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Evaluation of Irreversibility Analysis for Different Coal Types of a Thermal Power Plant

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Abstract

In this study, first law (energy conservation) and second law (exergy) analyzes of thermodynamics were performed for a thermal power plant. It is very important to perform energy and exergy analyzes in industrial plants. These analyzes can provide guidance on improving energy efficiency and recycling waste energy. In this study, energy and exergy analyzes were made for coals with different chemical contents in nine different countries. According to the results of the analysis, the highest first-law efficiency was found in Serbian coal (second type), as 53.61%. The second highest law efficiency was determined as 46.67% in Bangladesh coal (sixth type). Environmental Destruction Index (EDI) and Sustainability Index (SI) values were determined for all coal types. According to the results of the analysis, the highest EDI value was obtained as 4.00 at the temperature of 305 K for the 2nd coal type, and the highest SI value was obtained as 1.91 at the temperature of 293 K for the 6th coal type, according to the changing reference temperature values. According to this study, the highest second law efficiency was obtained from Bangladesh coal with a carbon (C) content of 77.84%.

Subscripts

i inlet

o outlet

1. INTRODUCTION

The limits of efficient use of energy resources are determined by the first and second laws of thermodynamics. The first law of thermodynamics emphasizes that energy cannot be created out of nothing and existing energy cannot be destroyed. Since the total energy does not change, it has been important to determine what is consumed in energy systems [1]. As a common result of the first and second laws of thermodynamics, it was determined that the exergy is consumed in the energy systems. Thus, while designing energy systems, it became important to design using first and second laws of thermodynamics. And exergy analysis method was developed for systematic performance analysis of these systems [2].

Exergy analysis has been done for many systems and there are many examples in the literature [3- 11]. In one of these studies, exergy and energy analysis was made for a power plant in Serbia. The main purpose of this article is to determine the individual energy and exergy losses of the system components. Energy and exergy efficiency were determined under different loading conditions. Load variation was tested at 100 % and 60 % full load. The energy and exergy losses for the examined plant are presented as a result of the analysis. The results show that energy losses have mainly occurred in the condenser where 421 MW is lost to the environment while only 105.78 MW has been lost from the boiler. Still, the irreversibility rate of the boiler is higher than the irreversibility rates of other components. Finally, the exergy destruction rates of

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the components were determined [12]. In another study, in a coal fueled thermal power plant (TPP), a flue gas with a high CO_2 content can be obtained and this provides CO_2 sequestration in an efficient and energy-efficient manner. Exergy analysis of the power plant is made for detailed analysis. The power plant is divided into four sections: boiler, turbines and feedwater heaters (FWHs), air separation unit (ASU) and flue gas treatment unit (FGU). The exergy of each model (including physical exergy and chemical exergy) has been achieved. Exergy efficiency was achieved for two models of boilers. The exergy efficiencies of the oxy combustion system used in the study and the conventional system were compared [13]. First and second laws analyzes of thermal power plants were compared based on some parameters in Indian conditions. In the study, thermal power plants using subcritical, supercritical and ultra supercritical steam conditions are discussed. The study covers the effect of condenser pressure on plant and exergy efficiency. The effect of high grade coal on performance parameters compared to typical Indian low grade coal was also investigated. The greatest exergy loss occurred in coal combustion and steam generator. The maximum possible plant efficiency was found to be approximately 41% for the supercritical steam plant and approximately 44.4% for the ultrasupercritical steam plant [14]. In the study of Rudra et al.[15], versions are being studied to improve the efficiency of coal-fired steam power plants with some steam parameters.For exergy analysis, a version of a process simulation computer code (ASPEN Plus) is used. The overall exergy efficiency for the coal-fired process is 36%. The study also describes the effects of condenser pressure on plant and exergy efficiency. As a result of the study, the maximum possible plant efficiency was found to be approximately 40.2% for the supercritical steam plant and approximately 44.8% for the ultra-supercritical steam plant. Both conventional and advanced exergy analysis methods were applied for a supercritical power plant which uses coal as fuel in othr study. As a result of the study, it was found that the boiler subsystem still has the largest preventable exergy destruction. Much of the avoidability is exergy destruction in feedwater preheaters; the components are mostly internal while there are leftovers, indicating that the improvements mainly depend on the following. improvements in the design and operation of the component [16]. In a study of qualitative analyzes of coals in Bosnia and Herzegovina, the study includes some features: ash (A), moisture (W), combustible matter (V^g) etc. In this paper, arithmetic mean, absolute range, standard deviation and variations coefficient values were determined using statistical parameters. The analysis showed significant deviations in the ash properties and some values were found like moisture is 36.23 %. Bosnia do not deviate much from the characteristics of the coal in the surrounding countries. It is foreseen that the results obtained will be used in problems such as coal combustion analysis in thermal power plants, optimization of electricity filter, decrease of SO_2 in flue gas [17]. A study was conducted to investigate the effects of steam parameters (pressure, temperature) on energy and exergy efficiency of the power plant under different load conditions for five different TPPs. The Soma TPP, which operates under subcritical conditions, has a single intermediate superheat and has six feedwater preheaters, has been taken as the reference power plant. For the other four cases, the Simulations were made using the Ebsilon program and the analysis results found were compared with the reference plant. When the energy and exergy efficiencies of Case 4 and the Reference Power Plant are compared, the energy efficiency increased by 9.24 % and the exergy efficiency increased by 8.06% under 100% loading conditions. As a result of this study, it has been shown that steam conditions under different loadings have a significant effect on the first and second laws efficiency of the systems [18]. Acır and others [19], first and second law analyses were made for a 160 MW TPP. Irreversibility and energy- exergy efficiencies were determined. The energy efficiency was determined as 42-76% for the total plant. It was observed that dead state temperatures directly effect the exergy efficiency of the TPP.

