Original Article: Application of Combined Pinch & Exergy Analysis in Steam Power Plant

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ABSTRACT

The ability of pinch technology to provide a general approach to process design and analysis, but it is incapable of analyzing systems that include power in addition to heat. On the other hand, exergy analysis the main limitation of exergy analysis is the lack of a comprehensive system design method. The combined analysis of punch and exergy, obtained from combining the two mentioned methods, uses both methods to remove both methods' limitations. In this article, by introducing the Ahvaz Ramin power plant as the studied power plant, an attempt has been made to identify and examine effective improvements using the CPEA (Combined pinch and Exergy Analysis) method. Three proposed correction scenarios have been used to optimize the power plant: 1- Approaching the pins, 2- Increasing the steam in the boiler 3- Decreasing the condenser pressure. The results show that it is possible to increase the studied power plant's efficiency by about 1.7% by using this method. The fuel consumption of 1569 cubic meters per hour reduces emissions by about 1.7 percent (equivalent to 20 tons per hour). Therefore, the production of pollutants is significantly reduced. Thermo-flow software (Steam Pro) simulated the power plant and Aspen Pinch software for CPEA analysis.

Introduction

Exergy analysis based on the first and second thermodynamics laws makes it possible to determine the optimal method of analysis of energy systems and a clear knowledge of energy levels and undesirable thermodynamic processes of a system. Exergy analysis consists of two basic steps: the first step is to identify and investigate undesirable thermodynamic processes in the system based on the determination of exergy losses. The second step is to determine the system's possible corrections based on unavoidable exergy and unavoidable exergy concepts. It can display system information in simple hybrid diagrams [1-4] and comprehensive hybrid diagrams [1-5]. Composite Curve (CC) diagrams target the amount of external energy required (thermal load) and investment cost. In Grand Composite Curve (GCC) diagrams, CC is the horizontal

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enthalpy axis and the vertical temperature axis. Pinch technology uses the concept of process integration and pre-design targeting to provide a thermodynamic overview of in-process flows. Using the concept of exergy analysis in pinch technology, the new CPEA method has been developed. The basic tools used in CPEA are very important: Exergy Combination Diagram [6], and the second diagram, and Another important place diagram is exergy [7].The vertical axis is the Carnot coefficient in this diagram, and the horizontal axis is the enthalpy. Exergy Composite Curve(EGCC) and ECC diagrams graphically show changes in component conditions and their impact on the entire system. ECC and EGCC diagrams The GCC and CC diagrams can still describe the interactions between different system components, and the effect of any change in system components on the whole system can be easily seen in the EGCC and Exergy Composite Curve (ECC)diagrams.

The area enclosed between the hot and cold flow lines shows the number of exergy losses due to heat transfer between the hot and cold streams. Linhoff and Dahl [5] (1991) used pinch and exergy analysis to analyze low-temperature cooling systems. sing this method, they reduced the required axial work to 3.831 MW. They also (1995) examined the combined method of pinch and exergy to design a closed cycle gas turbine [6]. Zheng and Dahl (1995) [6] applied the combined combination of pinch and exergy to the combined cycle of steam turbine and closed cycle gas turbine and achieved an increase in cycle efficiency of about 0.82%. Zheng and Dahl (1995), (1996) [6-7] also used this method to analyze and improve the efficiency of several samples of other thermal power plants. Zheng and Dahl (1996) also presented a conceptual approach to thermal power plants [7]. Favrat and Stein (1996) [8] developed pinch technology using exergy factors and analyzed cogeneration systems and heat pumps. Lavarik et al. (2003) [9] investigated the reduction of entropy production in a methanol production process using pinch technology. Manin and Zhou (1998) [10-11] applied economic studies with a combined Pinch and Exergy analysis to a combined power generation cycle. Their optimization increased the studied cycle's efficiency from 45.02% to 49.85%, taking into account economic considerations. Surin and Paris [13] (1999) used the combined analysis of pinch and exergy to study and identify the optimization potentials in a hydrogen production unit and increase the unit efficiency from 55.7% to 56.6%. They showed that pinch exergy analysis could find the desired changes with the least process change, least equipment modification, and less computational volume. Anantarman and Gundershen [14] (2006) used a combination of exergy analysis and pinch to investigate a methanol unit and identified opportunities for optimization. This research presented a new approach to studying process units using the developed pinch and exergy method. Gonderschen et al. (2007) [15] proposed an extended pinch-exergy analysis considering compressive exergy for refrigeration systems' optimal design. In this method, innovative rules and a new concept of pinning are presented to optimize. Khoshgoftarmanesh et al. (2007) [16] presented the thermoeconomic analysis schematically to evaluate a 1000 MW nuclear power plant's performance by presenting EDL and ECDL coefficients. Also, in this paper, new coefficients were presented to draw combined diagrams of pinch and exergy. Ataei and Yu (2010) [17] analyzed and optimized a 320 MW power plant using combined pinch and exergy analysis. Qanadzadeh Sadeghzadeh (2017) [19,18] used pinching and exergy techniques to improve efficiency and reduce pollutants in the ethylene oxide production process [4-6].

