



Application of Pinch Technology for Waste Heat Recovery in The Linear-Alkyl-Benzene Sulfonation Process

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In this study, an optimum waste heat recovery system in the linear-alkyl-benzene sulfonation process was designed through three different scenarios, using pinch technology. In these proposed energy conservation schemes, the waste heat was recovered for boiler feed water preheating, saturated steam production and combined saturated steam and power generation as three different energy conservation scenarios. All the scenarios provided hot air needed for the silica-gel regeneration from waste heat recovery. The boiler feed water preheating in the first scenario, might save fuel consumed in the boiler. The saturated steam, produced in the second and third scenarios, could be used to partially fulfill the plant steam requirement and the power, generated in the last proposal, would be supplied to the plant. Economic analyses of the three proposed waste heat recovery scenarios were performed in order to determine the superior one. The results showed that about 150 kW power and 27.4 % of the plant's steam demand could be provided in the optimum scenario and the simple payback time was less than 22 months.

Key Words: Sulfonation process, Pinch technology, Waste heat recovery, Power generation, Economic analysis.

INTRODUCTION

Pinch technology (PT) has reached a very high level of industrial application over the years and has been successfully applied to improve waste heat recovery (WHR), to design better heat exchanger networks (HEN's)¹⁻⁵, combined heat and power (CHP) systems^{6,7} and to address optimum utility systems⁸⁻¹². Usually, between 20-50 % of energy consumption in most process industry can be saved by applying this technology¹³. An overview with references to original research is given in the text book of Smith¹³. In addition, there have been a number of expansions of the PT; which include mass pinch¹³, water pinch⁸⁻¹³, hydrogen pinch¹⁴, oxygen pinch¹⁵ and any combination of them¹⁶⁻¹⁸.

The design task of PT is to maximize WHR with optimum costs. Huang & Elshout and Umeda and colleagues introduced the concept of using PT for optimum WHR in HENs¹⁻³. The use of these techniques to minimize energy consumption and minimize the number of units and total heat transfer area was reported by Hohmann, Linnhoff and Flower, Linnhoff and colleagues and Townsend and Linnhoff^{1,2,4}. In 1984 a method for optimizing both energy cost and capital cost was proposed by Ahmed, Linnhoff and Townsend¹. This allowed for an overall optimum mode to be identified. This optimization technique is based on a graphical method, that present composite curves

and grid diagrams. The underlying principles of this technique are the concepts of pinch-point allocation and cross-pinch-heat-transfer. They allow for targeting of maximum possible WHR prior to design and guidelines leading to close optimum design solutions¹. The targeted maximum WHR, minimum total annual cost can be achievable at the design stage by using pinch design method (PDM)¹⁻⁵. The development of this technology that followed introduced super targeting (ST), plus-minus-principle (PMP) and grand composite curve (GCC) concept in the targeting stage and load maximization (LM), three-golden-laws (TGL), Cp-matrix (CM), temperature driving force plot (TDFP), remaining problem analysis (RPA) in the synthesis stage^{1-5,13}.

The aim of this study is to minimize energy consumption, by using recovered heat from dual linear-alkyl-benzene (LAB) sulfonation process (sulfurex units) hot flows, in a detergent powder factory, using PT. Two similar sulfurex units, with capacities of 3 t/h and 1 t/h, were installed to sulfonate the LAB in the detergent powder factory under investigation. The stream flow rates in those sulfurex units are different, but flow temperatures, pressures and other operational conditions are similar.

As a result of the implementation of the PT in those sulfurex units through three different scenarios, recovering the waste heat for boiler feed water (BFW) preheating, production

of saturated steam at 7 bar and combined 7 bar saturated steam and power generation has been investigated to reduce the total energy demand of the factory. In addition, providing the hot air needed for the silica-gel regeneration from WHR has been considered in all scenarios. Finally, economic analyses of the three proposed WHR scenarios were performed in order to determine the optimum one.

Description of the sulfurex unit process: The linear-alkyl-benzene ($C_{12}H_{25}$ -), LAB, is sulfonated in the sulfurex units. First, solid sulfur is melted with steam. Then it is collected in a storage tank and is blown from the upper part of the storage tank by an ejector into a furnace with a stomide pump, where it makes contact with oxygen and dehumidified air. The dehumidified air is needed to burn sulfur.

Dry air in sulfurex units is prepared as follows: first, ambient air is sucked into the blower after passing through filters; then, it is cooled to 25 °C using cooling water in a radiator. The outlet air compression causes the temperature to increase to 100 °C. The air is then passed through another water radiator, reducing its temperature to 40 °C, before entering the chiller.

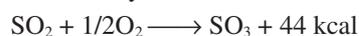
The outlet air from the second radiator enters a quad radiator with -5 °C using ethylene glycol as its coolant. During this operation, 95 % of the existing water is condensed and exhausted. The temperature of ethylene glycol is kept at -5 °C in a chiller using freon gas and its interior heat is absorbed by the freon and then exhausted to ambient. Then, air that has been dehumidified to 95 % relative humidity enters a silica-gel tower. This tower completely dries the air that enters into the furnace. The silica-gel column has two silica-gel beds, each of which operates singly for 8 h shift while the other regenerates. Air from the chiller enters the silica-gel column one at one point and then enters the furnace from a lower point. The air is dehumidified and passes over the silica-gel seeds (red crystals) at about 20-30 °C. During this time, the other part of the tower is reduced. During the first 4 h, a 120 °C hot air flow is supplied by a fan-it passes from a hot water radiator and flows in one direction through the tower. This dehumidifies the silica-gel crystals. During this period, the silica temperature reaches 110-120 °C. It takes 3 h to reduce the temperature through circulation; this reduces the temperature of the tower to 40 °C. The same fan is used at this stage despite the cold water flowing through the radiator. The resulting humidified flow exits the system and the silica-gel remains in standby mode for 1 h. Finally, by changing the status of valves we change the flow direction and use the part of silica-gel column that has been regenerated.