In this study, first and second law analysis of thermodynamics are performed and irreversibility is investigated. Coal chemical data of nine different countries and operating data of a thermal power plant in Turkey are used. According to the mines they are extracted from, coal compounds vary. First of all, coal chemical data of nine different countries to be analyzed are obtained. Then, based on the energy conservation and exergy principles of thermodynamics, thermodynamic analyzes of these coals are made. According to the results of the analysis, the first and second law efficiencies are determined for the total power plant for each coal type.

2. SYSTEM DESCRIPTION

A coal-fired power system consists of many basic elements. The coal-fired power system is mainly based on a regenerative Rankine cycle consisting of a boiler, turbines, a generator, a condenser, feedwater heaters, a deaerator and several pumps. In the boiler, the steam is heated to the designed pressure and temperature with the thermal energy released by the coal. The steam then expands in the turbine to generate power and the steam from the turbine is condensed into the feed water in the condenser [20]. Figure 1 shows the schematic diagram of the coal- fired power plant system [21].

Thermal power plants are facilities that first convert the chemical energy in the fuels into heat energy and then into electrical energy. In generally natural gas, coal, diesel, fuel-oil, hard coal are used as fuel in thermal power plants. Within the scope of this study, it is aimed to make an energy and exergy analysis of a TPP with the use of different coal and in this study and a 210 MW thermal power plant using different coals is examined.