I. Methods and materials

A. Casestudy

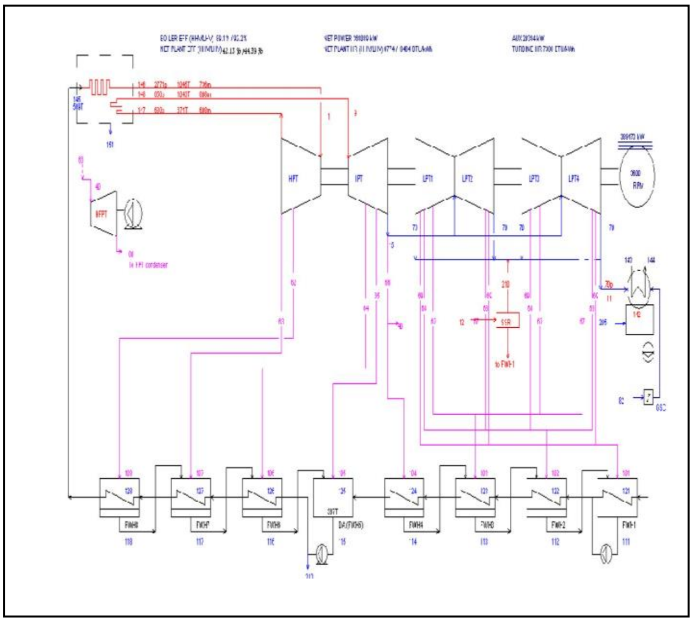

Figure 1. Schematic of Power Plant Cycle same as RAMIN Ahwaz simulation in (Steam Pro) Thermoflow

Figure 1 shows the simulated Ahvaz Ramin power plant's simulated model that has been selected as the power plant under study. The cycle of the Ahvaz Ramin power plant is a steam turbine cycle. The plant includes a reheating unit with eight turbines [6-8]. These eight substrates provide the steam needed to preheat the feed water. The eight preheating feed water stages include an air conditioner, four low-pressure preheaters, one medium pressure preheater, and two high-pressure preheaters. The main fuel of the power plant is furnace oil. The Ahvaz Ramin power plant simulation has been done using Thermoflow software (Steam Pro) 13.0, specialized software in power plant simulation. The main information and specifications of the simulated power plant are given in Table 1. The type of boiler, the type and layout of the steam turbine network, and the network of heat exchangers and the corresponding condenser are entered as equipment input in the Steam Pro software. Also, the weather conditions, type of fuel, and the amount of power as input to the software.

