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Optimization of heat exchanger network in styrene production plant using pinch technology

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Abstract:

Pinch technology is a systematic technique for analysing heat flow through an industrial process based on fundamental thermodynamics to minimize energy consumption and maximize heat recovery. This technique was widely applied in downstream sectors, particularly in refineries and petrochemical facilities, where there are complex heat exchangers networks. During operation of heat exchangers, the major aim is to focus on the best performance of the network and to reduce the external energy costs by utilizing the most energy within the system. This research aimed to design an optimum heat exchanger networking for a styrene production plant using HINT software, which uses pinch technology. Composite curve, grand composite curve, heat cascade diagram, and grid diagram were constructed. The pinch temperature was determined to be 509.3 K and the optimal value of ΔTmin found to be equal to 20 K. The minimum hot and cold utility requirements obtained were 14,332.0 kW and 7,375.0 kW, respectively. The estimated total heat transfer area was found to be 9,400 m2. Generally, the obtained results are considered to be promising for achieving considerable improvements in energy savings and cost reduction.

Keywords: Process Optimization, Pinch Technology, Heat Exchanger Network, Hint Program, Energy Recovery.

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تحسين شبكة مبادلات حرارية لمصنع إنتاج الستايرين باستخدام المكاملة الحرارية

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الملخص

تقنية المكاملة الحرارية هي تقنية منهجية لتحليل تدفق كمية الحرارة خلال العملية الصناعية تعتمد على الديناميكا الحرارية الأساسية وذلك لتقليل استهلاك الطاقة وزيادة استرداد كمية الحرارة إلى أقصى حد. تم تطبيق هذه التقنية على نطاق واسع في الصناعات النفطية، وخاصة في المصافي والمنشآت البتروكيماوية، حيث توجد شبكة مبادلات حرارية معقدة. أثناء تشغيل المبادلات الحرارية، يكون الهدف الرئيسي هو التركيز على أفضل أداء للشبكة وتقليل تكاليف كمية الطاقة الخارجية من خلال استخدام أكبر قدر من كمية الطاقة داخل النظام. الهدف من هذا البحث هو تصميم شبكة مبادلات حرارية مثلى لمصنع إنتاج الستايرين باستخدام برنامج الهنت

الذي يستخدم تقنية المكاملة الحرار ية. تم تحديد درجة حرارة ا نقطة الاختناق على أنها 509.3 كلفن ووجد أن القيمة المثلى لفرق درجة الحرارة هو20 درجة. كان الحد الأدنى لمتطلبات التسخين والتبريد التي تم الحصول عليها 14332.0 كيلووات و7375.0 كيلووات على التوالي. وقد وجد أن إجمالي مساحة نقل الحرارة المقدرة هي 9400 متر مربع. بشكل عام تعتبر النتائج التي تم الحصول عليها واعدة لتحقيق تحسن كبير في توفير الطاقة وخفض التكاليف.

الكلمات المفتاحية: تحسين العمليات، تقنية التحليل النقطي، شبكة المبادلات الحرارية، برنامج الهنت، استعادة الطاقة.

1. Introduction

Pinch technology is a methodology for minimizing energy consumption of chemical processes by calculating thermodynamically feasible energy targets and achieving them by optimizing heat recovery systems, energy supply methods and process operating conditions. Pinch technology presents a simple methodology for systematical analyzing chemical processes and the surrounding utility systems with the help of laws of thermodynamics. The first law of thermodynamics provides the energy equation for calculating the enthalpy changes and the second law determines the heat flow direction. The requirements of energy can be minimized by apply pinch analysis which useful to increase process efficiency and decide the exact heat exchanger. This analysis is carried out by maximizing the recovery energy or minimize external energy sources [4] until form a simple heat exchanger network [5]. Pinch analysis is used to get optimal maximum energy recovery (MER), raising total energy utility, and design the heat exchanger network (HEN) [6]. In a pinch analysis, heat exchange occurs between hot and cold streams which are limited by the minimum temperature (ΔT_{min}) [7]. Energy targets can be reached from total heating and cooling that fit in the heat exchanger network because of ΔT_{min} or “pinch point”. The pinch defines the minimum driving force allowed in the exchanger unit. Pinch separate two systems, they are above pinch needs heat and below pinch as the heat source [8]. The use of pinch technology allows to find the optimum utility requirements for the process. Maximizing the use of lower-temperature utilities reduces the cost of hot utilities. The stages in a process of pinch analysis of a real process plant or site are a collection of data from the plant which includes temperature and flow heat capacity, selection of initial ΔT value, Construction of composite curves and grand composite curves, estimation of optimum hot and cold utility requirements, design of heat exchanger network [9].

This research aims to apply the pinch technology on Styrene production plant to create a minimum investment cost with practically fixed and a minimum operating cost for the heat exchanger network and to achieve a maximum amount of heat exchange among hot and cold process streams.

