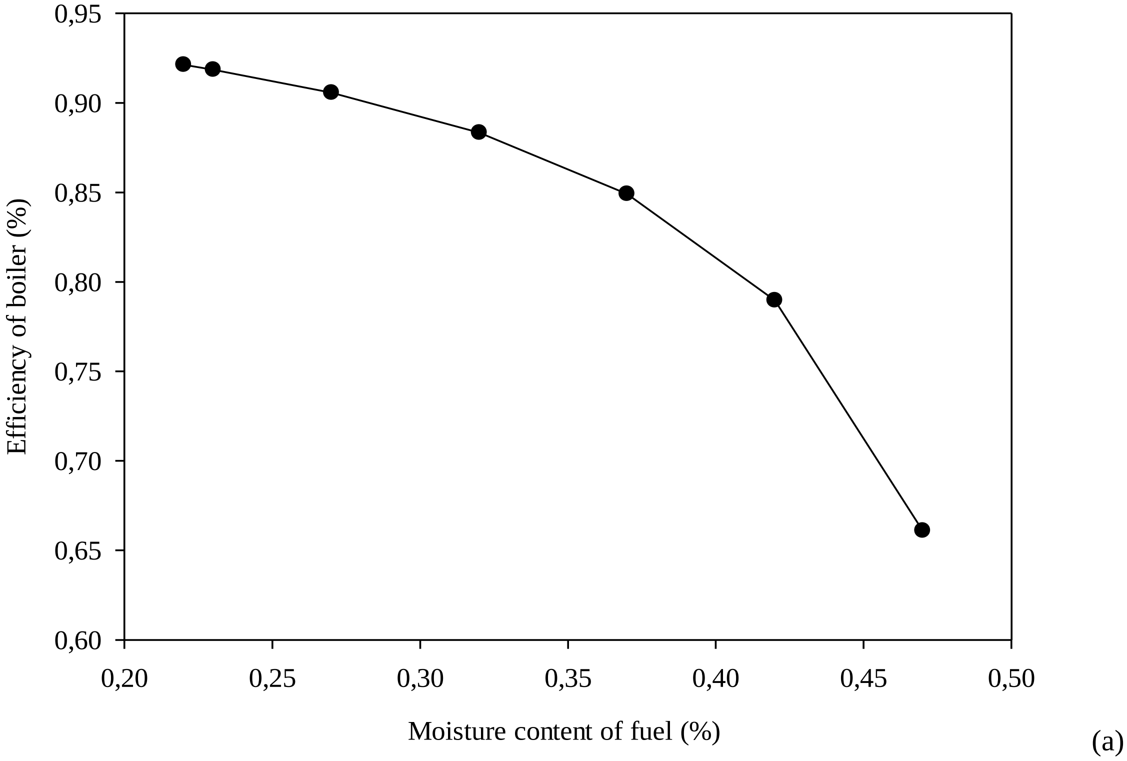


Figure 2. The effect of condenser pressure on power plant thermal efficiency and revenue loss

The thermodynamic analyses of the considered thermal power plant are determined by means of equations given in the previous section. Firstly, the thermal efficiency of the power plant was estimated for design operation conditions. Then, the thermal efficiency decrease due to the changing working conditions was determined in case of any failure in the equipment by keeping the heat entering the boiler constant. According to the determined efficiency results, the revenue losses in the power plant were calculated by considering unit electricity price (2.25 cents/kWh) and unit fuel cost (0.31 cent/kg) [21]. Table 3 shows the work input of the pump, work output of turbines, heat inlet of the boiler and thermal efficiency of the power plant.

Since the condenser pressure determines the output conditions of the low pressure turbine, it directly affects the power that can be produced from the turbine. Moreover, it is known that there is a decrease in efficiency with rising condenser pressure.