The outlet air from the silica-gel, at approximately 30 °C, is connected to the lower part of the furnace by isolated pipes. Molten sulfur is sprinkled into the top of the furnace. Then, the combustion operation begins. In a 3 t/h sulfurex unit the amount of sulfur that enters the furnace is 200 kg/h and the amount of dry air consumed is 3000 m³/h. During sulfur combustion, the temperature of combustion gases is between 600 and 750 °C. Combustion products, including SO₂ (7 % of weight), oxygen, nitrogen and a small amount of steam, exit the furnace at an average temperature of 660 °C. The furnace outlet flow is cooled to 430 °C as it passes through a U shaped exchanger and a vertical exchanger, each of which is a 2-tube

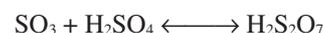
exchanger with shell-configuration air flow. Then, after crossing the filter, the exhaust enters the catalyst tower to separate out impurities such as sulfur that did not react or metal particles that form due to corrosion.

The exhaust gas then enters into a first-floor catalyst at 430 °C. The catalyst tower consists of three stages and there are 1000 L of catalyst bed containing vanadium pentoxide in each stage. The gas in the first floor is located near the catalytic bed and after the oxidation reaction and conversion of about 70 % of SO₂ to SO₃, gas at 570 °C exits and is cooled to 460 °C in the heat exchanger. The gas then enters the second floor of the catalytic bed. During this stage, 20 % of the conversion is complete and the gas is cooled with air in a heat exchanger. Its temperature is reduced from 540 °C to 410 °C. Next, the gas enters the third floor of the catalytic bed where the oxidation reaction is approximately completed and the output gas exits the tower at 510 °C.

The tower catalytic reactions can be written as follows:



In order to prepare LABS, SO₂ gas enters the sulfonators and reacts with LAB. The best temperature conditions for this reaction are about 45 °C. Thus, the temperature of outlet gas from the catalyst should be reduced to this value. For this purpose, three non-aligned heat exchangers are aligned in the direction of the SO₃ gas flow. This ultimately reduces the gas temperature to 60 °C. It is possible that a small amount of steam remains at ambient temperature due to improper operation of the dehumidifier systems. As described before, it may react with SO₃ gas to produce H₂SO₄. Thus, the resulting sulfuric acid produces oleum:



Oleum is very corrosive and harmful. It should be separated from the gas¹⁹. To remove this acid, triple exchangers must be installed vertically and additional pipes should be installed at the bottom of the exchangers so that the oleum is separated from the gas by gravity^{19,20}. The acid can be neutralized with soda^{19,20}. If the acid is not separated, then the detergency power of products will be compromised, corrosion during the path will be intensified and vanadium pentoxide waste production will increase, resulting in a final product that is contaminated with sulfuric acid.

Finally, sulfonators output LAB together with product gas and neutralize the resultant sulfur composition with soda. The result is sodium alkyl benzene sulfonate paste. At this stage, sodium three polyphosphate (Na₅P₃O₁₀), sodium sulfate (Na₂SO₄), sodium silicate (Na₂OSiO₂), sodium carboxymethylcellulose (CMC), whitener additive and required fragrances are added in accordance with the production formula. The resultant composition is sent to a spray dryer tower by a pump so that it is converted from a paste to a powder under hot air flow.

EXPERIMENTAL

The aim of energy consumption optimization in the sulfurex units, installed in the sample factory, is to design an optimum WHR system, using PT that can preheat the BFW or

that may produce a part of the factory's required steam and power. Table-1 lists the relevant HEN stream data for the sulfurex unit (3 t/h capacity).

Configuration of HEN for the sulfurex unit and its diagram in the existing status have been shown in Figs. 1 and 2, respectively.

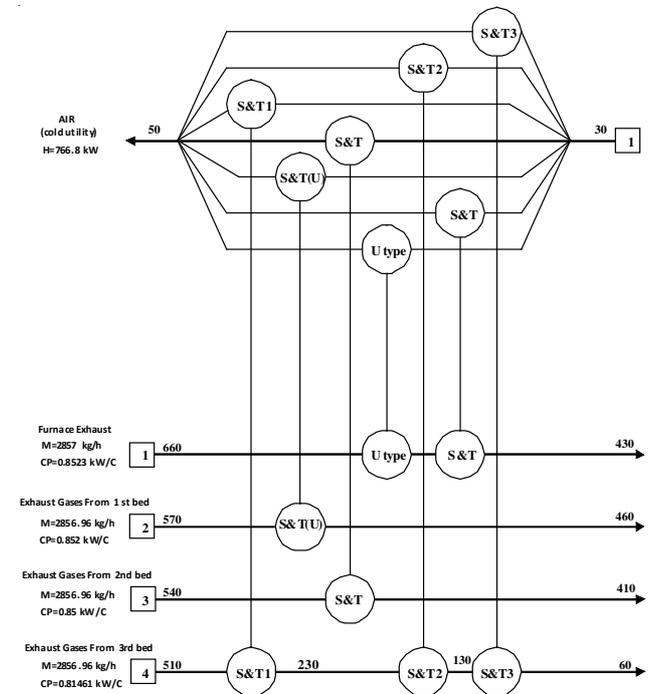


Fig. 2. HEN diagram for the sulfurex unit (3 t/h capacity) in the existing status

As illustrated in Fig. 2, the HEN does not feature process-to-process heat exchangers and the thermal streams of these two units enter the air coolers. In other words, cold utility selection has not been optimized to date in the sulfurex

units under study. The selected cold utility is the only blown air flow and the interior heat in the sulfurex unit (from the hot streams) is wasted. Table-2 illustrates the layout of the cold utility selection for sulfurex units of 3 t/h and 1 t/h capacities.