2. Material and methods

Process Integration enables the maximum heat exchange between process streams using “Pinch Technology”, that revealed various methods to maximize process-to-process heat exchange and minimized the use of utilities through an integrated network of heat exchangers. Heat integration software (HINT) is a non-commercial software used for Heat Exchanger Network (HEN) design. Hint is more powerful software for the designing purpose and gives the insight of area and cost targeting and optimize the Energy done by the heat exchanger network [9].

2.1 Pinch Technology

Pinch analysis is a methodology for reducing energy consumption of processes by calculating thermodynamically feasible energy targets (or minimum energy consumption) and achieving them by optimizing heat recovery systems, energy supply methods and process operating conditions. Such pinch analysis results in substantial financial savings. The method is based on thermodynamic principles and allows to determine the best heat exchangers network and utility system. It analyzes possible heat exchanges between cold streams and hot streams in order to minimize irreversibilities. The process data is represented as a set of energy flows, or streams, as a function of heat load against temperature. These data are combined for all the streams in the plant to give composite curves. The point of closest approach between the hot and cold composite curves is the pinch temperature (pinch point). Hence, by finding this point and starting design there, the energy targets can be achieved using heat exchangers to recover heat between hot and cold streams. In practice, during the pinch analysis, cross-pinch exchanges of heat are often found between a stream with its temperature above the pinch and one below the pinch.

2.2 Process Description of Styrene production

The feed Ethylbenzene was mixed with recycled ethylbenzene, heated, and then mixed with superheated steam Figure (1). The Steam serves as an inert in the reaction, which drives the equilibrium in equation (1) to the right by reducing the concentrations of all components [10].

Ethylbenzene feed is mixed with recycled ethylbenzene, heated, and then mixed with high-temperature, superheated steam Figure 1. Steam is an inert in the reaction, which drives the equilibrium shown in Equation (1) to the right by reducing the concentrations of all components [10].

$$C_6H_5C_2H_5 \leftrightarrow C_6H_5C_2H_3 + H_2 \quad (1)$$

$$Ethylbenzene \quad Styrene \quad Hydrogen$$

The styrene formation is highly endothermic, so the superheated steam also provides energy to drive the reaction. The Ethylbenzene decomposition to benzene and ethylene, and the hydrodealkylation to methane and toluene, are unwanted side reactions, Equations (2, 3).

$$C_6H_5C_2H_5 \rightarrow C_6H_6 + C_2H_2 \quad (2)$$

$$Ethylbenzene \quad Benzene \quad \text{Ethylene}$$

$$C_6H_5C_2H_5 + H_2 \rightarrow C_6H_5CH_3 + CH_4 \quad (3)$$

$$Ethylbenzene \quad Hydrogen \quad Toluen \quad Methan$$

The mixture enters then the adiabatic packed beds reactor with interheating. The high-temperature reactor effluent were cooled and then sent to a three-phase separator, in which light gases (hydrogen, methane, ethylene), organic liquid, and water exit in separate streams. The hydrogen stream is further purified and the organic stream containing the desired product benzene/toluene is distilled to remove the benzene and toluene and distilled again to separate unreacted Ethylbenzene for recycle from the styrene product.