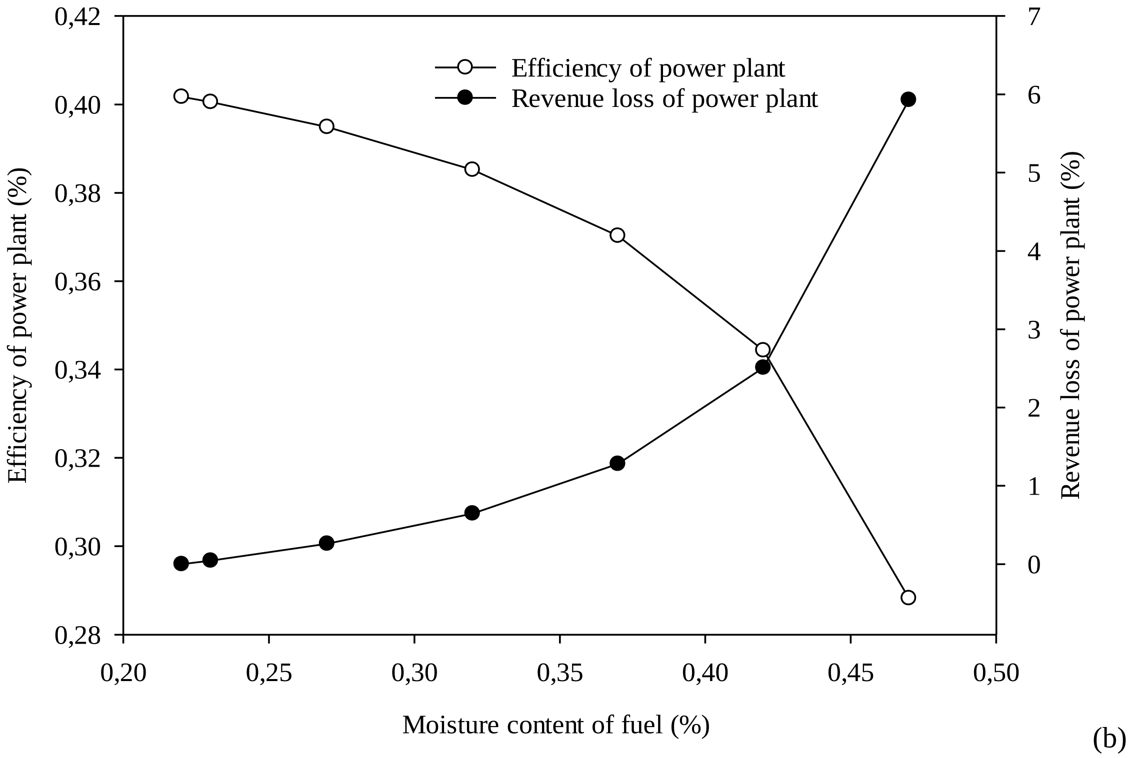


Figure 3. The impact of fuel moisture content increment on (a) the boiler efficiency (b) power plant thermal efficiency and revenue loss

