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Examining the Possibility of Optimizing Energy Consumption in Dezful Carbon Black Plant with the Help of heat integration Technology

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ABSTRACT

Given the limited resources of energy today, preventing energy waste and its efficient consumption in industry are considered as important principles that have been the particular focus of industrialized countries during recent decades. In this study, we have used heat integration method to optimize energy consumption in heat exchanger grid in Dezful Carbon Black Plant (DCBP). One of the problems ahead in energy analysis of this plant was the existence of process restrictions that would hinder optimization by changing the structure of exchangers. After analyzing grid of exchangers, we found that a lot of energy is recycled in this project, and the problem is of threshold type in analysis of internal heat integration. Many process restrictions made turning the threshold problem into a pinch problem and then making changes in the lowest temperature difference of the grid impossible. Moreover, examining compound curves of the grid showed great exergy losses in the grid, to improve which we propose using a Stirling engine for gaining maximum exergy in the grid. Finally, in one part of the process, used to reduce the temperature through direct injection of water into flow, we have suggested installing a new heat exchanger in the flow path. According to the need of the factory, this exchanger can be considered as the supplier of steam for heating of oil-storage tanks that reduces water consumption in that part of the plant.

Keywords: *energy optimization, carbon black, integration of internal heat, pinch, exergy*

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INTRODUCTION

Pinch technology is a method to minimize energy consumption based on thermodynamic calculations. This objective is achieved by optimizing heat recovery, process energy-supply methods, and its operating conditions. This technology is known as heat integration, energy integration, or pinch technology integration.

Pinch technology ensures minimal energy consumption in designing heat exchanger grid.

Today, advanced software such as Pinch Express TM, Super Target TM, and Aspen Pinch TM are used in the analysis of complex industrial processes.

Exergy analysis benefits from the first and second laws of thermodynamics to calculate exergy flow in the system and to determine non-optimal components. However, unfortunately, this method does not provide a practical solution to avoid exergy losses. On the other hand, pinch technology is considered a holistic approach to design processes, which has the ability to target the highest possible amendments before the final designing and simulation. This method uses the first law of thermodynamics to calculate enthalpy changes in flow passing through a heat exchanger, and the second law determines the direction of heat flow.

In traditional design, the process is designed first and determined by heat and mass balance of temperatures and flow rate. Then heat-recovery system design is completed and the remaining cases are determined. Each of these steps is performed independently of the others. Nevertheless, in a pinch design, using pinch technology, process integration offers a solution to minimize energy consumption before designing heat recovery grid and constraints of heat recovery system and utilities are considered later. Pinch design determines opportunities for optimizing processes and improving energy integration. This method helps optimize heat transfer equipment during the designing (Ian C Kemp, 2007).

DCBP, which has recently been constructed in the industrial town of Dezful, is one of the four producers of rubber raw materials in Iran. We studied this plant as a case study, so that with the help of Thermal Integration Technology optimize the energy grid and offer a new and improved grid with lower costs and higher efficiency. The plant has different exchangers with relatively large size due to specific process conditions of soot production. One of the problems ahead in energy analysis of this plant is the existence of process restrictions that would hinder optimization by changing the structure of exchangers. Thus, in the proposed models, while complying with the process restrictions, we have tried to offer it is tried to offer applicable models according to the current situation of the factory. As DCBP is constructed in a region emerging from industry point of view, the existing problems in the region, including lack of appropriate infrastructure for water and power supply for industry have led to serious and active threats in the field of energy supply. These problems are increased equipment failure, increased pauses in production, and overall increase in the price of the product for the factory. Therefore, due to these conditions, maximum use of the internal potentials and renewable energy within the plant can even have a greater impact on the final price of the products. Furthermore, since Dezful Industrial Town No.2, location of the plant, is close to residential and agricultural areas, any gas waste produced by the plant is strongly pollutants according to Department of Environment. Thus, any attempt to recycle more energy increases efficiency and productivity that in turn lead to reduced fuel consumption in this complex and can be an effective factor in reducing environmental threats in this area {2}.