TABLE-2
COLD UTILITY SELECTIONS FOR SULFUREX UNITS AS CURRENTLY CONFIGURED

Sulfurex unit capacity (t/h)	Cold utility	ΔH (kW)	T_s ($^{\circ}C$)	T_i ($^{\circ}C$)	M (kg/h)
3	Air	766.8	30	50	135532
1	Air	255.6	30	50	45177

In order to obtain information such as pressure drops across all of the network streams, we wish to analyze the potential for network pressure drops and heat transfer coefficients for the sulfurex unit across selected streams. This analysis was performed using a program that implements the Bell-Delaware method^{21,22}. The results of this calculation are given in Table-3. In the factory under study, both sulfurex units were similar, but one of them only operates at one-third of the capacity of the other. In this study, only the calculations for the larger sulfurex unit (3 t/h capacity) are given; we generalize the results to the other sulfurex unit that features a 1 t/h capacity.

TABLE-3
SUPPLEMENTARY INFORMATION FOR HEN STREAMS IN THE SULFUREX UNIT (3 t/h CAPACITY)

Flow name	Cp (kW/ $^{\circ}C$)	h (W/m ² / $^{\circ}C$)	ΔP (Pa)	ΔH (kW)
Furnace exhaust	0.85230	15.01	200.0	196.03
Exhaust gases from 1st bed	0.85200	15.90	266.6	93.72
Exhaust gases from 2nd bed	0.85000	14.69	133.3	110.50
Exhaust gases from 3rd bed	0.81461	25.12	533.3	366.57

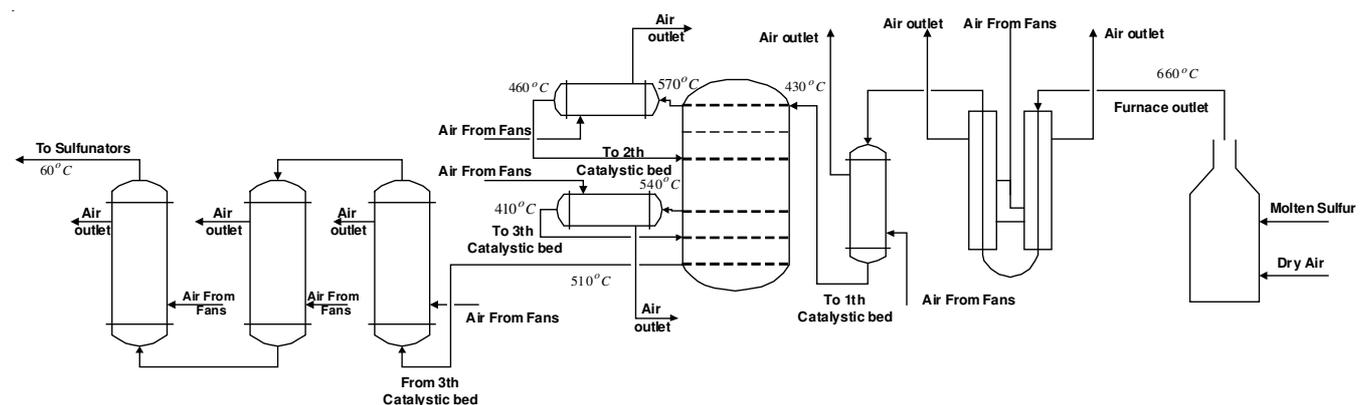


Fig. 1. Configuration of HEN for the sulfurex unit in the existing status

TABLE-1
HEAT EXCHANGER NETWORK STREAM DATA FOR THE SULFUREX UNIT (3 t/h CAPACITY)

Flow name	Flow type	Phase	T_s ($^{\circ}C$)	T_i ($^{\circ}C$)	M (kg/h)	ρ (kg/m ³)	Cp (kJ/kg $^{\circ}C$)	μ (kg/m)	K (W/m $^{\circ}C$)
Furnace exhaust	Hot	Gaseous	660	430	2857.00	0.511810	1.073953	0.036560	0.054187
Exhaust gases from 1st bed	Hot	Gaseous	570	460	2856.96	0.521925	1.073590	0.039381	0.054670
Exhaust gases from 2nd bed	Hot	Gaseous	540	410	2856.96	0.562175	1.071069	0.037101	0.052155
Exhaust gases from 3rd bed	Hot	Gaseous	510	60	2856.96	0.915950	1.026474	0.031510	0.038319

It is known fact that the interior heat in sulfurex unit hot streams is wasted, the factory requires 40 tons of saturated steam at 7 bar for each 8 h operating period. In addition, the sulfurex units of 3 t/h and 1 t/h need at least 3480 and 1160 kg/h air at 120 °C for the silica-gel regeneration, respectively. In the current factory configuration, the hot air is produced independently, but it can also be produced *via* WHR. As a result, the net demand for steam can be reduced.

Three scenarios to reform the dual sulfurex units will be discussed. In these three scenarios, two selected networks for two sulfurex units are reviewed, as threshold problems¹³. We reformulate these networks to take advantage of WHR from existing hot streams using PT. In the first scheme; we maximize the preheating of the BFW, in the second scheme; we also maximize the production of 7 bar saturated steam and in the last one; combined saturated steam and power generation are considered. The hot air for silica-gel regeneration can be produced in all schemes.

Table-4 lists the project economical data. Major limitations that must be taken into consideration, in addition to financial constraints and return on investment metrics, include thermal metrics involving outlet streams from furnaces and at the entrances and exits of the vanadium pentoxide catalytic beds. It is also noted that the collection of undesired products such as sulfuric acid and oleum by gravity separation in the sulfurex units¹⁹. To address these issues, all the new exchangers are designed for vertical installations. Similarly, they are designed such that the temperatures on both sides of the exchanger streams will not surpass certain limits.