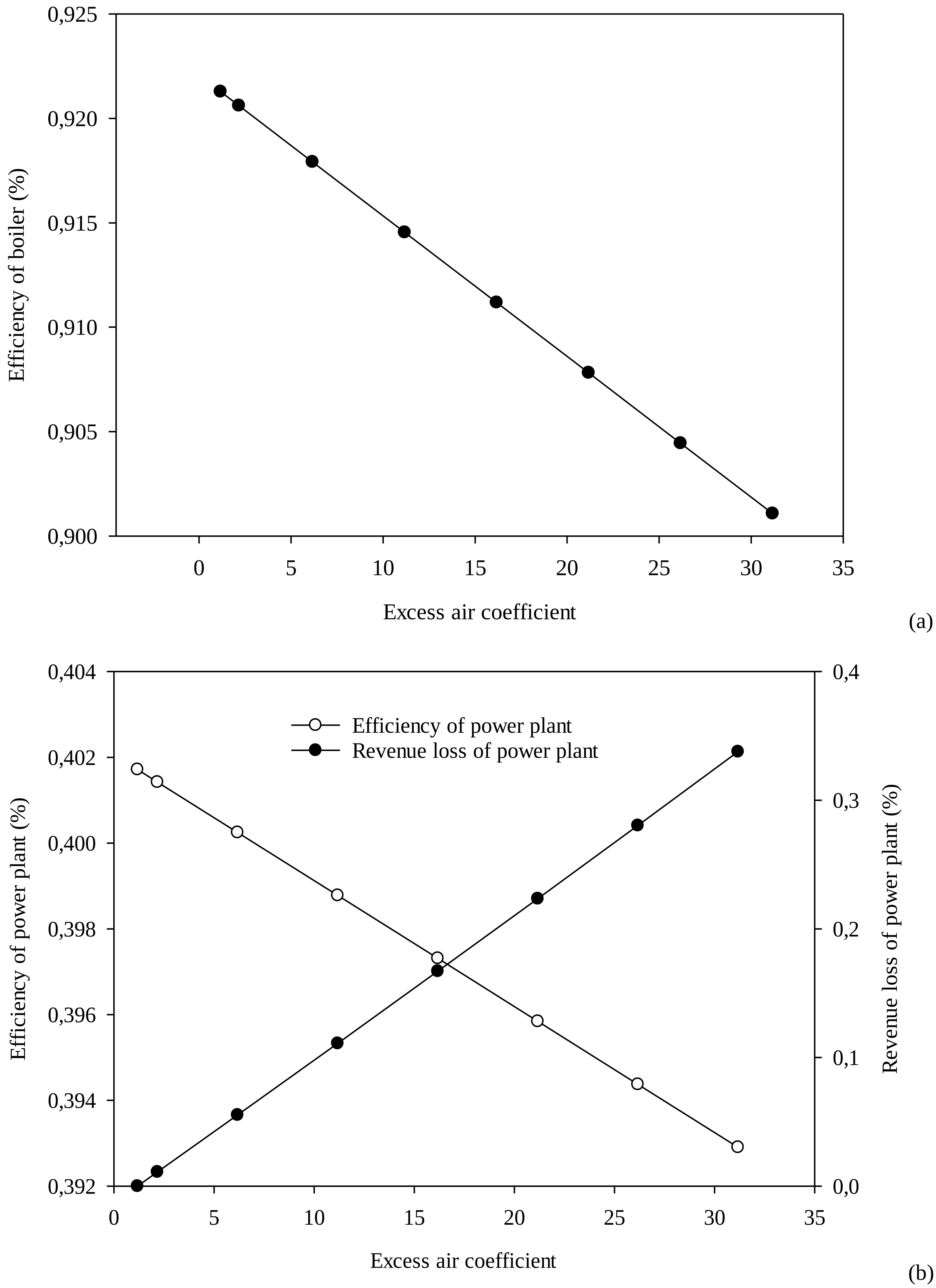


Figure 4. The effect of excess air coefficient increments on (a) the boiler efficiency (b) thermal efficiency and revenue loss

The effect condenser pressure increment on the reduction of thermal efficiency and revenue loss variation were presented in Figure 2. It can be observed that the thermal efficiency reduces with the increment of condenser pressure as shown in Figure 2. The thermal efficiency of the power plant decreases from 40.17% to 39.95% for the condenser pressures of 8.5 kPa and 11.5 kPa, respectively. In other words, the reduction in thermal efficiency was determined at 0.22% with the increment of condenser pressure to 30% since the amount of heat entering the boiler remained constant despite the decreasing turbine power when the condenser pressure increased. Also, Figure 2 depicts the variation of revenue loss with the increment of condenser pressure. The increment of condenser pressure up to 30% corresponds to 0.48% revenue loss. The cost of revenue lost is approximately equal to 126134 $/year.

In coal-fired thermal power plants, the boiler is designed according to coal with certain chemical and physical properties, and when the coal has these properties, it performs by the design values. In cases where coal properties change, the thermal efficiency and performance of the unit are directly affected. If the amount of water contained in the coal is higher than the design value, it will cause blockages in the system, plastering, excessive material wear and reduction in the boiler combustion chamber temperature, which will adversely affect the power plant load and efficiency. Figures 3(a) and 3(b) represent the impact of fuel moisture content increment on the boiler efficiency, thermal efficiency and revenue loss, respectively. In Figure 3(a), the fuel moisture content rises from 22% to 47%, the boiler efficiency falls from 92% to 66%, respectively. In Figure 3(b), when the fuel moisture content reaches 47%, the thermal efficiency of the power plant reduces to 28%. The reason of both them can be explained with the reduction in the heating value of fuel with elevated moisture content. The revenue loss is equal to 4.25% and the cost of revenue lost is approximately equal to 1095623 $/year.

The effect of excess air coefficient increment on the boiler efficiency, power plant thermal efficiency and revenue loss was shown in Figure 4(a) and Figure 4(b), respectively. It can be observed that both the boiler and power plant efficiencies diminish by 2% and 1% with the variation of excess air coefficient in the range between 1.17 and 31.17, respectively.