TABLE 1. MAIN SPECIFICATION OF SIMULATION POWER PLANT

	Real	Simulated		Real	Simulated
$W_{net,out}$	315 MW	315 MW	m_{fuel}	9.14 kg/s	9.14 kg/s
$T_{superheat}$	560 C	560 C	$\eta_{HPT,1}$	81 %	81 %
$P_{superheat}$	5.178 bar	5.178 bar	$\eta_{HPT,2}$	88 %	88 %
$m_{superheat}$	1.315 kg/s	1.315 kg/s	$\eta_{IPT,1}$	86 %	86 %
Reheater	1	1	$\eta_{IPT,2}$	87 %	87 %
FWheater	8	8	$\eta_{LPT,1}$	88 %	88 %
Pcon	0.05 bar	0.05 bar	$\eta_{LPT,2}$	89 %	89 %
PP_{FWH}	6.5 c	6.5 c	$\eta_{LPT,3}$	87 %	87 %
δP_{subtle}	0.05 %	0.05%	$\eta_{LPT,4}$	87 %	87 %
$\delta P_{dearetor}$	0.0851 %	0.0851%	$\eta_{LPT,5}$	87 %	87 %
$\delta P_{reheeater}$	9.9 %	9.9 %			

Fuel is the primary energy source in the steam power plant, which releases the chemical exergy of the fuel after combustion in the furnace. This initial exergy is wasted due to the incomplete combustion process, air preheater, and chimney losses. The remaining exergy is given to the steam cycle, which is lost during the heat transfer process between the combustion products and the steam. Within the steam cycle, the feed water preheating system, responsible for raising the feedwater temperature entering the boiler using steam drawn from the turbines, also loses some exergy during heat transfer. We also have some exergy losses in the condenser due to heat exchange with an external source (5). Furnaces, preheaters, and condensers form the steam power plant's network of heat exchangers [17]. The remaining exergy given to the cycle is delivered to the power generation turbine system after the exergy is lost in the HEN. According to Equation 1, fuel consumption, HEN, and turbine system are related, and a change in each causes a change in the other two (3).

$$\Delta EX_{FUEL} = EX_{Power} + \sigma T_{OHEN} \quad (1)$$

$$\sigma T_{OHEN} = \sigma T_{OF} + \sigma T_{OP} + \sigma T_{OC} \quad (2)$$

ΔEX_{FUEL} is the exergy of fuel, EX_{Power} is exergy delivered to the turbine system, σT_{OHEN} is exergy wastes in Heat Exchanger Network(HEN). σ_{TOF} is exergy losses in the furnace, σ_{TOP} is exergy losses in the preheaters, σ_{TOC} is exergy losses in the condenser to introduce the thermodynamic description of the power plant and determine the effects between these three main parts on each other, a new diagram called the combination pinch and exergy diagram is introduced. This chart will be examined further in the next section [8-10].

Analysis Method

Pinch analysis is a common method for targeting and designing chemical and thermal processes. CC and GCC curves are the two main tools in pinch analysis, in which enthalpy concerning temperature is plotted. The energies studied in the two diagrams CC and GCC are only thermal loads. These graphs cannot be used to analyze thermal power plants. The concepts of CC and GCC are developed to discuss systems that include heat and power. As shown in Figure 2, the CC curve for a heat transfer system is converted to ECC and EGCC curves [11-13].

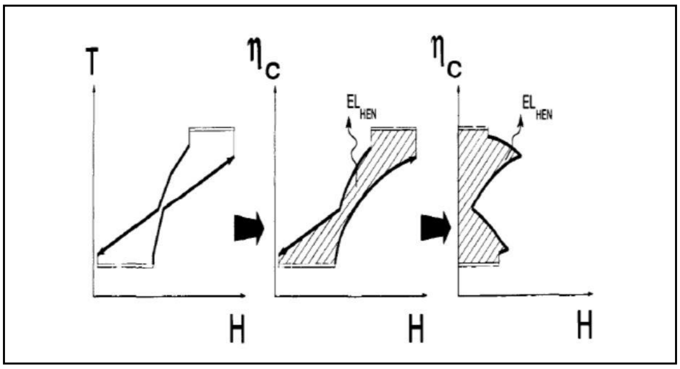

Figure 2. Schematic of exergy transfer from CC to ECC and EGCC (2)