TABLE-4
PROJECT ECONOMICAL DATA

Interest rate (%)	15
Maximum payback time (months)	40
Hours operation per year (h/yr)	8000
Hot utility cost (\$/kW yr)	40
Cold utility cost (\$/kW yr)	1.5
Power cost (\$/kW yr)	480
Operation cost to produce 1 ton of saturated steam at 7 bar (\$)	3.6
Heat exchanger cost function (\$)	$3118 + 920(A)^{0.7}$
Pump cost function (\$)	$129288(q)^{0.448}(H)^{0.224}$

Other restrictions pertain to new heat exchanger material selections and areas that should be added to the network for either hot water or steam production. Thus, the materials used for the exchangers need to be stainless steel 316 or 317, similar to the air coolers. Corrosion in the pipes and thermal equipment will be non-uniform if they are made from carbon steel material because sulfur compounds account for about 7 % by weight of the combustion and outlet gases from the catalytic beds and because the temperature of these gases generally exceeds 400 °C (excluding the output gas from the third bed). Another important limitation, which must be considered in the case of new designs for the two networks, is that-because of natural movements of the furnace outlet gases and catalytic beds in the network and because of the limited capacity of the blowers-network design modifications must be calculated using a constant pressure drop technique²³. The network can be modified so that the revised correction pressure will exactly equal existing values.

First scenario-preheating the BFW: In this scenario, the goal is to maximize preheating of the BFW and to supply the required hot air to the silica-gel tower for regeneration.

According to this plan, two cold utilities are needed for network balancing: (1) Boiler feed water at temperature of 25 °C and 8 bar pressure that can be preheated to 160 °C. The total flow rate is 5000 kg/h. 3750 kg/h of this total will be preheated in the 3 t/h sulfurex unit and 1250 kg/h in the 1 t/h sulfurex unit. (2) Air heated to a 30-120 °C temperature range will be used to provide 120 °C hot air for silica-gel regeneration. The 3 t/h and 1 t/h sulfurex units need 3480 kg/h and 1160 kg/h of 120 °C hot air for silica-gel column regeneration, respectively.

Second scenario- saturate steam production: In this WHR scenario, the aim is to maximize the production of 7 bar saturated steam, from condensed water or consumed steam at 130 °C. In addition, the scenario will allow for the possible production of 120 °C hot air for silica-gel regeneration and will also take into account the lack of a need to use steam in the radiators.

According to this scenario, two cold utilities are needed for network balancing: (1) 1450 kg/h of condensed water flow at 130 °C is converted to 7 bar saturated steam. This stream is divided into two parts using a 1:3 ratio to be used as a cold utility in 1 t/h and 3 t/h sulfurex units, respectively. (2) Air at 30-120 °C to be supplied for silica-gel regeneration, same to the first scenario.

Third scenario-combined saturate steam and power generation: In this scenario, cold utility selection for two selected networks in two sulfurex units will be performed in order to maximize the production of 110 bar super heated steam and also to supply hot air needed for silica-gel regeneration, using recovered heat. The super heated steam produced in two sulfurex units is collected and expanded in a steam turbine to produce power. The steam turbine outlet condition is set to saturated steam at 7 bar to supply a part of the saturated steam requirement in the factory.

Accordingly, two cold utilities suggested in this scenario are as follows: (1) 1370 kg/h of condensed water flow at 130 °C is converted to 110 bar super heated steam. This stream is divided into two parts using a 1:3 ratio to be used as a cold utility in 1 t/h and 3 t/h sulfurex units, respectively. (2) Air at 30-120 °C to be supplied for silica-gel regeneration, same to the first scenario.

RESULTS AND DISCUSSION

Retrofit of HENs using PT should be done in two different stages *i.e.*, targeting and design^{23,24}. Since the case study description and the required process and economic data gathering have been done in the previous parts, we can target the HENs regarding the economical and other mentioned restrictions through the three considered scenarios.

Stage-1: Targeting: The steam data for the proposed cold utilities in the aforementioned WHR scenarios are given in Table-5. Table-5 shows, each selected networks of two sulfurex units are threshold problems. It means only cold utility consumes in the network. The nature of single utility HENs is different from the issues of conventional PT discussed

TABLE-5
STREAM DATA FOR THE PROPOSED COLD UTILITIES

Cold utility	Scenario 1	Scenario 2	Scenario 3	M (kg/h)	T _s (°C)	T _t (°C)	h (W/m ² °C)	HTC (W/m ² °C)
Super heated steam generation (at 110 bar)	–	–	✓	1370	130	353.0	6800	4626.70
Saturate steam generation (at 7 bar)	–	✓	–	1450	130	164.9	6000	3926.70
BFW	✓	–	–	5000	25	160.0	3750	2819.55
Air	✓	✓	✓	4640	30	120.0	111	110.59

previously. Retrofit of these networks using the conventional PT tools would be inappropriate because the WHR cannot be increased by decreasing the minimum temperature difference. In these problems, changing the minimum temperature difference may only result reduction of the energy losses or providing the steam generation opportunities in the HEN²⁵.

Accordingly, we wish to estimate values of the required utilities based on technical and economical limits. The operating point, ΔT_{\min} , has been determined based on an investment limit given new heat transfer areas that allow for the reconfiguration of sulfurex units²⁶⁻²⁸. This operating point differs from the minimum temperature between hot and cold process streams (ΔT_{\min}) in most of the pinch studies²⁶⁻²⁸. It expresses the minimum temperature difference between hot streams and the proposed dual cold utilities in selected networks of sulfurex units. The restrictions on targeting and reform of two existing sulfurex units selected networks expressed in previous parts. Given relevant economic and process data, a maximum payback time of 40 months to reconfigure the two sulfurex units and other

existing constraints mentioned previously, we could target networks for the two sulfurex units based on the three scenarios, using PT targeting tools with constant pressure drop consideration²³. Targeting results are listed in Table-6.