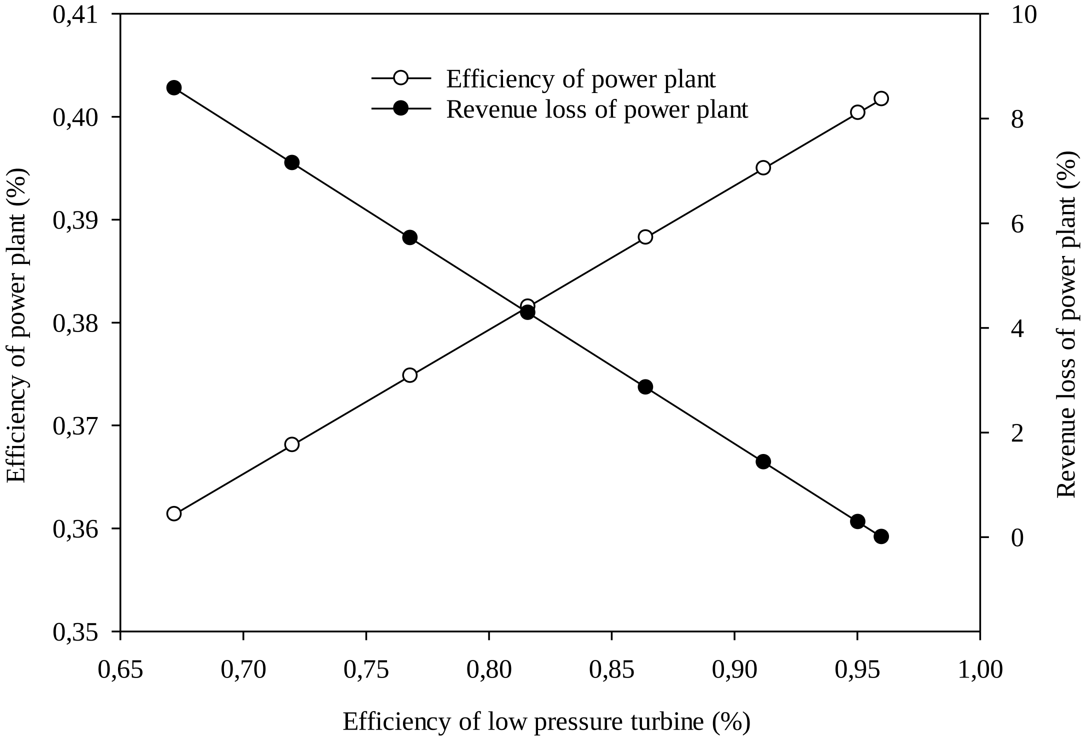


Figure 5. The effect of low pressure turbine efficiency reduction on the power plant thermal efficiency and revenue loss

It is known that the more excess air coefficient results in increased flue gas losses which clarifies the reduction in efficiencies. Moreover, the highest revenue loss was obtained as 62404 $/year for the highest excess air coefficient which is 31.17.

The performance loss of steam turbines is seen directly as a reduction in power generation. Wear and contamination and decrease the turbine isentropic efficiency. The effects of low pressure turbine contamination on the power plant's thermal efficiency and revenue loss were depicted in Figure 5. It should be noted that the reason for turbine efficiency decrement is contamination. It can be seen that these parameters increase as low pressure turbine contamination increases. If the low pressure turbine efficiency decreases to 67% from 96%, the power plant efficiency reduction is 4%. The cost of revenue is approximately 2320292 $/year.

Figure 6 represents the variation in power plant efficiency with intermediate pressure turbine efficiency. By reducing the turbine efficiency by 30%, the power plant efficiency decreased from 40.17% to 40.08%. The revenue loss increased by 0.19% as seen in Figure 6 corresponding to 52515 $/year.

The change in power plant efficiency with different high pressure turbine efficiencies was given in Figure 7 and it can be seen that the power plant efficiency decreased from 40.17% to 36.71% where high pressure turbine efficiency reduced from 84% to 59%. Thus, the income of the power plant diminished by 7.33% according to Figure 7 and it is equal to 1985386 $/year.

It is well known that a thermal power plant can encounter the failure of preheaters. In case of failure of them, the thermal power plant efficiency decreases. The variation of the power plant thermal efficiency and revenue loss were determined by considering that the feed water pre-heaters in the plant are out of service and the results were given in Table 4. It can be understood that the power plant's thermal efficiency reduces with the increment number of pre-heaters. According to the results, it is observed that the power plant efficiency has decreased from 40.17% to 36.09% when the pre-heaters are no longer in to be in use because of any reason. Plant revenue decreased by 9.4%, this loss corresponds to 2434661 $.