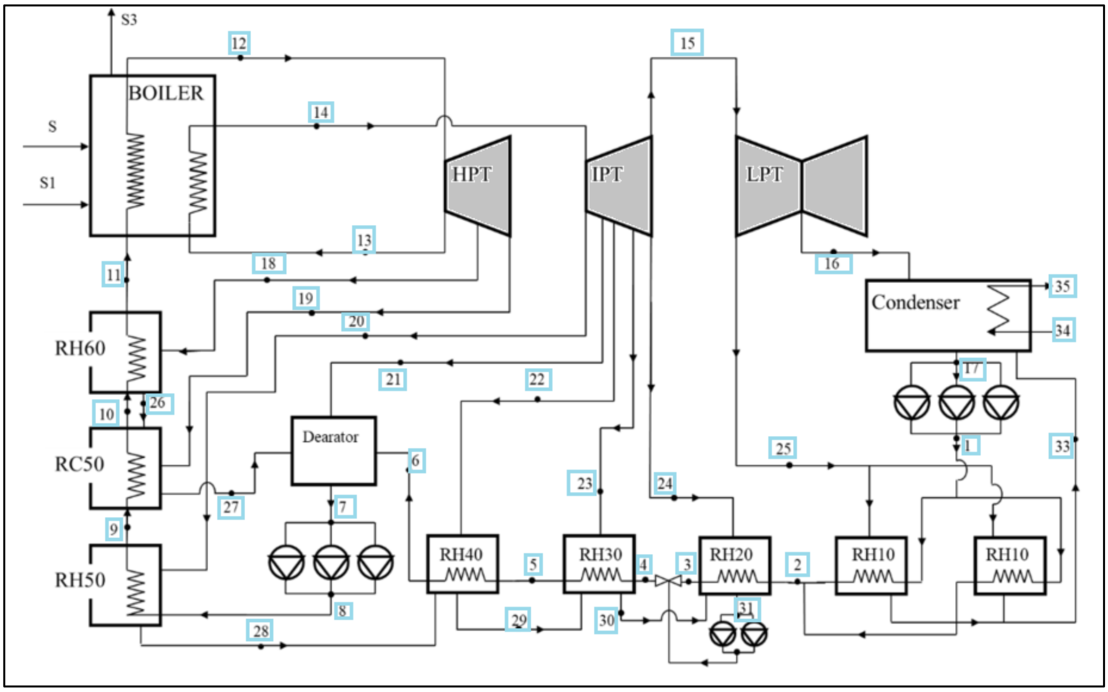

Figure 1. *Schematic diagram of the coal- fired power plant system*

3.COAL DATA

Coal is a type of fuel that is often used in thermal power plants. In each region, the coal content shows different characteristics. Table 1 shows the content values of coals in some regions. The data in Table 1 and Table 2 are taken from References [12- 16], [22- 24].

The data presented in Table 1 show, respectively, the carbon, sulfur, hydrogen, nitrogen (azote), oxygen, moisture, ash and lower calorific value of the coal. Chemical exergy and total exergy values for different coal are also shown in Table 2.

Table 1. *Chemical properties of different coal*

Country	C	S	H	N	O	W	A	LHV (kcal/kg)
Turkey	41.5	3.5	2.25	0.66	9.0	14.73	28.6	2300
Serbia	20.38	0.65	1.83	7.98	0.6	23.56	-	1637
China	60.51	0.43	3.62	0.7	9.94	13.8	11	5446
India	38.9	0.6	2.6	0.7	6.7	5.7	43.1	3421
S.Africa	68.1	0.5	3.5	1.7	7.5	2.4	-	6148
Bangladesh	77.84	0.6	5.4	1.68	11.20	3.28	21.5	5430
Greece	34.43	0.84	2.77	0.96	16.26	12	27.93	1259
Bosnia	39.32	3.46	3.78	0.8	11.05	32.20	9.21	3758
Canada	52.1	0.9	4	0.5	15.25	-	21.5	-

Table 2. *Chemical Exergy and total exergy for different coal*

	Energy (kW)	Chemical Exergy (kW)	Total Exergy (kW)	β
Turkey	389456	10190	412823	1.060
Serbia	277191	7403	299897	1.082
China	922164	24338	985919	1.069
India	579273	15318	620520	1.071
S.Africa	1041033	27364	1108477	1.065
Bangladesh	919455	24288	983906	1.070
Greece	213185	5749	232898	1.092
Bosnia	636337	17019	689445	1.083
Canada	841902	22447	909327	1.080

The exergy β factor based on LHV is calculated [25]. [26] as in Equation 1.

$$\beta = 1.0437 + 0.1882\left(\frac{h}{c}\right) + 0.0610\left(\frac{o}{c}\right) + 0.0404\left(\frac{n}{c}\right) \qquad (1)$$

The type of coal for each country is named in Table 3.