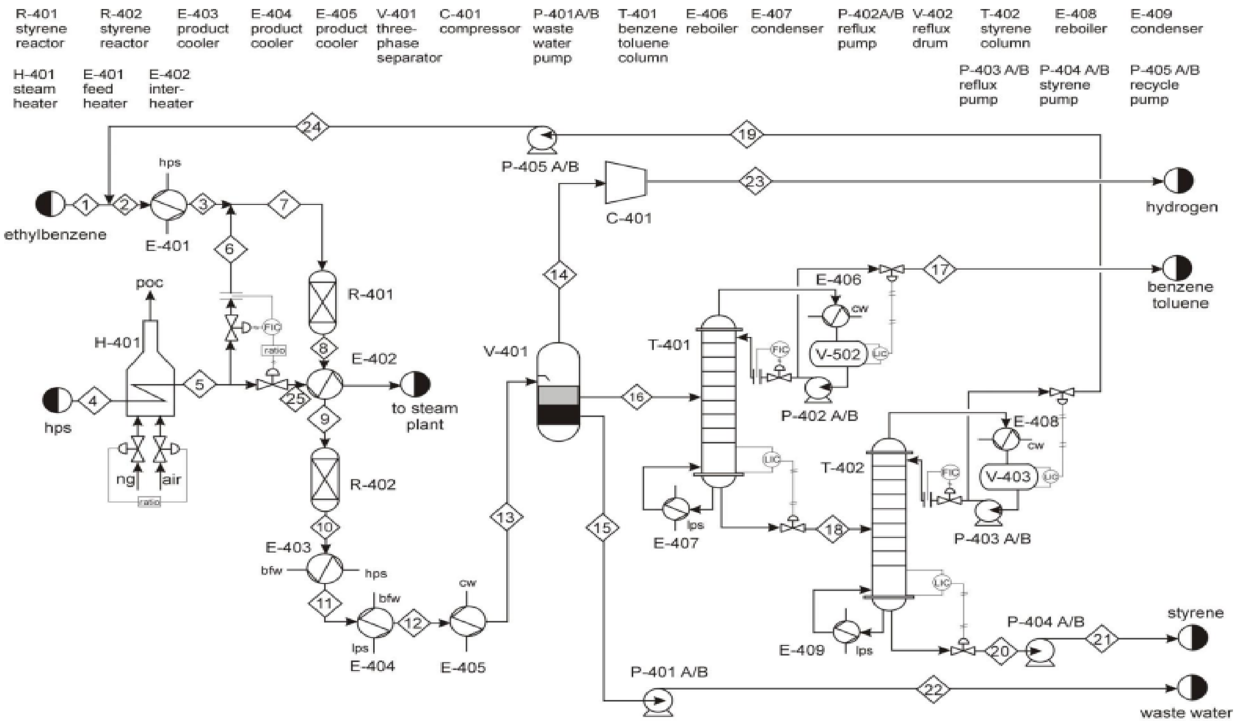

Figure 1. Styrene Process Flow Diagram [10].

2.3 Selection of Initial ΔT_{min} value

To achieve the energy recovery system of this production, the minimum approach temperature, ΔT_{min} must be determined [4, 9]. Choosing the right value of ΔT_{min} has a great effect on determining the size of the heat exchanger in a network that will be designed. The ΔT_{min} plays big role since, the decreasing value of ΔT_{min} have a big effect on reducing the utility consumption and cost for the plant. On the other hand, it can be related that decreasing in ΔT_{min} will increase the heat recovery, equipment and cost for the plant. Since styrene production is under the petrochemical plant, thus the range for ΔT_{min} that will be used is between 10 °C to 20 °C. This range is obtained from Table 4 that shows the ΔT_{min} that can be provided and use for various type of plant. Based on practical constrains, ΔT_{min} chosen is 10°C and it is not chosen based on economic analysis. With the best selection of ΔT_{min}, the interval temperature of each stream for source temperature and target temperature can be preceding

ΔT_{min} = Hot stream temperature (T_H) - Cold stream temperature (T_C).

Some shell and tube heat exchanger values based on Linnhoff March's application experience are tabulated in Table 4 [5].

Table 1: Typical ΔT_{min} values.

No.	Industrial Sector	Experience ΔT_{min} value
1	Low-Temperature Process	3 – 5 °C
3	Petrochemical	10 – 20 °C
2	Chemical	10 – 20 °C
4	Oil Refining	20 – 40 °C

2.4 Data Extraction Flowsheet

Material and Energy balances are used for Pinch Analysis to give the necessary information relates to the extraction data. There are ten (10) streams from styrene process flow diagram (PFD) need to be taken into account for the problem of integrating the utilization of energy; a five (5) cold stream (C) and a five (5) hot stream (H). Following thermal data was extracted from the PFD sheet:

- Supply temperature (T_S°C): the available temperature.
- Target temperature (T_T°C): the temperature which must be taken to.
- Mole flow rate (n in kmol/h)

The heat capacity of all components can be calculated by using equation (4), where A, B, C and D are constants in Table 2 [8].

$$Cp\left[\frac{kJ}{kmol \cdot K}\right] = \mathrm{R} \cdot [A + B \cdot T + C \cdot T^2 + D \cdot T^{-2}] \qquad (4)$$

Table 2: (T_S°C), (T_T°C) and average Temperature and the flow rate of all components.

Stream		Ts	Tt	Tav.	H2O	hylbenzer	Styrene	Hydrogen	Benzene	Toluene	Ethylene	Methane	n-total
H1	10-11	530.1	267	671.7	3000	102.88	120.09	119.38	1.37	1.86	0.16	0.65	3346.39
H2	11-12	267	180	496.65	3000	102.88	120.09	119.38	1.37	1.86	0.16	0.65	3346.39
H3	12-13	180	65	395.65	3000	102.88	120.09	119.38	1.37	1.86	0.16	0.65	3346.39
H4	18-19	125	90.8	381.05	0	102.73	0.06	0	0	0	0	0	102.79
H5	18-20	125	123.7	397.5	0	0.06	120.03	0	0	0	0	0	120.09
C1	2-3	116	240	451.15	0	223.73	0.06	0	1.21	1.21	0	0	226.21
C2	4-5	253.7	800	800	4016.13	0	0	0	0	0	0	0	4016.13
C3	8-9	504.3	550	800.3	3000	132.35	91.06	90.69	1.28	1.52	0.07	0.31	3317.28
C3	16-17	65	69.9	340.6	0	0.1	0	0	1.37	1.86	0	0	3.33
C4	16-18	65	125	368.15	0	102.88	120.09	0	1.37	1.86	0	0	226.2

The heat capacity flow rate (CP): the flow rate $\dot{n}$ Table 2 times the heat capacity Cp equation (4).

$$CP\ in\ \left[\frac{kW}{K}\right] = \sum \dot{n}_i \left[\frac{kmol}{h}\right] \cdot Cp_i \left[\frac{kJ}{kmol \cdot K}\right] \qquad (5)$$

$$\Delta H = CP \cdot (T_t - T_s) \qquad (6)$$

All process stream data are summarized in table 3.