Description of the process

The plant uses natural gas as a part of the fuel needed for the reactor, and generally, a certain ratio of (Cracked fuel oil) CFO, (Coal tar) CTR, other derivatives of heavy, and aromatic oil are used as oil feed, and finally soot is produced in the reactor. There are two high temperatures in process: preheated air temperature in air preheater heated to 800°C by means of hot gases of the reactor and the flame temperature in the combustion chamber of the reactor that reaches temperature of about 2000°C. At the time of this research, the production line of industrial soot out of hard grade soot is the only existing production line with production capacity of 20000 tons per year that has been exploited. According to the existing development plan, the vision of the factory is to set up three production lines along the mentioned line. Feed oil turns into gas with soot inside the reactor and at high temperature. By passing through a cyclone, soot is separated from gas and collected in bag filters. Then, by passing through pelletizer and dryer, the final product is produced. Twenty percent of the gas produced is burned in the combustion chamber of the dryer to provide the heat of drying soot, and the remaining 80% is emitted into the atmosphere through the chimney. In fact, soot formation reaction within the reactor takes place using kinetic and thermal energy of hot gas from the exhaust gases of combustion and air. Shearing force of gas flow atomizes and disperses hydrocarbon feed that, and due to temperature and high velocity of atomizing, soot is formed. Then spraying water stops the reaction. This process produces uniform soot particles with a smooth surface and has high quality and efficiency. For energy grid analysis of the plant, the first step is recognizing the key conditions of the process.

In the information of Heat Exchanger Grid, air pre heater preheats the air entering the oven using hot exhausting gases from the oven, and then off gas boiler recovers the energy contained in the exhaust gas from air pre-heater exchanger and produces saturated vapor with pressure of 400 kPa. In this exchanger, per hour, 2.5 tons of 25°C water changes into saturated steam of 151 ° C. Since the heat transfer coefficients are very different for water while warming up until saturation temperature and boiling mode, and for simplifying integration calculations, it is assumed that this exchanger has two parts: pre-heater and evaporator. In pre-heater part, water reaches saturated temperature, and in the evaporator part, water boils and turns to steam. Then in the process, oil pre heater exchanger heats the oil entering the reactor to a temperature of 260 ° C.Moreover, in another part of the process, there is a exchanger called oil cooler. As a part of the preheated oil does not enter the reactor and returns to oil storage tank, and this is while returned oil has high temperatures and will cause technological restrictions to feed pumps and there is the risk of rising temperature of the tanks, to reduce the temperature, an oil cooling exchanger is used to cool the temperature of the mentioned oil to 90°C using process cooling water.

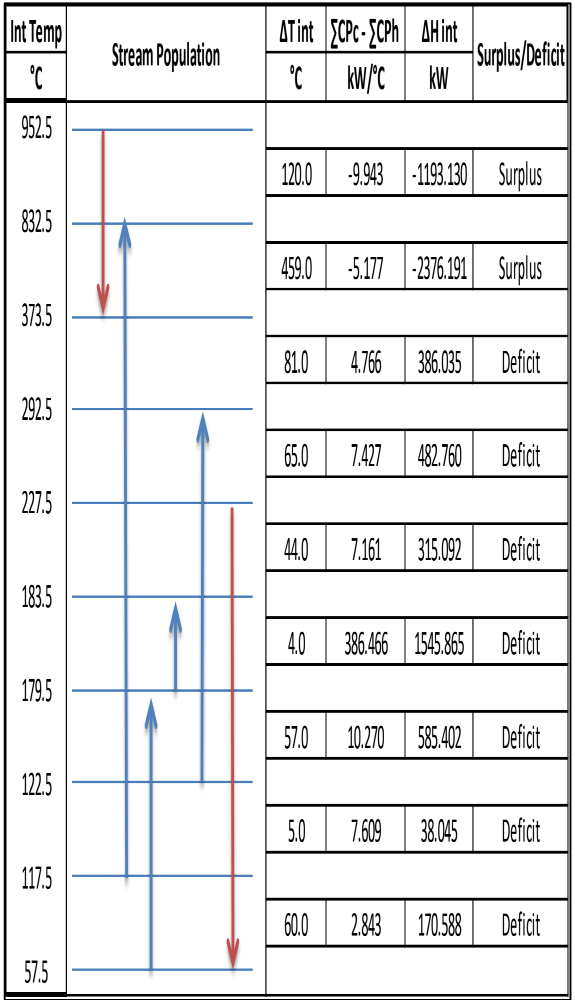
Drawing the grid of heat exchangers of carbon black plant