Table 3. *Coal types by country*

Country	Coal type
Turkey	Coal 1
Serbia	Coal 2
China	Coal 3
India	Coal 4
S.Africa	Coal 5
Bangladesh	Coal 6
Greece	Coal 7
Bosnia	Coal 8
Canada	Coal 9

4.NUMERICAL ANALYSIS

In this study. analyzes for nine different coals were made for six different system temperatures. As a result of the energy and exergy analysis made for each case, the second law efficiency was obtained for the basic components of the system; such as boiler, condenser, heaters and pumps. However due to the excess of the coal type and the wide range in the system temperature, the total efficiency of the system was examined instead of examining the efficiency of all components.

4.1. Energy and Exergy

Energy cannot be created or completely destroyed. However it can transform into different forms of energy during the process. The upper limits of the transformation are determined by the second law of thermodynamics. The ability of energy to do work is called exergy. Exergy analysis of thermal systems helps to determine the nature of the energy's ability to do work and its location and amount in the system.

To evaluate the performance of thermal power plants energy and exergy efficiencies or specific heat consumption values are checked.

According to the principle of conservation of mass, the amount of material entering and leaving a control volume must be equal and is given by the following equations [27-28].

$$\sum \dot{m}_i = \sum \dot{m}_o \tag{2}$$

In a continuous flow open system, the total energy entering and leaving the control volume as heat, work, kinetic, potential or mass flow is equal.

$$\dot{Q}_i + \dot{W}_i + \sum \dot{m}_i \left(h + \frac{v^2}{2} + gz \right)_i = \dot{Q}_o + \dot{W}_o + \sum \dot{m}_o \left(h + \frac{v^2}{2} + gz \right)_o \tag{3}$$

If the kinetic and potential energy changes are neglected, the equation takes the Eq. 4.

$$\dot{Q}_i + \dot{W}_i + \sum \dot{m}_i h_i = \dot{Q}_o + \dot{W}_o + \sum \dot{m}_o h_o \tag{4}$$

In this equation, $\dot{m}$ = mass flow, h = enthalpy, Q = heat and W= work. The exergy values entering and leaving the control volume are obtained in the following equations. The exergy destruction rate equation is derived from the exergy balance for the control volume of the equilibrium component of any power plant as follows [1].

$$\dot{E}x_D = \Sigma(\dot{E}x)_i - \Sigma(\dot{E}x)_o + \left[\Sigma\left(\dot{Q}\left(1-\frac{T_0}{T}\right)\right)_i - \Sigma\left(\dot{Q}\left(1-\frac{T_0}{T}\right)\right)_o\right] + \dot{W} \tag{5}$$

In this equation, Ex_{in} is incoming exergy streams and Ex_{out} is outgoing exergy streams, T_0 is surrounding temperature, Q is heat transfer rate, T is fixed temperature and W is work transfer rate.

Equation 6 is used to calculate the physical exergy through the control volume.

$$\dot{E}x = \dot{m}\left[\left(h-h_0\right) - T_0\left(s-s_0\right)\right] \tag{6}$$

In this equation, h is specific enthalpy and s is specific entropy.

The exergy efficiency [29] is calculated as in Equation 7.

$$\eta_{II} = \frac{\dot{W}_{net}}{\dot{E}_{fuel}} \tag{7}$$

The Environmental Destruction Index (EDI) of the system can be defined as the inverse of the exergy efficiency [30].

$$EDI = \frac{1}{\eta_{II}} \tag{8}$$

The Sustainability Index (SI) concept which ensures the efficient use of resources is also dependent on exergy efficiency [31].

$$SI = \frac{1}{1-\eta_{II}} \tag{9}$$

In this study different country coals are numbered; Turkish coal is coal type 1, Serbia; coal type 2, China; coal type 3, India; coal type 4, S.Africa; coal type 5, Bangladesh; coal type 6, Greece; coal type 7, Bosnia; coal type 8 and Canada; coal type 9 and these mappings are shown in Table 3.

3. RESULTS AND DISCUSSION

The results obtained first law efficiency analysis applied to the thermal power plant using operational data are given Figure 2. According to the results in Figure 2, the highest 1st law efficiency is obtained in the 2nd coal type and this value is 53.61%. The lowest efficiency value was determined as 6.1% in the coal type 6.