Table 3: Process stream data.

Streams	T_s in °C	T_t in °C	CP in $\left[\frac{kW}{K}\right]$	ΔH in [kW]
H-1	530.1	267	47.51	-12,500.6
H-2	267	180	42.83	-3,726.0
H-3	180	65	40.00	-4,599.6
H-4	125	90.8	4.59	-157.0
H-5	125	123.7	5.32	-6.9
C-1	116	240	11.74	1,456.0
C-2	253.7	800	43.18	23,591.3
C-3	504.3	550	50.65	2,314.5
C-4	65	69.9	0.10	0.5
C-5	65	125	9.79	587.5

2.5 Composite Curves

Composite Curves were subject to various stages of development, and by several authors described and applied, such as [11-13]. The curves are used to simultaneously visualize cold streams, hot streams and heat transfer potential between them on the same graph. It is a graphical technique for determining the heat cascade. In each temperature interval in the hot stream and in the cold stream scale, the total heat power is calculated separately for the hot and cold streams.

$$\Delta H_{hot,i} = Cp_{hot,i}\ x\ \Delta T_i \qquad (7)$$

$$\Delta H_{cold,j} = Cp_{cold,j}\ x\ \Delta T_j \qquad (8)$$

The composite curves represent both the heat source and sink profiles and their superposition allows us to graphically recover the maximum heat recovery (MER). ΔTmin between the two curves guarantees a technically and economically feasible heat exchanger network.

2.6 Heat exchanger network design

Heat exchanger networks (HEN) are an arrangement of heat exchangers whose purpose is to recover energy from hot process streams to heat cold process streams using the least amount of hot and cold utility streams, while achieving specific target outlet temperatures for the process streams [2]. Once the utilities flow sheet was established, the Heat exchanger network (HEN) design can be started. The design of the HEN usually starts at the pinch, since this is the most constrained region. The key rule to achieve the previously calculated energy targets is to avoid heat transfer across the pinch. Following feasibility criteria are necessary to design the pinch heat exchangers:

- At the hot side of pinch, $\mathbf{N_{Cold} \geq N_{Hot}}$ cold streams must be bigger or equal to hot streams and at the cold side of pinch $\mathbf{N_{Hot} \geq N_{Cold}}$.
- At the hot side of the pinch, $\dot{m}Cp_{Cold} \geq \dot{m}Cp_{Hot}$ the heat capacity flow rate of cold stream must be higher than that of hot stream and at the cold side of the pinch, $\dot{m}Cp_{Hot} \geq \dot{m}Cp_{Cold}$.
-

3. Results and discussion

HEN analysis was considered to minimize interactions with external heat or cooling resources. The heating and cooling duties not serviced by heat recovery must be provided by external utilities including steam and cooling water. The cooling water is very suitable because of the abundance of water and of its high heat capacity.

The analysis of heat exchanger network was considered to minimize interactions with external heat or cooling resources. Cooling and heating duties not serviced by heat recovery must be provided by steam and cooling water. The use of steam as a heat exchange medium is because the steam has a high latent heat and therefore it is very effective as a heating medium [11, 15]. HINT program was used to produce the composite curves, grid diagrams. The heat transfer coefficient was assumed for all streams by $h = 0.2\ \frac{kW}{m^2\ °C}$.

3.1 Heat cascade

Cascading the heat surplus from one interval to the next implies the temperature difference which can make the heat to be transferred among the hot and cold stream Table 3. Starting from a zero-heat input at the highest temperature (H1) in Table 3 net heat change (ΔH) is added to each temperature interval to form a heat cascade. The pinch temperature is located where zero is found in Figure (2). Minimum cooling and heating duties are found at the top of the first column and the bottom of the second column, respectively.