As seen in Table-6, recovering the waste heat, for providing hot air needed for the silica-gel regeneration in all scenarios, preheating of BFW in the first scenario, production of saturated steam at 7 bar in the second scenario and combined 7 bar saturated steam and power generation in the last scenario, which reduce the total energy demand of the factory. Table-6 shows that in addition to supply a part of saturated steam and whole of the hot air required for the process, 150 kW power can be generated using recovered waste heat in the third scenario. The targeted payback time for the last scenario is shortest. However the required investment is higher than all.

Design: After targeting the studied networks, each of the two selected networks of sulfurex units were modified by adding four new heat exchangers, considering the two proposed cold utilities in each of scenarios. This modification

TABLE-6
TARGETING RESULTS

Sulfurex units	Parameters	Scenario 1	Scenario 2	Scenario 3
3 t/h capacity	Minimum temperature difference, ΔT_{\min} (°C)	30	30	30
	Total targeted hot utility consumption (kW)	0	0	0
	Total targeted cold utility consumption (kW)	766.8	766.8	766.8
	– Targeted hot air production (kW)	88.8	88.8	88.8
	– Targeted BFW preheating (kW)	678	0	0
	– Targeted saturated steam production (kW)	0	678	0
	– Targeted super heated steam production (kW)	0	0	678
	– Targeted power generation (kW)	0	0	112.5
	Targeted area (m ²)	254.56	321	290
	Targeted investment for new heat exchangers (\$)	83921	90615	84300
1 t/h capacity	Minimum temperature difference, ΔT_{\min} (°C)	30	30	30
	Total targeted hot utility consumption (kW)	0	0	0
	Total targeted cold utility consumption (kW)	255.6	255.6	255.6
	– Targeted hot air production (kW)	29.6	29.6	29.6
	– Targeted BFW preheating (kW)	226	0	0
	– Targeted saturated steam production (kW)	0	226	0
	– Targeted super heated steam production (kW)	0	0	226
	– Targeted power generation (kW)	0	0	37.5
	Targeted area (m ²)	74.84	101.6	92
	Targeted investment for new heat exchangers (\$)	46189	47340	47060
Total	Total hot air production at 120 °C (kg/h)	4640	4640	4640
	Total BFW preheating (kg/h)	5000	0	0
	Total Saturated steam at 7 bar production (kg/h)	0	1450	1370
	Total power generation (kW)	0	0	150
	Total targeted benefits resulting from net energy saving (\$/yr)	40896	46496	44192
	Total targeted benefits resulting from net power generation (\$/yr)	0	0	72000
	Total targeted benefits (\$/yr)	40897	46496	116192
	Total targeted investment for new heat exchangers (\$)	130110	137955	131360
	Targeted investment for power generation (\$)	0	0	75000
	Total targeted investment (\$)	130110	137955	206360
Targeted payback time (yr)	3.18	2.97	1.78	

was obtained using the PDM, accounting for the constant pressure drop technique²³ and given existing limitations. Simplified flow diagrams of modified HEN for the 3 t/h sulfurex unit, according to the triple scenarios are shown in Fig. 3. It is noted that the modified HENs depicted in this figure are only for the 3 t/h sulfurex unit but are extendable for the 1 t/h sulfurex unit as well.

Figs. 4-6 show the modified HEN flow diagram for the sulfurex unit after the modification according to the three scenarios. All new items in Figs. 3-6 have been shown in black and the any parts of the sulfurex process that are not shown in those figures remain in the network without any modifications.

In other words, only the method of cooling for the hot process streams in the process is changed.

According to the first scenario in Fig. 4, 5 t/h of BFW, divided into two parts with a 3-1 ratio, would be preheated to 160 °C by the WHR systems. The preheated water would then be mixed in and sent to the boilers. This preheating would result in 904 kW of energy savings. In addition, if this plan were implemented, each of the two sulfurex units would produce 120 °C hot air needed for silica-gel regeneration. This would result in 118.4 kW of more energy savings.

According to the second modification scenario depicted in Fig. 5, 1.45 t/h under pressure condensate flow at 130 °C,