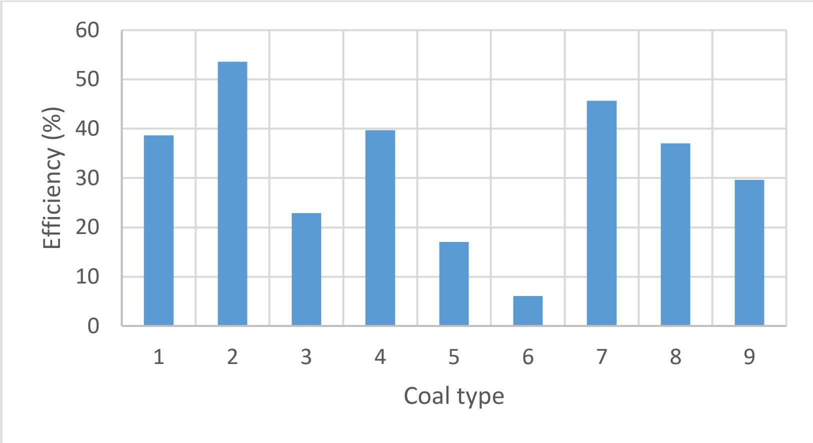

Figure 2. *Total first law efficiency for coal types*

The second law efficiency datas obtained as a result of the analyzes made for nine different coal values are given in Table 4. While the first law total efficiency remained constant with the changing ambient temperature, the second law total efficiency took different values according to the changing temperature.

Table 4. *Total second law efficiency for coal types*

Second law efficiency (%)						
Temperature (K)	278	283	288	293	298	303
Coal type 1	32.64	32.54	32.21	31.88	31.68	31.24
Coal type 2	26.01	25.98	26.25	26.02	25.33	24.96
Coal type 3	39.50	39.32	39.25	39.50	38.24	37.73
Coal type 4	31.72	31.63	31.31	31.72	30.79	30.37
Coal type 5	42.64	42.43	41.99	42.22	41.25	40.71
Coal type 6	46.67	46.42	45.94	47.67	45.11	44.52
Coal type 7	28.79	28.73	28.44	28.79	27.99	27.59
Coal type 8	32.66	32.55	32.22	32.66	31.69	31.25
Coal type 9	36.29	36.15	35.78	36.10	35.17	34.70

The second law efficiency datas obtained as a result of the analyzes made for nine different coal values are given in Table 4.

According to the results in Table 4, with the increasing temperature value, the total second-law efficiency tended to decrease in all coal types. While the total second law efficiency was 46.67 % for the 6th coal type at 278 K. The total efficiency decreased to 44.52 % at 303 K. Type 2 coal has the second-lowest law efficiency compared to other coals. While its second law efficiency was 26.01 % at 278 K, it decreased to 24.96 % at 303 K.

In Figure 3. for different types of coal. the change in entropy with temperature is shown. According to the graph. the highest entropy production was observed in the 2nd coal type. while the lowest entropy production was observed in the 6th coal type.

Irreversibility describes the amount of exergy destroyed or wasted work potential in a closed system. When examined according to varying coal types, the highest irreversibility value was obtained in coal type 2 and the lowest irreversibility value was obtained in the 6th coal type.