Batched surfaces show exergy loss of the heat transfer process [14-16]. Combining pinch and exergy analysis makes it possible to predict production-oriented work for power systems with good accuracy. This hybrid method is developed to target work-oriented. This method only analyzes the heat transfer processes plotted on the H-chart, and this method cannot analyze processes associated with pressure or composition changes. In other words, it cannot analyze the H-η diagram of major power plant processes such as turbines and compressors. The combined analysis of pinch and exergy is introduced to overcome this limitation by introducing a new diagram called H-η or extended. This method covers the whole system and provides targeting information for corrections. Simultaneously, the main directions, modifications, and improvements of the system's development's possible parts are identified effectively. Exergy losses are divided into two parts, avoidable and preventable, to obtain the maximum saving potential that can be calculated for each correction. Inevitable energy losses are defined as the minimum energy losses that cannot be prevented in a process due to technical and economic constraints. Preventable waste offers maximum practical potential for process development. With this method's help, the system is analyzed, and the main reasons for its shortcomings are identified. The possible corrections and the maximum practical potential of these corrections are obtained by analyzing the preventable losses caused in different types [17-19].

Results and discussion

Results

Basic information is extracted for the power plant's hot and cold currents to draw the Flue Gas Exergy Composite Curve (FGECC) of the studied power plant. In the steam cycle, hot currents are: subcurrent flows and steam passing through the condenser, and cold currents are: feed water streams that need to be heated and steam passing through the heater. The studied power plant's hot and cold currents, including inlet and outlet temperatures, along with their enthalpy changes, are given in Table 2. Because the external hot heat load required for the cycle is 817525 kW, the minimum allowable temperature difference calculated for the system is 3.23 ° C. Having the flow information and the minimum allowable temperature difference, the GCC and CC diagrams of the power plant are drawn, which are shown in Figures 3 and 4, respectively [20-22]. The amount of hot and cold heat load required is shown in Figures 3 and 4.

TABLE 2. A HOT AND COLD STREAM RELATED TO THE POWER PLANT STUDY

Tsupp (C)	Ttarg (C)	Duty (kW)	Flow
395	281	9491	Stream 1
281	280	38523	Stream 2
280	163	13832	Stream 3
321	274	6869	Stream 4
247	246	52318	Stream 5
246	163	11604	Stream 6
415	196	6356	Stream 7
196	195	24729	Stream 8
195	163	1837	Stream 9
323	163	4032	Stream 10
163	162	23874	Stream 11
244	138	2313	Stream 12
138	137	22197	Stream 13
137	33	4578	Stream 14
164	112	1081	Stream 15
112	111	22452	Stream 16
111	33	3366	Stream 17
38/87	86	21113	Stream 18
38/86	33	2049	Stream 19
61	60	19522	Stream 20
60	33	1010	Stream 21
33	163	129582	Stream 22
166	280	162935	Stream 23
280	356	155804	Stream 24
356	357	249398	Stream 25
375	538	272221	Stream 26
323	538	131940	Stream 27
34	33	433750	Stream 28