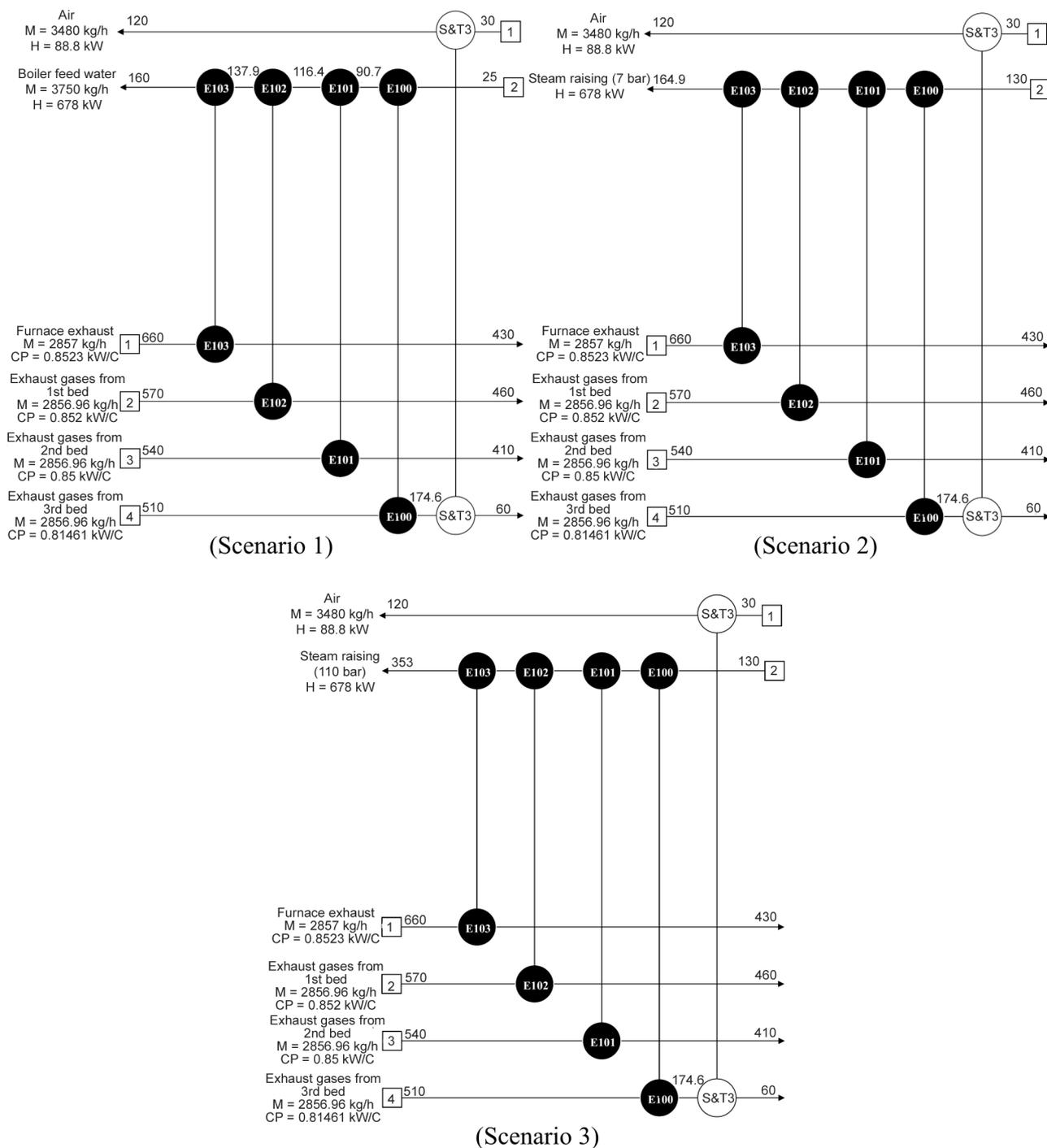


Fig. 3. Modified HEN diagram for the sulfurex unit (3 t/h capacity)

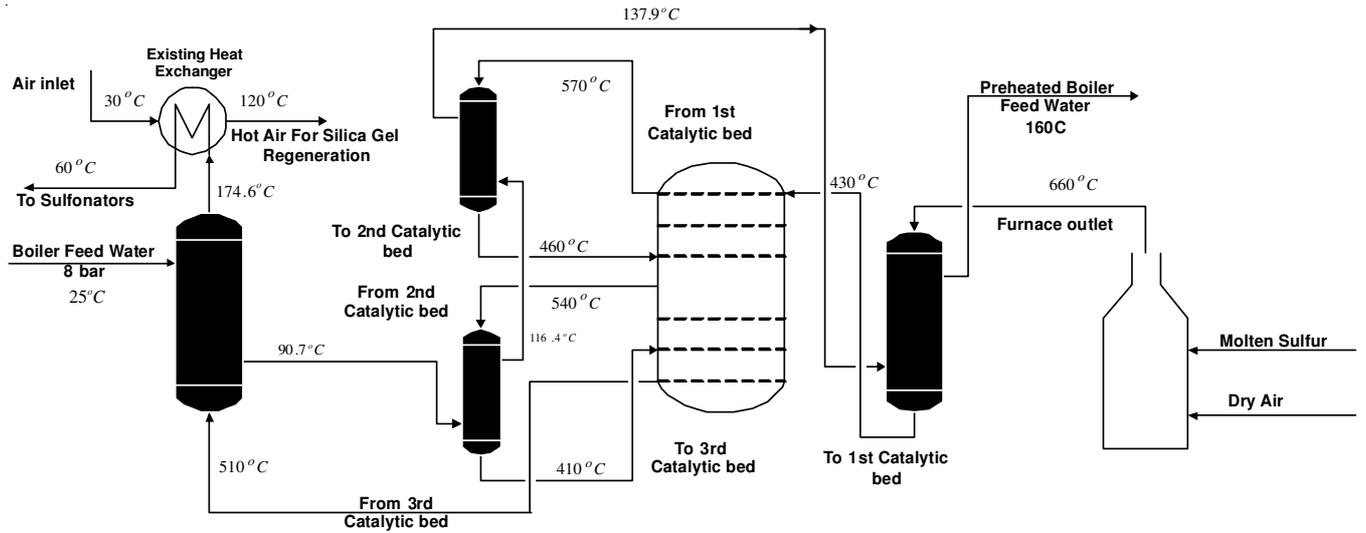


Fig. 4. Configuration of HEN for the sulfurex unit, after modification according to the first scenario