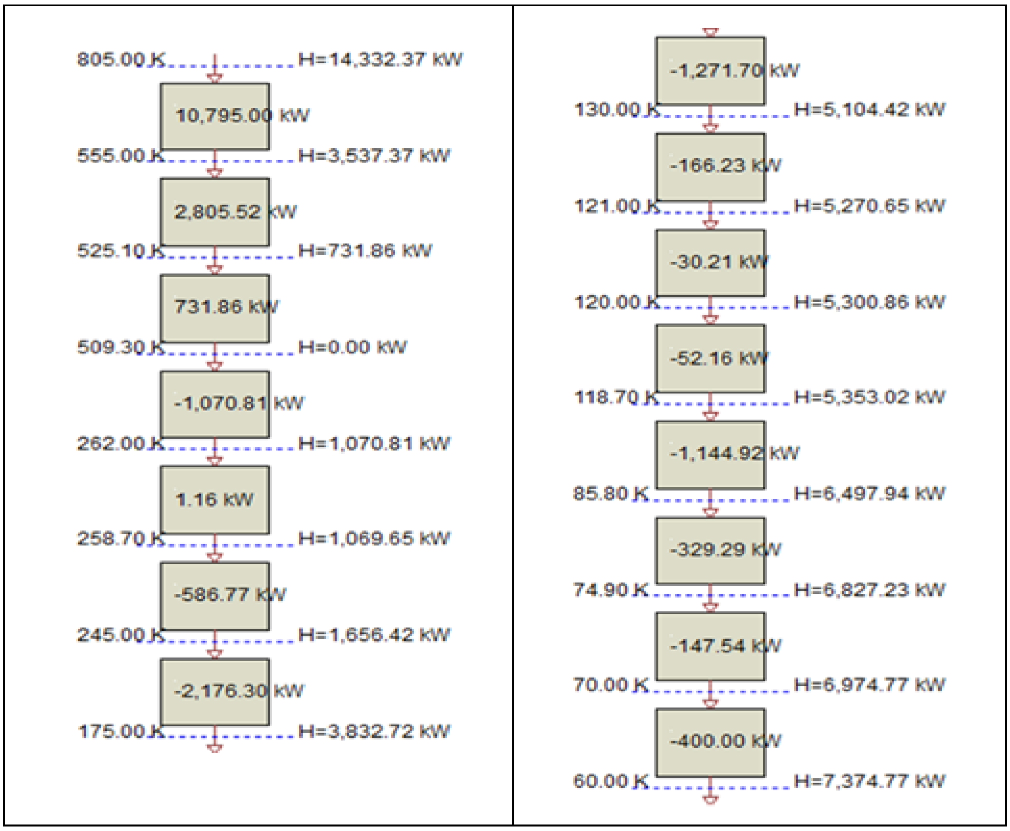

Figure 2. Heat Cascade Diagram.

Therefore:

- Minimum heat must be supplied from Hot Utilities Q_{Hmin} is 14,332.37 kW
- Minimum heat must be removed by Cold Utilities Q_{Cmin} is 7,374.77 kW.
- Pinch Point at interval, ΔT = 509.3 K.
- Cold Stream, T = 504.3 K.
- Hot Stream, T= 514.3 K.

3.2 Composite Curves

Composite curves can be used to indicate the minimum energy target for the process and to provide a countercurrent picture of heat transfer. This is achieved by overlapping the hot and cold composite curves, Figure (3). This overlap shows the maximum possible heat recovery. The hot composite curve reflects the heat supply and the cold composite curve the heat demand. The closest approximation of the hot and cold composite curves is the pinch characterized by ΔTmin.

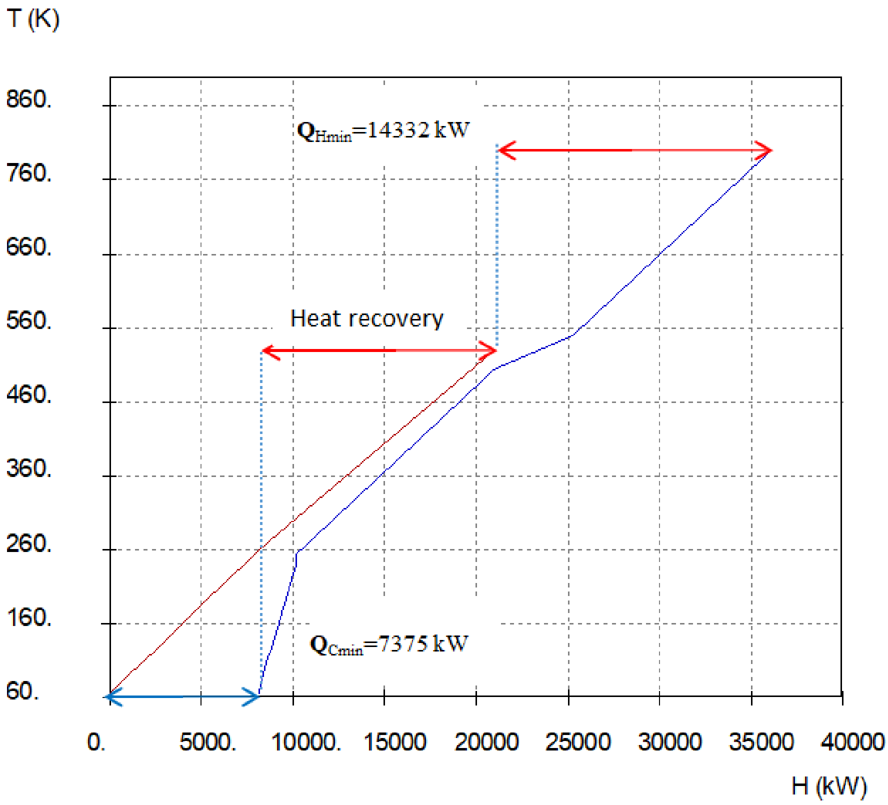

Figure 3. Composite curve method.