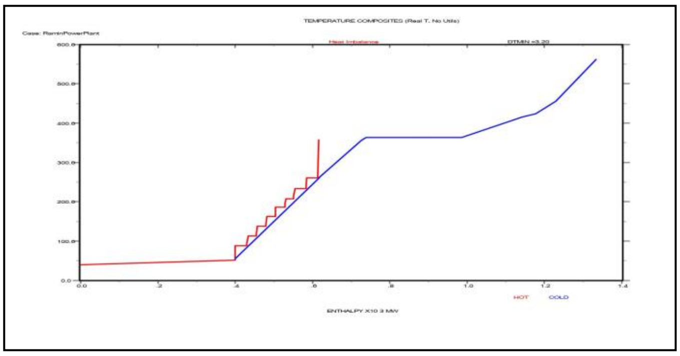

Figure 3. Schematic of CC curve of RAMIN Power Plant in the base case

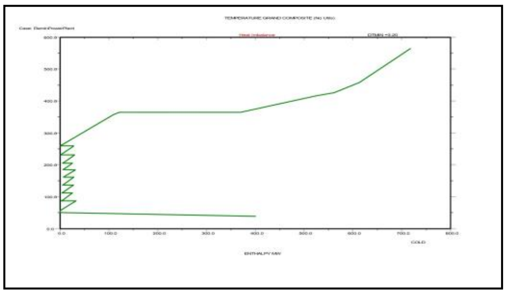

Figure 4. Schematic of GCC curve of RAMIN Power Plant in the base case

Using GCC and CC diagrams, we can draw EGCC and ECC diagrams. Figure 5 shows the ECC diagram of the power plant in the ground state. Figure 5 shows the corroded surface exergy losses due to heat transfer in the feed water preheaters, equal to 5560 kW. Figure 6 shows the EGCC diagram of the power plant in the ground state. Figure 6 shows the flushed surface, the superheated steam exergy delivered to the turbine system, equal to 360,510 kW [23]. Nevertheless, these diagrams do not show how to reach the fuel exergy and the complete exergy distribution within the system to develop these diagrams. The hot heat load used in the combustion products power plant and the cold heat load used in the combustion products power plant and the cold heat load used in the power plant are cooling water. By entering the combined diagram of the exergy of combustion products [18] as well as the combined diagram of the coolant exergy [19] in the EGCC diagram, we come to a new diagram that shows not only the thermal currents and temperature driving forces but also the exergy and axial work currents. The new chart is called CPEA. The CPEA diagram of the power plant under study is shown in Figure 7, showing the hash's total level in the fuel exergy given to the cycle by FGECC in Figure 7. The diagonally incised surface shows the total exergy loss in the heat exchanger network, and the vertically exaggerated exothermic surface shows the steam reaching the turbine system to produce power. As shown in the figure, if there is a change in fuel consumption, we will see changes in the HEN exergy losses and the exergy reached to the EX_{Power} turbine system [24-26].

Thus, the thermodynamic integration between fuel consumption, HEN, and the turbine system is shown in a diagram. In CPEA, the interactions between the different components of the power plant can be shown, and a conceptual view of the power plant can be obtained [27-29].