Grid of heat exchangers of carbon black plant is drawn in Figure (1). In this grid, only cold utility is used, which is cooling water, and hot utility has not been used. In fact, one can conclude that the analysis of this grid is of threshold problems type. In the grid illustrated in Figure 1, red lines represent hot flows and blue lines indicate coldflows.

Figure 1: Heat exchanger grid of DCBP [Aspen]

We use program table algorithm for analysis. First, we calculate the difference of minimum approach temperature in the grid to correct it in the next steps. Given that the problem is threshold and that we have only one type of cold utility in the grid, and since the only cold utility in the grid is oil cooling exchanger, it can be concluded that the lowest temperature difference in this grid is related to oil cooling exchanger. Minimum temperature difference in this exchanger is 65°C. Table (2) shows algorithm of solving the problem.

Table 2: Algorithm of solving the problem



Int Temp °C	Stream Population	ΔT int °C	∑CPc - ∑CPh kW/°C	ΔH int kW	Surplus/Deficit
952.5					
		120.0	-9.943	-1193.130	Surplus
832.5					
		459.0	-5.177	-2376.191	Surplus
373.5					
		81.0	4.766	386.035	Deficit
292.5					
		65.0	7.427	482.760	Deficit
227.5					
		44.0	7.161	315.092	Deficit
183.5					
		4.0	386.466	1545.865	Deficit
179.5					
		57.0	10.270	585.402	Deficit
122.5					
		5.0	7.609	38.045	Deficit
117.5					
		60.0	2.843	170.588	Deficit
57.5					

In the above table, the amount of heat required and extra heat in each one of temperature ranges of heat-transfer have been obtained. Now, it is the time to form the cascade of heat transfer. In each temperature range in the modified grid, it is the product of the difference in temperature of that temperature range of the resultant of specific heat capacity of the heat flow in the same temperature range that we calculate and set the resulting number as the enthalpy differences in that temperature range (ΔH_{int}).

The results of the cascade of heat transfer for the modified grid of process have been shown in Table 3. In this table, we move from top to bottom assuming zero input kilowatts of energy to each interval, and after each algebric sum ΔH_{int} of each interval from the previous, we record results in columns in front of each.

Table 3: Algorithm of problem solving and heat transfer cascade

Int Temp	ΔH int	Cascade
°C	kW	kW
952.5		0.000
	-1193.130	
832.5		1193.130
	-2376.191	
373.5		3569.320
	386.035	
292.5		3183.286
	482.760	
227.5		2700.525
	315.092	
183.5		2385.433
	1545.865	
179.5		839.568
	585.402	
122.5		254.166
	38.045	
117.5		216.121
	170.588	
57.5		45.534

As Table 3 shows, this problem just needs cold utility. At the bottom of the table and in the result of completing thermal cascade, only 45.534 kilowatts of extra energy of the process is seen that is the heat energy, to cool which we have to use cold utility. In fact, in this grid, there is no hot utility, based on which we conclude that the problem is of threshold type, and if the difference of minimum temperature is more than 65 degrees, cold utility consumption remains constant. Comprehensive compound curve clearly shows that in heat exchanger grid of this plant there is so much temperature driving force that leads to a lot of exergy loss. In this research, power generation using Stirling engine has been reviewed to reduce exergy loss in the grid.