The minimum hot utility (Q_{Hmin}) for the example problem is 14332 units which is less than the existing process energy consumption of 20990 units. The potential for energy saving is therefore 20990 - 14332 = 6658 units by using the same value of ΔT_{min} = 10 °C as the existing process.

3.3 Grand Composite Curve

Grand Composite Curve is a tool that used for setting multiple utility targets. The illustration of the Grand Composite Curve starts with the composite curve. The first step is to make adjustments in the temperatures of the composite curves as shown in Figure 4. This involves increasing the cold composite temperature by ½ ΔT_{min} and decreasing the hot composite temperature by ½ ΔT_{min}. This temperature shifting of the process streams and utility levels ensures that even when the utility levels touch the grand composite curve, the minimum temperature difference of ΔT_{min} is maintained between the utility levels and the process streams. The temperature shifting therefore makes it easier to target for multiple utilities. As a result of this temperature shift, the composite curves touch each other at the pinch (509 grad). In Figure 4, the pinch-point temperature is identified where the curve touches the T-axis. The slope of the curve shows how the process acts. A Positive slope, the process is acting as a net heat sink. Conversely, a negative slope suggests that the process is acting as a net heat source. The grand composite curve displays the net heat-flow characteristics of a process versus its temperature. This allows us to quickly identify regions where heating and cooling utilities are required.

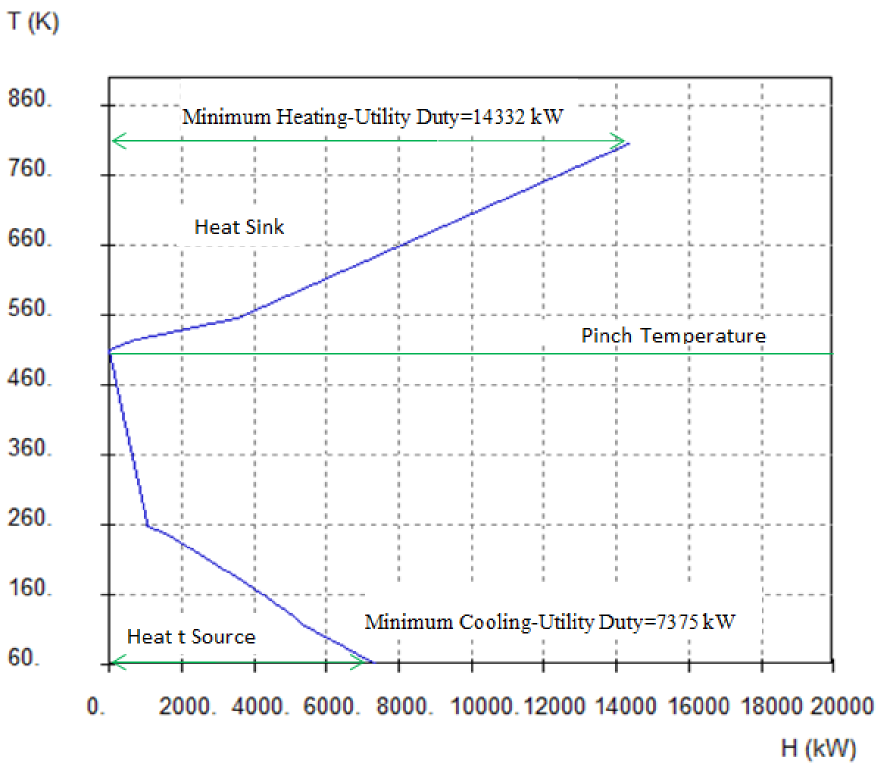

Figure 4. Grand Composite curve method.

3.4 Heat exchanger network design

Heat exchanger network (HEN) is one of the major techniques of energy saving. HEN synthesis is the heat integration between hot and cold process streams to reduce heating and cooling utility consumption in industrial processes. An initial HEN can be obtained according to the Area Targeting method in order to meet the maximum heat recovery. The capital cost of a heat exchanger network is directly dependent on the total heat exchange area. Therefore, an estimate of the required area for a heat-exchanger network is necessary for evaluating its economic feasibility. So, the area can be estimated from the Hint calculated area versus the minimum temperature difference (ΔT_{min}). Figure 5 shows the relationship between the area and temperature ΔTmin, where the area can be read at 10 degrees.