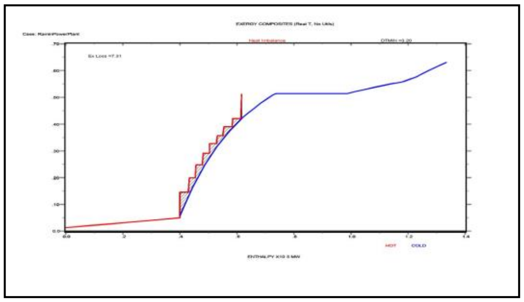

Figure 5. Schematic of exergy Composite Curve in the base case

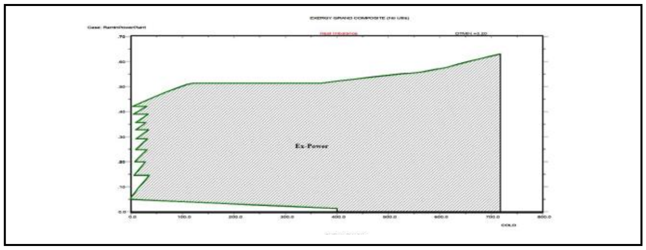

Figure 6. Schematic of exergy Composite Curve in the base case

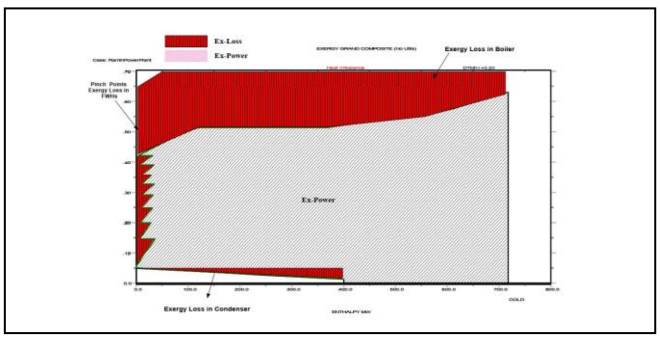

Figure 7. Combined Pinch- Exergy Composite Curve of Power Plant in the base case

Discussion

Again, consider Figure 7, as shown in the figure, the input exergy is the fuel exergy delivered to the cycle by the combustion products. After the exergy is lost in the furnace, preheaters, and condenser, the remaining exergy is delivered to the power generation turbine system. The total exergy losses (furnace exergy losses + preheater exergy losses + condenser exergy losses) are 400145 kW, and the exergy is delivered to the turbine system for power generation (Ex-Power) at the base state is 418000 kW [30-32]. Figure 7 shows the diagonal hatched surface representing the total exergy losses and the vertical hatched surface representing the exergy delivered to the turbine system. According to Figure 7, any reduction in furnaces' exergy losses, preheaters, and condensers will increase the output power and reduce fuel consumption. The power plant's thermal efficiency in the ground state is 44.39%, and fuel consumption is 21.9 kW/s. Using Figure 7, ways to reduce exergy losses, the identification and impact of these changes on the whole system are examined [33-35].

Strategy 1: Lower Pinch points

To reduce exergy losses in preheaters, we examine the distribution of temperature driving forces in the preheating system (Figure 8). Figure 9 shows an enlarged view of the preheater system in the CPEA (Figure 8). According to Figure 9, it can be seen that the smallest allowable temperature difference, which is 3.32 degrees Celsius, occurs only at point A and the system has only one pinch point. Since it is possible to create another punch at the condensation temperature of each vapor substrate, it can be said that the temperature driving forces in this system do not have a uniform distribution. According to thermodynamics principles, reducing driving force during the heat transfer process is one of the factors of irreversible reduction. Therefore, to reduce the driving forces in other condensation steps and bring it to the minimum allowable temperature difference in the system, the thermal efficiency of the power plant will be improved due to the reduction of the hot heat load required by the power plant. To close the other density steps' temperature difference, the substrates' flow rate must be changed. To do this, the energy relationship between the two closely saturated temperatures is written. Total exergy losses are reduced to 210.245 kW. Power plant efficiency increases by 0.4% to 44.56% and fuel consumption decreases by 0.46% to 21.8 kg/s. Also, the amount of pollutants from fuel consumption is reduced by 0.46%.

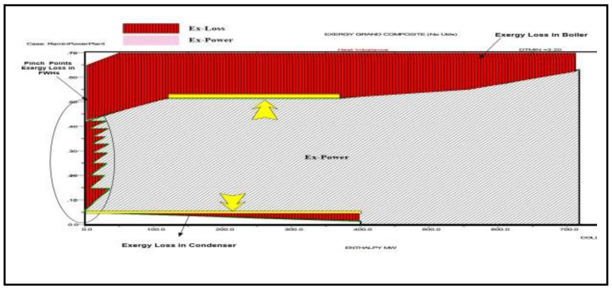

Figure 8. Identification of improvement in combined pinch-exergy representation

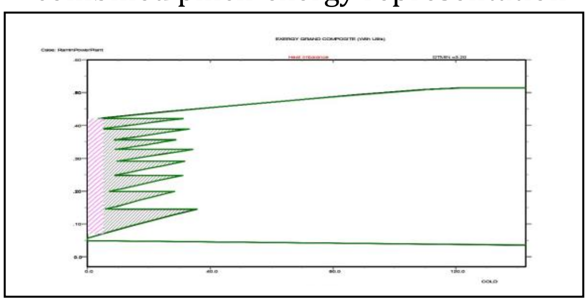

Figure 9. Nonuniform distribution of driving forces in feedwater heaters system

Strategy 2: Increase of steam in the boiler After approaching the pins to reduce the furnace's exergy losses