Examining the optimal value of TΔ_{min} of the grid and the existence pinch

The grid studied in this study is of threshold type. In threshold problems, at a specific temperature difference, pinch point disappears, and then only one utility is required. In this regard, in this study, we found that at temperatures less than 181°C, hot utility drops to zero and then by reducing the minimum temperature difference, the amount of cold utility does not reduce. Thus, the cost of energy required does not fall and by reducing minimum temperature difference, only the surface of the exchangers increases, which translates into increased investment costs. By reducing the minimum temperature difference to 181°C, heat recovery increases and hot and cold utilities reduce, and in less than 181 degrees, cold utility requirement in all temperature ranges is constant and equal to 45.2 kW. Moreover, in heat exchanger grid of the plant, minimum temperature difference is specifically related to oil cooler exchanger. In this exchanger, oil is cooled 260 ° C to 90 ° C. In this grid, with an increase in minimum temperature difference, surface of exchangers reduces, but we cannot use 25-degree cooling water to cool the oil and cold cycle should be used for this purpose, which has very high investment and operation costs and not practical in the case of this study. Moreover, reduction of minimum temperature difference to less than 65°C will make changes to energy cost, but it will lead to initial investment cost due to increased surface of exchangers and this scenario is loss making.

Modeling Stirling engine

In this study, Stirling engine is used to improve energy grid of the plant, to lower the temperature driving force, and to reduce exergy losses, resulting in the production of electrical power. We used Malmö Equation to model Stirling engine. To achieve this goal, it is assumed that two Stirling engines at 507.5 and 800°C, respectively, receive 1193 and 1507 kilowatts of heat from hot exhaust gases flow from the oven and after power generation repel the remaining heat at a temperature of 260°C to cold process flows. According to the results, the first Stirling engine, which works between 1073 K and 533 K, has higher efficiency and receives 1193 kilowatts of energy at its hot temperature and after producing 340 kilowatts of power repels 853 kilowatts of energy at a temperature of 533 K to cool process flows. The second Stirling engine has efficiency of 17.53%, receives 1507 kilowatts of energy at 780 K, and after producing 264 kilowatts of power repels 1243 kilowatts of heat to cool process flows at 533 K. Overall, in the new model, 604 kW of electrical power is generated. It should be noted that in the new model of heat exchanger grid, 2654 kW hot utility at a temperature of 533 K is required, and Stirling engines can provide only 2096 kilowatt and 559 kW remains that must be provided by the use of a new hot utility. However, after grid review, we find that the flow of hot gases exiting the oil-preheating exchanger with a temperature of 406°C is cooled by direct injection of water into the process, and thermal power required can be provided in this section. In that case, the gas temperature is reduced to 349.8°C and reduces water consumption in the plant.

Heat exchangers grid after the addition of Stirling Engines

With the addition of Stirling engines, heat exchangers grid also changes. Figure (2) shows heat exchanger grid after the addition of the Stirling engine. Heat exchangers grid has 8 exchangers in this case.

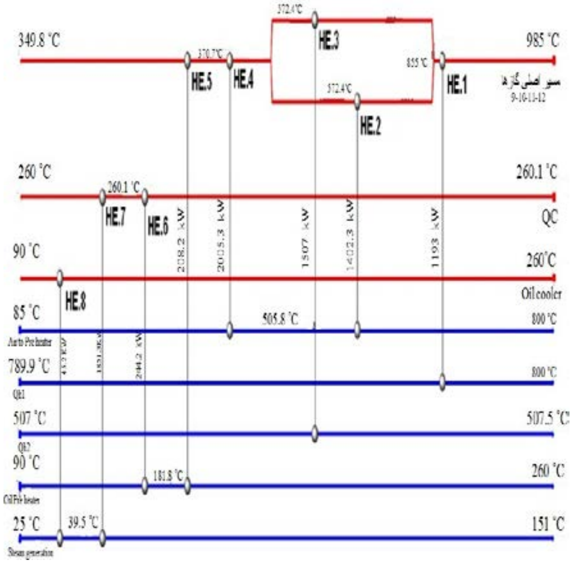


Figure 2: Heat exchangers grid after the addition of Stirling engines [Aspen]