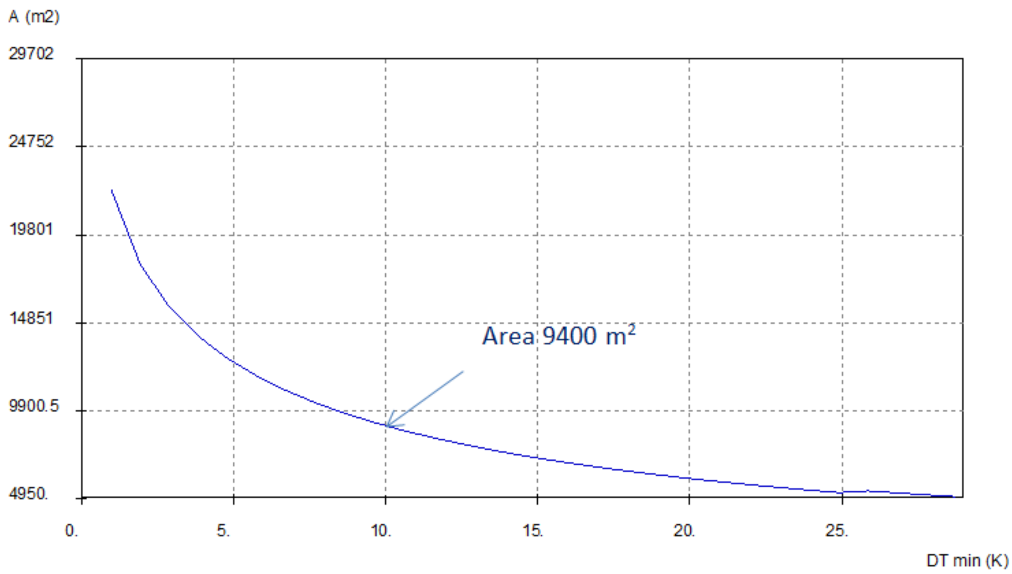

Figure 5. Area target vs. ΔT_{min}.

- **Capital Cost Targets**

A = 9,400 m², Q_{Hmin} = 14,332.0 kW, Q_{Cmin} = 7,375.0 kW

To ensure that new heat transfer area is not spread around throughout the existing heat exchanger network, a capital cost correlation should be used that is of the form [15]

$$Exchanger\ Cost\ (\$) = a + b \cdot A^{C} \qquad (9)$$

a, b and c are the cost law constants that vary according to the material of construction, pressure rating and the type of the heat exchanger. Typical values for a carbon steel shell and Tube exchanger would be:

a=16,000 b=3,200 c=0.7

Then:- $C.C\ (\$) = 16{,}000 + 3{,}200 \cdot 9{,}413.2^{0.7} = 1{,}951{,}376\ \$$

- **Operating Cost (O.P.C)**

- $Steam\ cost = 120\ \frac{\$}{kW.year} \cdot 14{,}332.0\ kW = 1{,}719{,}840 \frac{\$}{year}$
- $Water\ cost = 10\ \frac{\$}{kW.year} \cdot 7{,}375.0\ kW = 73{,}750\ \frac{\$}{year}$
- $Total\ energy\ cost = 1{,}719{,}884 \frac{\$}{year} + 73{,}748\ \frac{\$}{year} = 1{,}793{,}590 \frac{\$}{year}$

- **Annual Capital Cost (A.C.C)**

$$A.C.C = C.C \cdot \left[\frac{i \cdot (1+i)^n}{(1+i)^n - 1}\right] \qquad (10)$$

Where:
C.C =Capital cost **=** 1,951,376 $
i= Fraction interest per year = 0.1
n = number of years = 5 years

$$A.C.C == 1{,}951{,}376\ \$\ x \left[\frac{0.1(1+0.1)^5}{(1+0.1)^5 - 1}\right] = 514{,}768.0\ \$$$

Total Annual Cost [T.A.C] = Operating Cost (O.P.C) + Annual Capital Cost (A.C.C)

$$T.A.C = 1{,}793{,}590\ \$ + 514{,}768.0\ \$ = 2{,}308{,}358\ \$/yea$$

- **Grid Diagram**

The grid diagram is the most common scheme to represent a heat-exchanger network. Each heat exchange unit is represented as a vertical line connecting two streams. In Figure (6): Solid horizontal lines at the top of the diagram represent hot streams. These streams flow from the left to the right. Solid horizontal lines at the bottom represent cold streams, these flow from the right to the left. To perform MER design the grid diagram is divided into two parts, above and below the pinch with the following criteria [16]:

- At the hot side of pinch, $\mathbf{N_{Cold} \geq N_{Hot}}$ cold streams must be bigger or equal to hot streams and at the cold side of pinch $\mathbf{N_{Hot} \geq N_{Cold}}$.
- At the hot side of the pinch, $\dot{m}Cp_{Cold} \geq \dot{m}Cp_{Hot}$ the heat capacity flow rate of cold stream must be higher than that of hot stream and at the cold side of the pinch, $\dot{m}Cp_{Hot} \geq \dot{m}Cp_{Cold}$.

From the diagram we can determine the minimum amount of heat that must be removed by cold utilities and the minimum amount of heat that must be supplied by hot utilities.