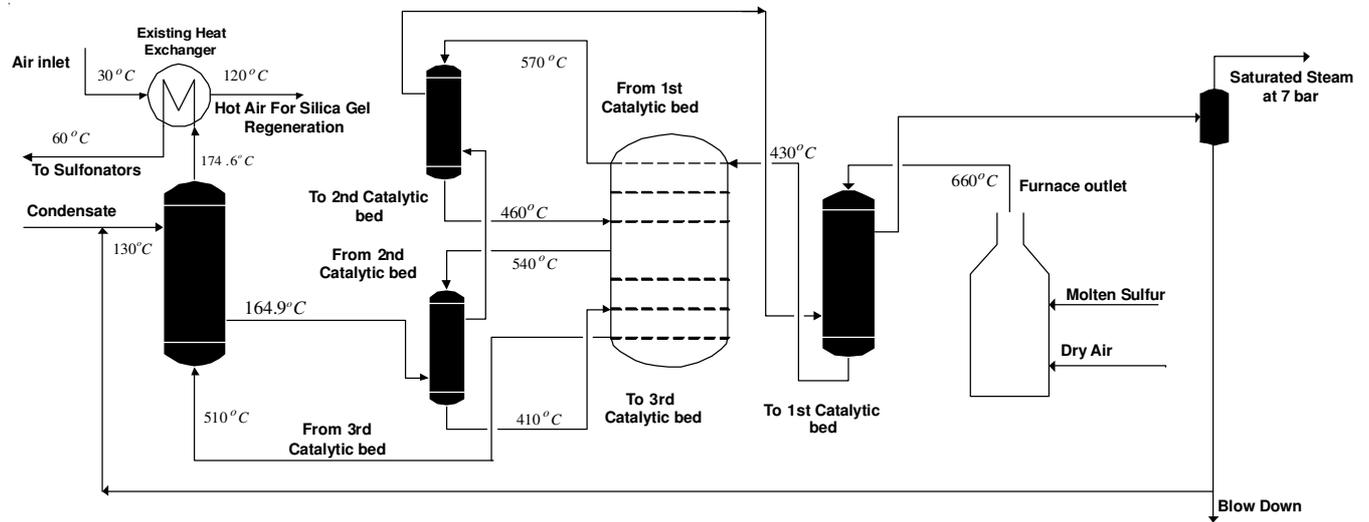


Fig. 5. Configuration of HEN for the sulfurex unit, after modification according to the second scenario

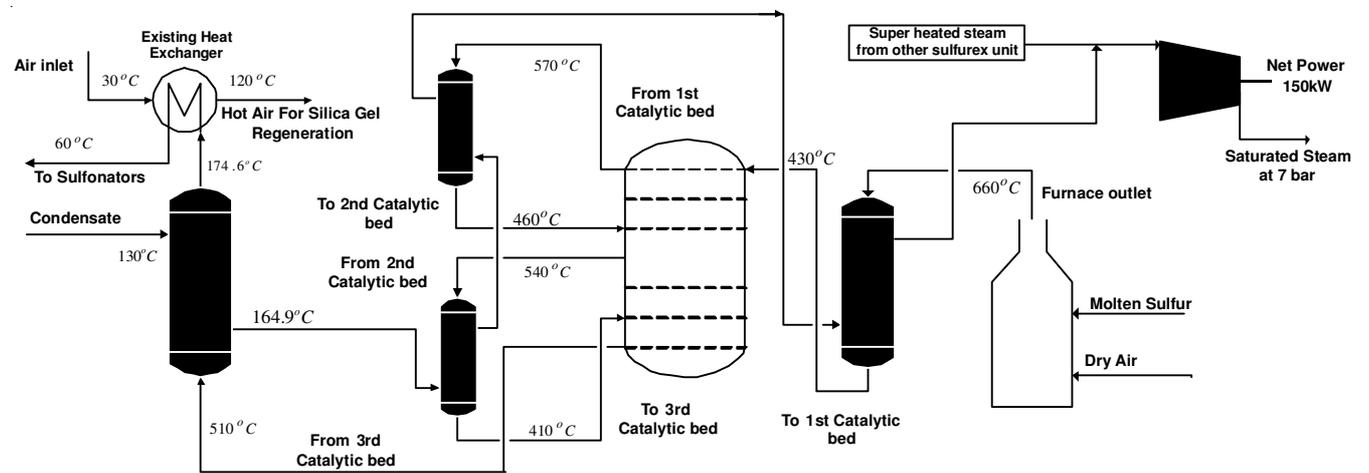


Fig. 6. Configuration of HEN for the sulfurex unit, after modification according to the third scenario

divided into two parts with a 3:1 ratio, should be converted to saturated steam at 7 bar in the introduced WHR system. 11.6 tons of 7 bar saturated steam would be produced from the recovered waste heat during each 8 h operating shift. In addition, the 3480 kg/h and 1160 kg/h of the hot air required to regenerate the silica-gel columns for the 1 t/h and 3 t/h sulfurex units, respectively, would be produced from the waste heat. Accordingly, if this scenario were implemented, in addition to supplying whole of the hot air needed for the process, 29 % of the required 40 tons of 7 bar saturated steam for each operating shift would be generated from the waste heat and without requiring fuel consumption.

According to the third modification scenario shown in Fig. 6, 1.37 t/h under pressure condensate stream would divide into two parts with a 3:1 ratio and convert to super heated steam at 110 bar in the introduced WHR system at both sulfurex units. The super heated steams at 110 bar pressure would send to a back pressure steam turbine to generate power and expand to 7 bar.

If this scenario were implemented, in addition to providing 37120 kg hot air at 120 °C required for silica-gel regeneration, 1200 kWh net power and about 11 tons of 7 bar saturated steam would be produced from the recovered waste heat during each 8 h operating shift. Accordingly, 100 % of the hot air demand, about 7.5 % of the power demand and 27.4 % of the steam demand in the factory can be supplied without requiring fuel consumption.

The results of the WHR system design for the two sulfurex units are given in Table-7 and compared to the targeting results, according to the triple modification scenarios.

Comparing the results in Table-7 suggests that the third WHR scenario requires a higher investment but offers a much lower return on investment. Thus, this scenario should be selected for WHR in the factory under investigation.

For the energy-saving projects, the environmental costs of fossil fuels as well as electrical usage must be assessed. According to Table-7, applying the optimum WHR to this factory can provide 1022.4 kW energy saving and 150 kW power generation. By reducing the energy consumption in the process plants, a considerable amount of air pollutants as well as greenhouse gases will be reduced^{12,16}. The reduction of air pollutant emissions for this factory is given in Table-8.