Given that in this project, Stirling engines are installed out of the flow, the engines will not cause any pressure drop in process gas path. However, installing boiler immediately after oil preheater to compensate hot utility requirements of the project could lead to pressure loss in the path. The boilers required in this project is almost the same boiler proposed to replace direct water injection, and pressure drop caused by it will be analyzed.

Replacement of a new boiler instead of direct injection of water into the process

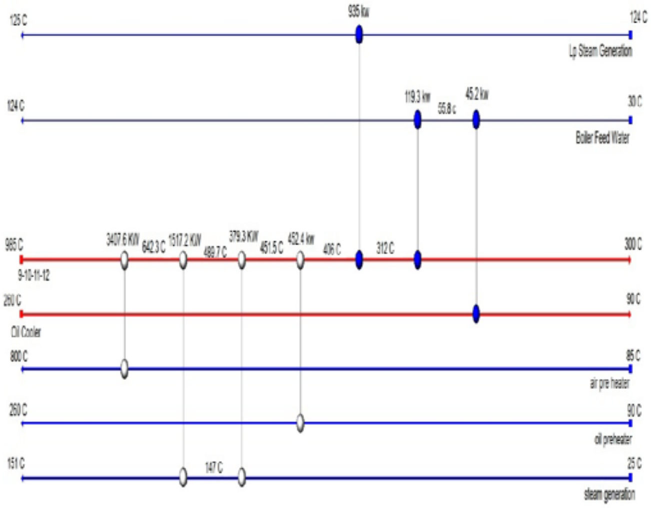
At this point, without noany changes in the present grid of heat exchangers, three exchangers have been added to the grid to cool the exhaust gas from oil-preheating exchanger from 300°C to 406°C, and thus while improving the energy recovery of that part of process, saves water in the plant.

Moreover, the implementation of this project would resolve the grid need to 45.2 kW utility and use heat of hot oil for preheating water. Below the grid is displayed after the project.

Figure 3: Heat exchangers grid for steam generation without changing the current grid [Aspen]

Check the pressure drop in new replacement of the new boiler instead of direct injection of water into the process

In this project, oil cooler exchanger is removed and instead of that two water heater exchangers are added to the grid. boilers and a boiler feed the network. Given the importance of considering process restrictions and since the second and third exchangers and the fluid flowing through the coils are process gases, pressure drop of the gasses passing through these two exchangers should be calculated.



Regarding the first exchanger, fluid flowing through the pipes is the oil returning to the tanks, and its pressure drop is negligible. To estimate the pressure drop in the path of the process gases after installing the exchangers, boiler information in the factory can be used as follows.

According to structural maps in the plant, in the construction of this boiler, 61 tubes, each with a length of 6 meters and a thickness of 3 diameter 76 mm (φ76×3×600), have been used as tube exchangers, and it was found that the heat transfer level of the boiler in the plant is almost equal to the level of the proposed boilers (combining second and third exchangers) (the sum of the transfer of the two proposed exchangers is 84 square meters). Since the structure of the two boilers is of the same type of shell and tube and fluid passing through the tubes is continuation of the process gases, it is suggested that a new boiler be made with the same design and structure of the existing boiler. With a good estimation, one can consider pressure drop in the proposed boiler equal to pressure drop in the existing boiler. Installation place of the proposed boiler is after oil pre-heater and at the place of water injection into the process. In fact, water injection into the process is removed and a new boiler is installed there. It will create 2 kPa equivalent to 204 mm of water pressure drop in the path of process. Pressure limit in this part of the process is the inlet pressure to the main filters, which should be maintained in the pressure range of 280 to 300 mm water. Currently, there is a branching path from the top of the cyclone to the filter outlet to control the pressure of the filters, so that besides controling the inlet pressure to the main filters, by gas injection above the cyclone, a driving force is created for the separated under the main filters.