Q_{Cmin}=	928.315 +	2270.45 +	4012.6 +	6.426 +	156.978 +	=7,374.77 kW
Q_{Hmin}=	23589.2 -10820.9 = 2314.7 - 750.658 =		12768.3 1564.042	12768.3 + 1564.042 = 14,332.37 kW		

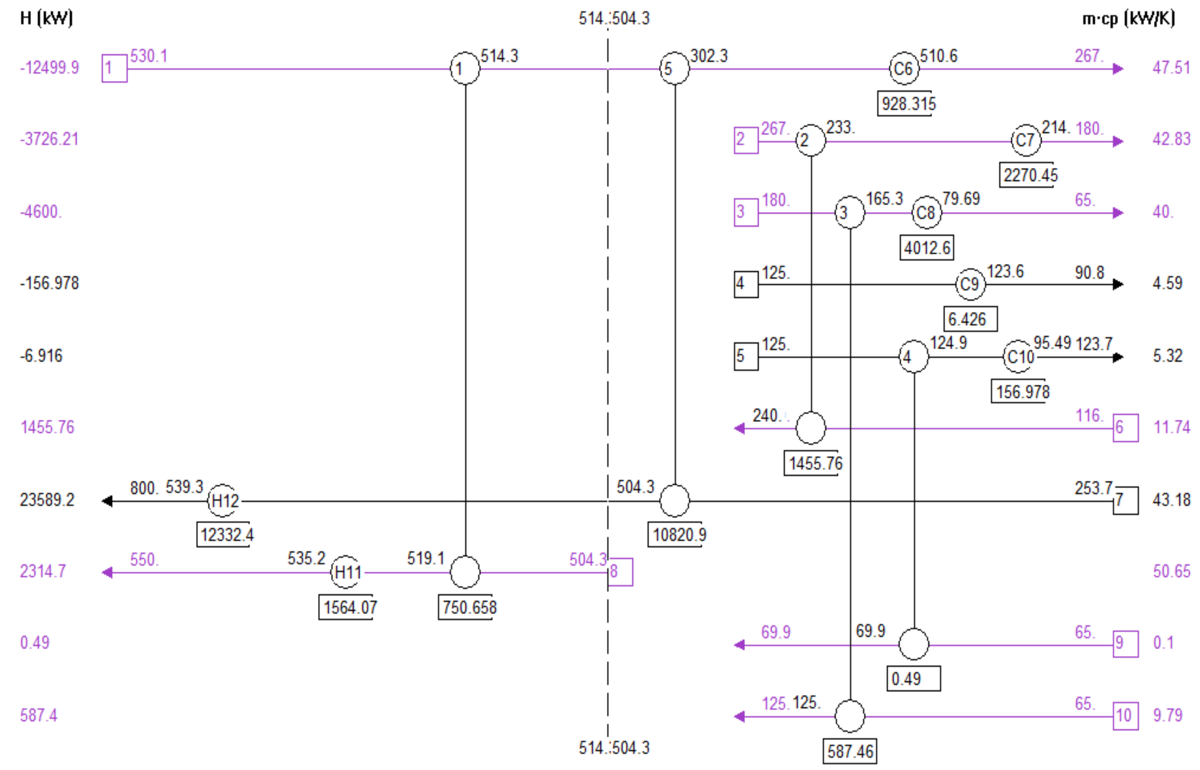

Figure 6. The grid diagram**.**

The determined targets are applied to design HEN that consists of 5 heat exchanger, 4 Cooler and 1 Heater. This heat exchanger network hopefully will achieve the minimum number of unites and the minimum external heat requirement. Compare and contrast of the utilities before and after heat integration are summarized in Table 4.

Table 4: Compare and contrast the utilities before and after heat integration.

	Before Heat Integration	After Heat Integration
Number of Heat Exchanger	10	5
Number of Cooler	5	4
Number of Heater	5	1
Hot Utility (HU), kW	20,990.1	14,332.37
Cold Utility (CU), kW	27,949.8	7,374.77
Total Utility, kW	48,939.9	21,707.14
Area, m^2	22,2000	9,400
Capital Cost Targets, $/year	3,544,556	1,951,376
Operating Cost (O.P.C), $/year	2,798,310	1,793,590
Annual Capital Cost (A.C.C) , $/year	935,045.0	514,768.0
Total Annual Cost, (T.A.C) , $/year	4,479,601	2,308,358

4. Conclusion

The pinch techniques were used to determine external utility requirements for a Styrene production plant. The problem table, heat cascades, shifted composite curve, and the grand composite curves were constructed. The pinch temperature (shifted) was determined to be 509.3 ^oC. The minimum hot and cold utility requirements are 14,332.0 kW and 7,375.0 kW, respectively, and the total area was 9,400 m^2. The minimum number of units targeting is 12 unit. The determined targets are applied to design a heat exchanger network that consists of 5 heat exchanger, 4 Cooler and 1 Heater. The calculated total annual cost of the Styrene production plant was $2{,}308{,}358\ \$/year$. After the process integration has been implemented, it is found that the percent of energy saving of the Hot and the Cold Utility was 31,7 % and 73,6 % respectively. The percent of cost saving was 48.5%.

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