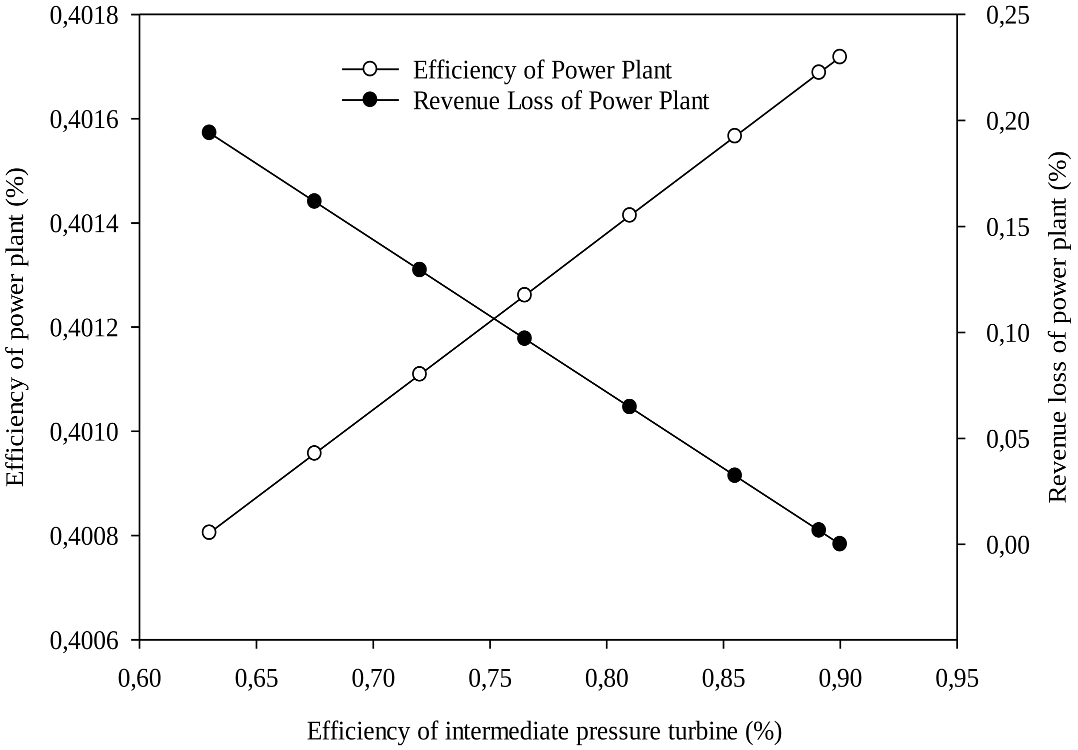


Figure 6. The effect of intermediate pressure turbine efficiency reduction on the power plant thermal efficiency and revenue loss