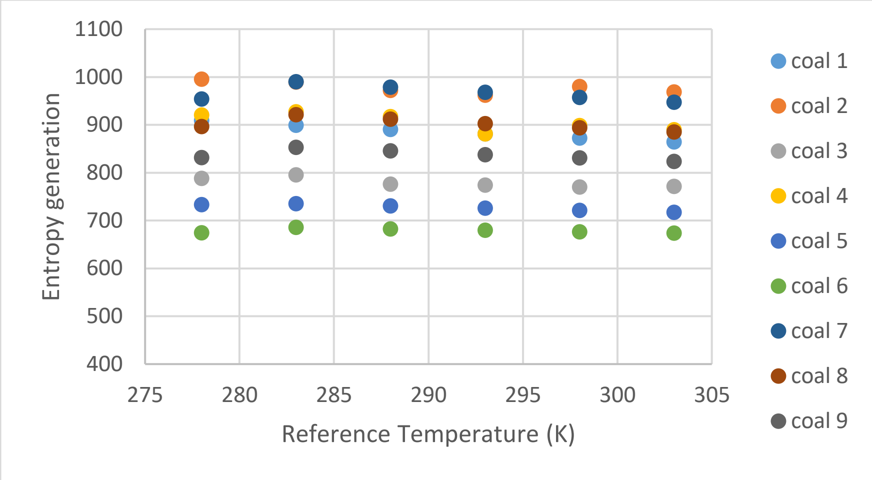

Figure 3. *Entropy generation change in the boiler according to temperature*

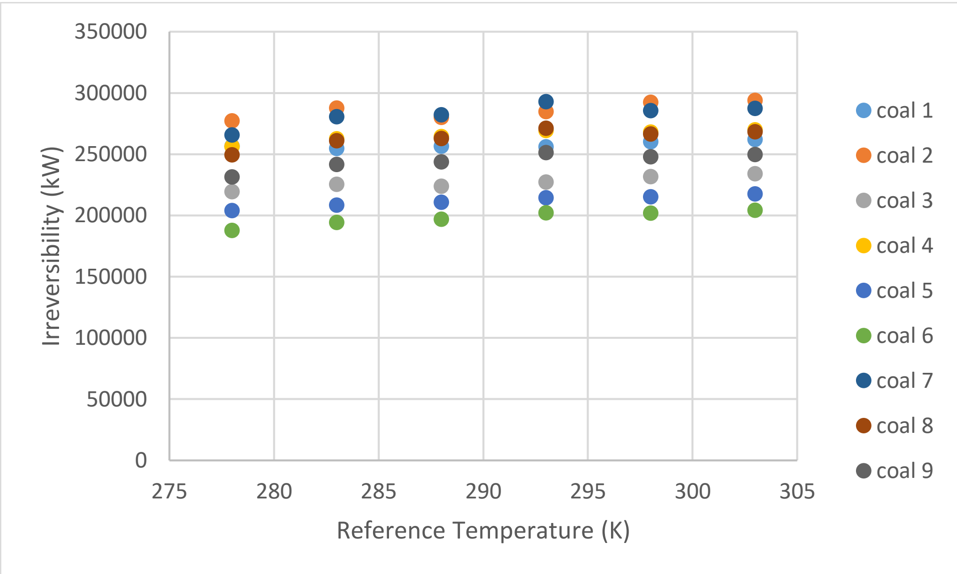

Figure 4. *Irreversibility change in the boiler according to temperature*

The change in temperature changes the irreversibility and second law efficiency, especially in the boiler. The irreversibility change in the boiler according to the changing temperature in all coal types is shown in Figure 4.

The Environmental Destruction Index (EDI) measures system's overall progress towards environmental sustainability [32]. Exergy creates a relationship between environmental impact and sustainability by making maximum use of resources, so that energy can be used more efficiently. The variation of this effect is shown in Figures 5 and 6.

As seen in Figures 5 and 6, SI decreases with increasing reference temperatures while EDI values increases. The results show that SI and exergy efficiencies decrease with increasing reference temperature in the system. Similar results have been obtained in the literature [21], [31].