TABLE-8
REDUCTION OF AIR POLLUTANTS EMISSION ACCORDING TO THE OPTIMUM WHR SCENARIO

NO _x (t/yr)	SO ₂ (t/yr)	SO ₃ (t/yr)	CO ₂ (t/yr)	CO (t/yr)	CH (t/yr)	SPM (t/yr)
1.28	1.026	0.016	224.27	0.00197	0.0384	0.1372

Conclusion

In this study, application of pinch technology for waste heat recovery in the linear-alkyl-benzene presented through three different scenarios. Besides the investment constraint and the desired return on investment, major constraints taken into account in the calculations were the thermal considerations related to outlet flows from the furnaces and at the entrances and exits from the vanadium pentoxide catalytic beds. In addition, the collection of undesired byproducts, such as sulfuric acid and oleum thanks to gravity separation, also was considered in the sulfurex units under study. Other constraints in the sulfurex design efforts focused on materials selection for the heat exchangers and for all heat transfer areas involved in producing hot water or steam. In addition, the existing blower solution was of limited capacity because outlet gases from furnaces and catalytic beds tended to flow in with natural movement. Finally, after the modification, the pressure drops were exactly equal to the current allowed drop because the network design was carried out using constant pressure drop calculation techniques and because the network was modified so that the selected network streams would not present a higher pressure drop following the modification.

In the first scenario, 5 t/h of BFW could be preheated to 160 °C and 4640 kg/h hot air at 120 °C, needed for the silica-gel regeneration might be provided in the WHR systems. This scenario needed 131930 \$ investment and resulted in 40897 \$/yr energy saving. Therefore, the simple payback time for the first modification scenario was about 3.23 yr.

In the second scenario, 1.45 t/h saturated steam at 7 bar and 4640 kg/h hot air same to the first scenario, could be produced in the introduced WHR system. This amount of saturated steam would supply about 29 % of the steam requirement in the factory without requiring fuel consumption. This scenario needed 140438 \$ investment and made 46496 \$/yr energy saving. Accordingly, the simple payback time for the second scenario was about 3.02 yr.

TABLE-7
RESULTS OF THE RETROFIT STUDY FOR TWO SULFUREX UNITS

Project parameters	Scenario 1			Scenario 2			Scenario 3		
	Targeting	Design	Error	Targeting	Design	Error	Targeting	Design	Error
Total hot air production at 120 °C (kg/h)	4640	4640	0	4640	4640	0	4640	4640	0
Total BFW preheating (kg/h)	5000	5000	0	0	0	0	0	0	0
Total Saturated steam at 7 bar production (kg/h)	0	0	0	1450	1450	0	1370	1370	0
Total power generation (kW)	0	0	0	0	0	0	150	150	0
Total targeted benefits resulting from net energy saving (\$/yr)	40896	40896	0	46496	46496	0	44192	44192	0
Total targeted benefits resulting from net power generation (\$/yr)	0	0	0	0	0	0	72000	72000	0
Total targeted benefits (\$/yr)	40897	40897	0	46496	46496	0	116192	116192	0
Total targeted investment for new heat exchangers (\$)	130110	131930	1.4 %	137955	140438	1.8 %	131360	132930	1.2 %
Targeted investment for power generation (\$)	0	0	0	0	0	0	75000	75000	0
Total targeted investment (\$)	130110	131930	1.4 %	137955	140438	1.8 %	206360	207930	0.8 %
Targeted payback time (yr)	3.18	3.23	1.4 %	2.97	3.02	1.7 %	1.78	1.79	0.5 %

In the last modification scenario, in addition to 4640 kg/h hot air production at 120 °C same to the first scenario, 1.37 t/h high pressure super heated steam might be produced in the introduced WHR system. The high pressure turbine could be expanded in a back pressure turbine to 7 bar to supply 27.4 % of the low pressure steam requirement of the plant and also produce 150 kW net power. The investment needed for this scenario and the net annual energy saving were about 207930 \$ and 116192 \$, respectively. Therefore, the simple payback time for this waste heat recovery scenario was about 1.79 year. Accordingly, the last scenario should be recommended.

In addition, the results showed that more than 1.28 ton NO_x, 1.026 ton SO₂, 0.016 ton SO₃, 224.27 ton CO₂, 0.00197 ton CO, 0.0384 ton CH and 0.1372 ton SPM per year would be reduced in the selected scenario of waste heat recovery.

Nomenclature

A	: Heat transfer area (m ²)
BFW	: Boiler feed water
CHP	: Combined heat and power generation
CM	: Cp matrix
CMC	: Carboxymethylcellulose
CP	: Heat capacity (kW/°C)
Cp	: Specific heat capacity (kJ/kg °C)
GCC	: Grand composite curve
h	: Heat transfer coefficient (W/m ² °C)
H	: Liquid head (m)
HEN	: Heat exchanger network
HTC	: Overall fouled heat transfer coefficient (W/m ² °C)
K	: Thermal conductivity (W/m °C)
LAB	: Linear alkyl benzene
LM	: Load maximization
M	: Mass flowrate (kg/h)
PDM	: Pinch design method
PMP	: Plus-minus principle
PT	: Pinch technology
q	: Volumetric flowrate (m ³ /kg)
RPA	: Remaining problem analysis
ST	: Super targeting
T _s	: Supply temperature (°C)
T _t	: Target temperature (°C)
TDFP	: Temperature driving force plot
TGL	: Three golden laws
WHR	: Waste heat recovery
Greek Letters	
ΔH	: Heat load (kW)

ΔP	: Allowable stream pressure drop (pa)
ΔT _{min}	: Minimum temperature approach on composite curves (°C)
ρ	: Density (kg/m ³)
μ	: Viscosity (kg/m)

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