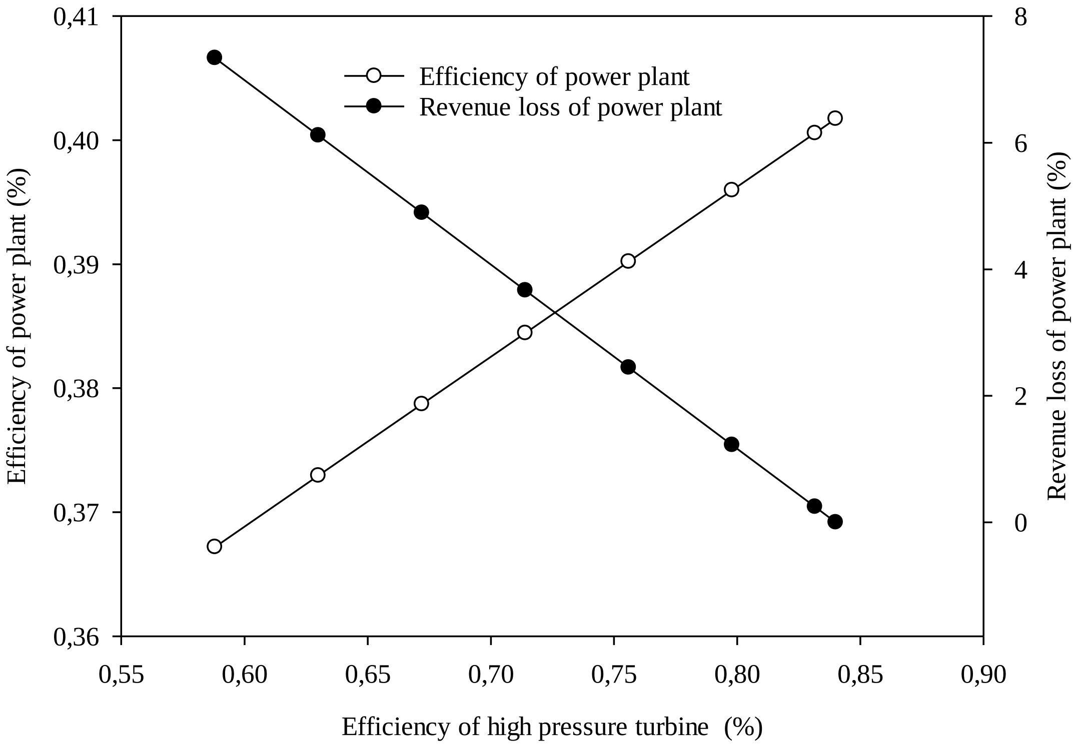


Figure 7. The effect of high pressure turbine efficiency reduction on the power plant thermal efficiency and revenue loss

Table 4. The variation of the power plant thermal efficiency and revenue loss in case of failure of heaters

	η_{th}	**Annual Revenue Loss ($/year)**	**Annual Revenue Loss (%)**
All pre-heaters are in use	0.402	0	0
Pre-heater (H1) is not in use	0.394	477637	1.9
Pre-heaters (H1) and (H2) are not in use	0.385	980542	3.8
Pre-heaters (H1), (H2) and (H3) are not in use	0.363	2277271	8.8
Pre-heaters (H1), (H2), (H3) and (H4) are not in use	0.355	2773364	10.8
Pre-heaters (H1), (H2), (H3), (H4) and (K1) are not in use	0.353	2903102	11.3
Pre-heaters (H1), (H2), (H3), (H4), (K1) and (K2) are not in use	0.360	2434661	9.4

5. Conclusion

In this study, the factors affecting performance in thermal power plants were determined by using thermodynamic analysis. Firstly, the boiler efficiency of the selected coal-fired thermal power plant was estimated using EN 12952-15 standard (indirect method) and power plant thermal efficiency was determined. Then, the parameters that reduce the efficiency of each equipment (condenser, boiler, turbines, and heaters) were determined and their impact on overall efficiency was researched for various operation conditions. In addition, the economic value of performance reduction was calculated. The main outputs of this research were given as follows:

- When the condenser pressure, which is 8.5 kPa at nominal power, is increased up to 30% (11.5kPa), the power plant efficiency was slightly decreased. Revenue loss for this difference was determined as 126134 $.
- According to EN 12952-15 standard, total heat input (the amount of heat excluding chemical heat, coal mill power, circulating gas fan power, circulation pump power and powers of other drive motors and chemical heat) and total heat loss (due to flue gas, unburned CO, enthalpy and unburned combustibles in slag and flue dust and radiation and convection) were estimated to get more accurate results boiler efficiency.
- When the moisture content of the fuel was increased, the lower heating value of the fuel decreased so the boiler efficiency decreased. The fuel moisture content rises from 22% to 47%, the boiler efficiency falls from 92% to 66%, respectively. The revenue loss of the plant due to the decrease in efficiency was 1095623 $.
- The increase of excess air coefficient increases the heat loss due to flue gas from the plant. Thus, both boiler and power plant efficiencies decreased by 2% and 1%, respectively. The revenue loss related to excess air coefficient was estimated 62404 $.
- The efficiencies of the low, intermediate and high pressure turbines were reduced by 30% to investigate turbine contamination effect. Among these turbines, significant turbine efficiency losses were seen in the low and high pressure turbines compared to intermediate one. The highest revenue loss equals 2320292 $ for low pressure turbine.
- When the feed water heaters were not in use, the boiler feed water inlet temperature gradually decreased. The power plant efficiency has decreased by approximately 4% when all pre-heaters are no longer in to be in use for any reason. Thus, the turbine power and the thermal efficiency of the power plant decreased and the annual income loss increased which is equal to 2434661 $/year.