Figure 8 shows that the inlet feed water pressure to the furnace can be increased. Increasing the feed water pressure from 178.5 times to 193.5 times reduces the total exergy losses to 20.206670 kW. Power plant efficiency increases by 0.89% (compared to the baseline) to 44.79%, and fuel consumption decreases by 1.13% to 21.67 kg per second. Of course, it is not possible to change the pressure of an existing boiler in practice, and the boiler must be designed for the desired pressure from the beginning. Also, the production of pollutants is reduced by 1.13 percent [35-37].

Strategy 3: reduction of condenser pressure

After applying the first and second corrections, to reduce the condenser's exergy losses, the condenser pressure can be reduced, according to Figure 8. As the condenser pressure decreases, the condenser saturation temperature line approaches the Cooling Water Exergy Composite Curve (CWECC) cold heat load (water cooler), and the surface area between the two lines indicates the loss of condenser exergy decreases. Reducing the condenser pressure from 0.05 bar to 0.045 bar causes the total exergy losses to reach 204742.9 kW. The cycle efficiency increases by 1.7% to 45.15%. The increase in efficiency is due to the increased exergy delivered to the turbine system, and the fuel inlet exergy is constant [36-38]. The diagonally hatched surface shows the total exergy losses after applying the three modifications mentioned above, and the bolder area of the exergy reached the turbine system, which has increased to 422438 Kw [39-41]. A comparison of total exergy losses, exergy reached the turbine system, efficiency, and fuel consumption between the base state and the optimized state is given in Table 3.

TABLE 3. COMPARISON OF BASE AND OPTIMUM CASE

Variable	Optimal	Reference
Total exergy losses	204742 kW	212819 kW
Exergy delivered to the turbine system	422438 kW	420030 kW
Exergy Efficiency	45.15 %	39.44 %
Fuel consumption	6.09 kg/s	9.14 kg/s

Conclusion

Simultaneous application of pinch and exergy analysis technology in the steam power plant optimization increases the power plant's thermal efficiency and reduces fuel consumption. Increasing the power plant's efficiency by 1.7% greatly impacts the amount of fuel consumption per kilowatt of production capacity as the amount of 8076.6 kW of exergy losses in the system has been reduced. This means that the amount of power delivered to the turbine has increased by 2047.8 kW. Therefore, for a certain production capacity, fuel consumption is reduced by 0.3 kg per second, equivalent to 1.08 tons per hour. As a result, the amount of emissions from the power plant is reduced by about 20 tons per hour, equivalent to 480 tons per day; Therefore, the production of pollutants is significantly reduced. Reducing fuel consumption to a certain power capacity reduces the power plant's operating cost, heat pollution, and environmental pollutant gases. This article tried to show how, using a simple diagram, effective corrections can be identified and targeted before going into design details. The traditional design and optimization of power plants are based on computer engineering and simulation experience, which requires both time and effort, while the combined pinch and exergy analysis used to analyze the power plant uses CPEA, which is a simple diagram. . In CPEA, different parts of the system are specified separately. Possible corrections can be easily determined on the chart. After determining the corrections, CPEA can graphically display the effect of changes in different system parts on each other and the whole system. Therefore, the thermodynamic integration between the different parts of the power plant is shown in a diagram, and a conceptual view of the power plant is obtained. CPEA provides the engineer with a deep physical approach and a higher engineering understanding of the relationships between parts within the plant to determine possible modifications.

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