This branch has a manual pressure control valve to set additional pressure to the filters that can adjust the amount of additional pressure at the entrance to the filters.

Economic estimates

Economic estimates and calculations related to the proposed projects are presented below.

Stirling Engines

There are reputable manufacturers in the world now that assume making Stirling engines with different powers. One of the factories offering table of construction cost to make Stirling engines with relatively high power is String advantage, INC. in America. According to the results, the construction cost of engines per kW engine power is $ 450. Moreover, cost of maintaining the engine per kilowatt hour is $ 0.01 that if were consider 335 days of continuous operation a year for these engines, the initial manufacturing cost and the cost of annual maintenance of Stirling engines in the proposed project is equivalent to 320,361.6 dollars. Considering the rate of 3450 tomans for one dollar (at the time of the study), annual cost will be equivalent to 1105247520 tomans. Sum of 307 million tomans is added to the above cost for the construction of the boiler water at water injection site, and the total cost of the investment will be 1412247520 tomans. In other words, it will have a cost of about one billion four hundred and twelve million tomans. Moreover, with the implementation of this project, 50% annual savings in power consumption will be attained, which is equivalent to 300 million tomans per year. Furthermore, the profit from full elimination of oil cooler exchanger is 40 million tomans, and 17% of reduction in water consumption at the plant will have equivalent to 30 million tomans annual savings. Thus, return on capital of Stirling engines project is evaluated 4.2 years.

Project of replacement of a new boiler instead of the direct injection of water into the process

According to linear regression of level and price of the exchangers proposed, the equation between exchanger level and its price is as follows.

Equation (1)

Exchange price (million toman) = 3.4627 × surface of exchangers (square meters)

Concerning the economic estimation of replacement of the new boiler instead of direct injection of water, the price of exchangers required for steam generation can be estimated as follows:

$$88.7 \times 3.4627 = 307.287$$

Price calculation by the above method is based on linear regression of prices of exchangers in the factory. Then the price of the first exchanger with cross-sectional area of 4.5 square meters and the price of the boilers with an area of 84.2 square meters based on curves and relationships to estimate price are estimated. According to estimates and that, the boiler capacity is 1.5 tons per hour; its estimated cost is estimated at $ 80 thousand. Therefore, the total price of the project is $ 85450 and assuming dollar exchange rate as 3450 toman, it is estimated 294802500 tomans or approximately 300 million tomans. As is seen, the result of estimating price in both methods is almost the same. Heat load of this exchanger is 1099.5 kW and since the efficiency of industrial boilers is about 83%, we can conclude that for the production of 1099.5 kW steam, one should consume 1099.5 divided by 0.83 equal to 1325 kW of natural gas. Natural gas heating value, on average, is o 37900 kJ per normal cubic meters of natural gas, and 1325 kW natural gas is equivalent to 125.8 normal cubic meters. Price per normal cubic meter of natural gas is 100 riyals i.e. 12580 tomans energy cost reduces per hour in the plant. If the factory has 7600 hours of production per year, we can state that 95629971 tomans annual energy cost is reduced. Exchanger installation cost is 307287000 tomans where the cost of investment returns at 3.21 years.