Nomenclature

c_F	Specific heat of fuel, kJ/kgK
c_{SL}	Specific heat of slag, kJ/kgK
c_{pA}	Specific heat of combustion air, kJ/kgK
c_{PG}	Integral specific heat between T_G and T_r of flue gas, kJ/kgK
c_{FA}	Specific heat of flue dust, kJ/kgK
h_{FW}	Feed water enthalpy, kJ/kg
h_{ST}	Active vapour enthalpy, kJ/kg
h_{SS}	Atomizing water enthalpy at the system inlet, kJ/kg
h_{BD}	Blowdown water enthalpy, kJ/kg
h_{RHI1}, h_{RHII1}	Reheated steam enthalpy, kJ/kg
h_{SRI}, h_{SRII}	Atomizing water into reheated steam enthalpy, kJ/kg
h_{SA}	Air heater enthalpy, kJ/kg
h_{SAE1}	Air heater inlet enthalpy, kJ/kg
h_{SAE2}	Air heater condensate enthalpy, kJ/kg
h_{fuel}	Fuel enthalpy, kJ/kg
h_{AS}	Atomizing steam enthalpy (NCV calculation), kJ/kg
H_{UU}	NCV of unburned combustibles, kJ/kg
H_K	NCV of fuel at reference temperature, kJ/kg
H_{COn}	Calorific value per m^3 of CO in standard conditions), kJ/m^3
J_A	Combustion air enthalpy (NCV calculation), kJ/kg
l_U	The ratio of unburned to supplied fuel mass flow rates

$\dot{m}_{RHI1}$, $\dot{m}_{RHII1}$	Reheated steam mass flow rate, kg/s
$\dot{m}_{SS}$	Atomizing water mass flow rate for main steam cooler, kg/s
$\dot{m}_{SRI}$, $\dot{m}_{SRII}$	Atomizing water for reheated steam mass flow rate, kg/s
$\dot{m}_{BD}$	Blowdown water mass flow rate, kg/s
$\dot{m}_{S}$	The water flow rate of the atomizing steam, kg/s
$\dot{m}_{SA}$	Air heater mass flow rate, kg/s
$\dot{m}$	Hot water mass flow rate, kg/s
$\dot{m}_{F}$	Fuel mass flow rate, kg/s
$\dot{m}_{AS}$	Atomizing steam mass flow, kg/s
$\dot{m}_{G}$	Flue gas mass flow rate, kg/s
$\dot{m}_{FA}$	Flue dust mass flow rate, kg/s
$\dot{m}_{SL}$	Slag mass flow rate, kg/s
$\dot{\mu}_{A}$	Combustion air mass to fuel mass ratio
μ_{AS}	Atomizing steam mass flow rate, kg/s
P_{M}	Pulverizer power, kW
P_{UG}	Recirculating gas fan power, kW
P	Other electric power, kW
T_{A}	Air temperature at envelope boundary, °C
T_{G}	Flue gas temperature, °C
T_{r}	Reference temperature, °C
T_{SL}	Slag temperature, °C
u_{SL}	Unburned combustibles content of slag
u_{FA}	Unburned combustibles content of flue dust
V_{God}	Flue gas volume at standard pressure (1 bar) and temperature (0°C), m^3/kg
V_{Gd}	Dry flue gas volume, m^3
Y_{O2d}	Oxygen content of dry flue gas
Y_{O2ad}	Oxygen content of dry air (0.20938 m^3/m^3)
Y_{COd}	CO content by volume of dry flue gas
$\dot{Q}_{G}$	Flue gas losses, kW
$\dot{Q}_{N}$	Useful heat output, kW
$\dot{Q}_{L,tot}$	Total losses, kW
$\dot{Q}_{RC}$	Losses due to radiation and convection, kW
$\dot{Q}_{CO}$	Loss due to unburned CO, kW
$\dot{Q}_{Z}$	Heat credits, kW
$\dot{Q}_{ZF}$	Heat input proportional to fuel burned, kW
$\dot{Q}_{Z,tot}$	Total heat input, kW
η_{B}	Boiler efficiency
η_{th}	Overall power plant efficiency
γ_{H20}	Moisture content of fuel
γ_{Ash}	Ash content in fuel

Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

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