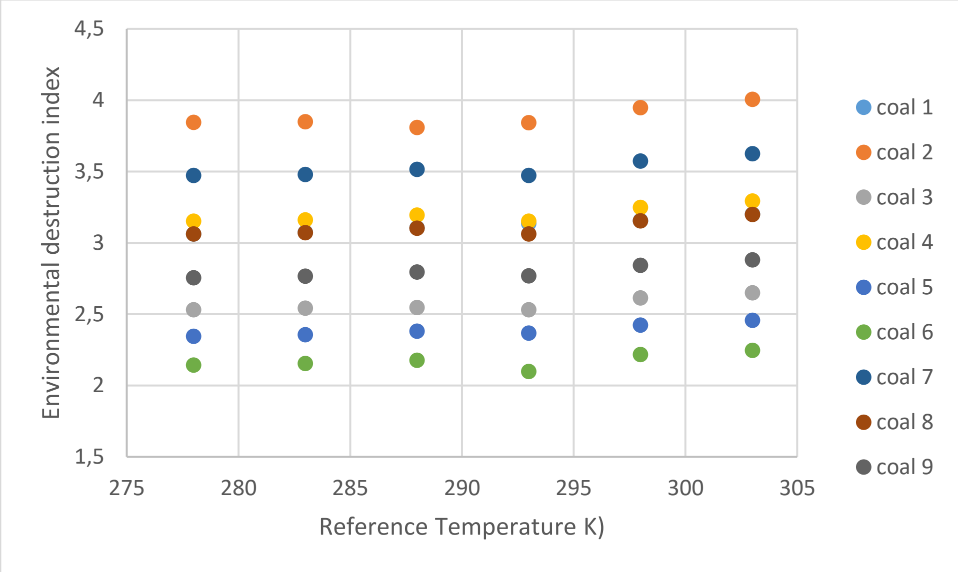

Figure 5. *Environmental destruction index change according to temperature*

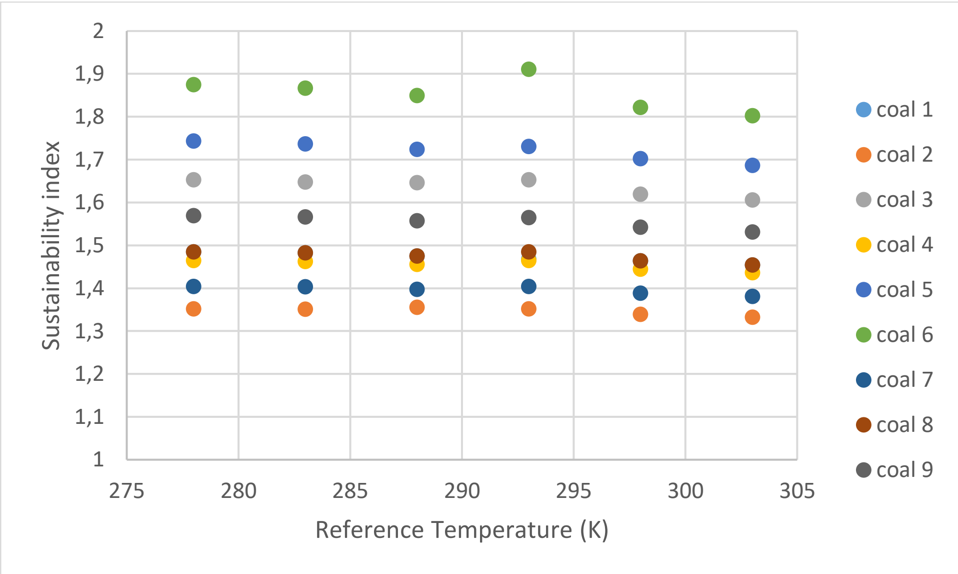

Figure 6. *Sustainability index change according to temperature*

4.CONCLUSIONS

In this study, first and second law analysis of thermodynamics were performed and irreversibility was investigated. Coal chemical data of nine different countries and operating data of a thermal power plant in Turkey were used. According to the results obtained, total first law and total second law efficiency values were determined for 9 different coals. According to these values, the highest first law efficiency was determined as 53.61 % in the second type of coal. The highest second law efficiency was determined as 46.67 % in the 6th coal type.

The lowest entropy production was seen in the 6th coal type, which is the type of coal with the highest exergy efficiency. According to the irreversibility values examined, it was observed that the irreversibility value of the second type of coal was higher with increasing temperature compared to the others and at 303 K, the irreversibility value reached approximately 300000 kW.

The results show that while the first law efficiency did not change with increasing reference temperature, the second law efficiency decreased in all coal types. The fact that the second law efficiency is the 6th highest coal type can be explained by the fact that this coal contains more carbon in its chemical content compared to the others.

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