CONCLUSION AND SUGGESTIONS

In integration analysis of exchanger grid of DCBP, it was determined that at present, four main exchangers are exchanging energy with gases from the process and the oil injected into the reactor. These four exchangers turned according to thermal load are air preheater, oil preheater, boiler, and oil cooler. We used internal integration technique with program table method to determine recovery and loss rates of energy in the grid of exchangers of this plant. After drawing the curves of energy cascade and comprehensive compound curve, it was found that due to lack of need of the grid for hot utility, the problem has no pinch points, and in fact, the problem is threshold, one of the special cases in the analysis of energy with internal integration method. Then in the analysis, assuming lack of process restrictions, the existence of pinch point was assessed for this grid, and it was determined that for the values of ΔT_{min} of the network for zero to 181 degrees Celsius, the utility required is fixed and is of cold type. From 181°C on, proportionally as ΔTmin is higher, the need for hot and cold utilities increases. Finally, with the aim of creating maximum energy recovery and minimal investment costs, almost the best ΔT_{min} of the grid was assessed to be close ΔT_{min}. In fact, we found that in the current project of the plant, energy recovery is done well and considered during the designing grid, and almost all recyclable energy is used. However, the existence of high temperature difference in this curve shows high rate of irreversibility and in fact, great loss of exergy in the grid. For this purpose, the use of Stirling engine with efficiency close to Carno was assessed. To improve exergy loss, the use of two Stirling engines with different temperature ranges was proposed that in case of realization could produce 604 kW electric power that is about more than 50% of the electrical power needed by hard soot production line. According to calculations, return on capital in the project is 4.2 years. Given the specific technology of these engines and relatively long return on capital, it seems that implementation of such a project is not cost effective in current situation. Currently, plant expansion project is underway and the new production line will be exploited in a near future after fixing problems, but one of the problems existing the plant is the discussion insufficient steam available at the plant level. Most of the steam generated at the plant is used to heat oil tanks and keeping oil transport routes hot, which are crucial in the production of the plant. According to production experts in the plant, lack of steam, especially in winter, has created many problems for the continuous production of this plant. According to the experts of the plant, in the near future and after establishing the new production line, the problem of steam will be more accentuated, so that they will have to buy an extra boiler for the complex. Thus, according to the above, the possibility of steam production with the help of process recyclable energies was studied, by taking into account the restrictions. In studying the details of the process, we realized that after oil preheater, direct injection of water into the gas is used to reduce the temperature of process gases, which leads to loss of great amount of recyclable heat energy and volume of water in the area. Thus, installing an inter-line boiler in that part of the process was evaluated taking into account the restrictions. According to the calculations, without any changes in restricted process parameters, the proposed boiler will be able to produce 1.5 tons per hour of low-pressure steam with temperature of 125 ° C that can be used exclusively for heating oil tanks. This can fully solve the problem of lack of steam in the plant even after launching the new line, and this is while its cost of investment will return within 3.2 years. Due to the high volume of excess gas produced in the main filters after product purification and released into the environment via chimneys, it is recommended that the subject of designing and installing a thermal power plant along the production line of the factory be examined and emissions of the process be used as plant feed. According to estimates, production of about 3 megawatts of electric power out of process emissions will be possible, which is more than electrical power required by the factory and surplus production capacity can be sold in urban grids. The existence of many technical problems in the regional power grid due to inefficient industrial infrastructure has led to great losses of this industrial complex solely due to electrical problems every year. Thus, installation of such a power plant would significantly reduce the damage caused by problems in the region's power grid. Moreover, this project can bring about tangible reduction in pollution of the region by burning emitted gases from the chimneys of this plant. It will be very important in terms of environmental considerations.

It also recommended that the issue of severe corrosion in process routes of the plant be studied, which is one of the biggest problems of the plant currently.

Finally, since the energy grid analysis of this plant has led to a special case of internal integration method (threshold mode), it is recommended that, in a separate study, energy grid of DCBP be examined with the help of exergy analysis and the results be compared with one another.

REFERENCES

1. (No references are mentioned for the items written in Introduction in the thesis)
   Resources of Introduction
   They are temporally shown by numbers below. Please note that I changed Introduction text to be able to give references.

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3. General information regarding the plant citing technical experts of DCBP