

COMBINING PINCH AND EXERGY ANALYSIS FOR PROCESS IMPROVEMENT – A CASE STUDY ON AN AROMATICS COMPLEX

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Abstract. Exergy Analysis, also known as *Thermodynamic Analysis*, is a tool that has been widely used to analyse the energy efficiency of continuous processes. It is a powerful analysis tool that is based on the First and the Second Law of Thermodynamics. *Pinch Technology*, on the other hand, is a tool for optimization of a plant's heat recovery. Pinch Analysis application however requires extensive process mass and energy balances data. Thus, it cannot provide a quick assessment of the efficiency of selected equipment or processes. Extensive literature exists on the applications of Pinch Analysis on chemical processes and Exergy Analysis on power plants for energy efficiency improvement. Study on combined Pinch-Exergy Analysis has so far been limited to power plant improvements. This work demonstrates that the powerful combination of Pinch and Exergy analysis can assist designers to pinpoint inefficiencies in specific locations in a plant and to help outline a strategy to improve the energy efficiency for the plant. In this work, an aromatics plant steady state model has been developed and used as a case study. The analysis shows that potential energy savings of up to 60% for hot utility and 20 % of cold utility are achievable for the aromatics plant.

Key Words: Steady state modeling, Pinch Technology, Second Law of Thermodynamics, exergy source, composite curves.

1.0 INTRODUCTION

Exergy is defined as the maximum potential work obtainable from a system, with the ambient environment referred to as the point of "zero work" potential. Exergy Analysis, also known as *Thermodynamic Analysis*, is a tool for the *analysis* of the efficiency of process energy usage. It is based the First Law and Second Law of Thermodynamics.

Pinch Technology is related to Exergy Analysis, in that, it provides engineers with a systematic approach to improve heat recovery in a process through optimal exchange of heat at the appropriate temperature levels. Since its inception during the late 60s, Pinch Technology has been applied successfully for the optimization of energy usage in the chemical process industries, resulting in up to 90 % energy and 25% capital savings [1]. Recent applications of Pinch Analysis technique have also led to reductions in environmental emissions [2].

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In this work, exergy analysis is performed on heat exchangers in an aromatics plant [3] to assess the efficiency of the individual heat exchangers in the plants' existing network of heat exchangers. Note that an increase in exergy loss translates directly to an increase in primary fuel consumption. Results of the exergy analysis help pinpoint the specific locations in the plant needing particular attention. With an overall understanding of the plant's equipment efficiency, we then focus on using Pinch Analysis technique to modify the heat exchanger network for the aromatics complex. The potential improvement from the existing plant's energy consumption is then highlighted.

2.0 METHODOLOGY

A model of a plant producing aromatics was developed through a steady state simulation of the plant with the aid of a commercial simulator. The model provides the mass and energy balance data that is needed for the exergy and pinch analysis studies.

A heat exchanger exergy loss is determined from the difference between the exergy power (in kW) of the hot stream (exergy source) and the exergy power of the cold stream (exergy sink) (*see* equation (8)) [4]. The ratio between the sink and the source exergy power gives the exergetic efficiency of the heat transfer process (equation (9)) [4].

The energy power being transferred in a heat exchanger can be determined from

$$P_{\text{en}} = UA\Delta T_m \text{ [W]} \quad (1)$$

where

$$\begin{aligned} U &= \text{overall heat transfer coefficient [W/m}^2\text{K]} \\ A &= \text{heat transfer area [m}^2\text{]} \\ \Delta T_m &= \text{log-mean temperature difference,} \end{aligned}$$

$$\Delta T_m = (\Delta T_1 - \Delta T_2) / \ln (\Delta T_1 / \Delta T_2) \quad (2)$$

(with ΔT_1 and ΔT_2 as illustrated in Figure 1).

Wall [4] defined the *exergy factor* as the ratio between the exergy E and the transferred heat Q .

$$\frac{E}{Q} = 1 - \frac{T_0}{T - T_0} \ln \frac{T}{T_0} \quad (3)$$

The net hot stream (denoted by the subscript H) exergy flow can be calculated from Wall [4] from the difference in exergy power at the stream's final and initial conditions. The hot stream's final and initial exergy flows ($P_{\text{ex,H1}}$, $P_{\text{ex,H2}}$) are defined as

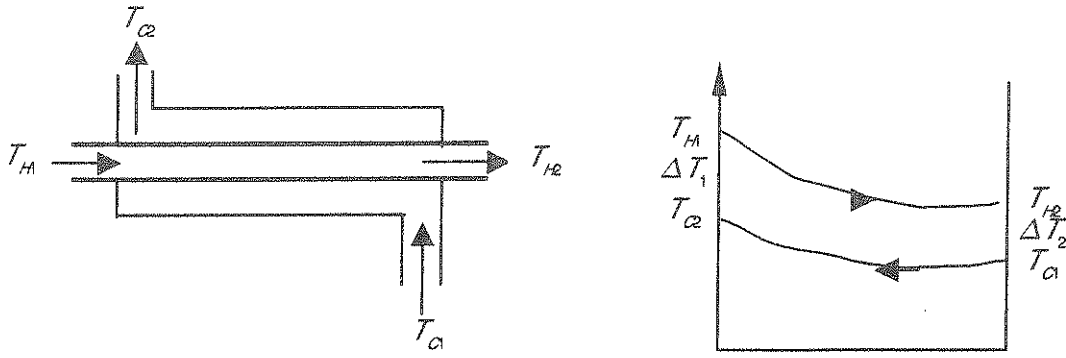


Figure 1 Countercurrent flow heat exchanger temperature profile

follows;

$$P_{\text{ex,H1}} = m_{\text{H}} C p_{\text{H}} \left(T_{\text{H1}} - T_0 - T_0 \ln \frac{T_{\text{H1}}}{T_{\text{H0}}} \right) \quad (4)$$

$$P_{\text{ex,H2}} = m_{\text{H}} C p_{\text{H}} \left(T_{\text{H2}} - T_0 - T_0 \ln \frac{T_{\text{H2}}}{T_{\text{H0}}} \right) \quad (5)$$

Thus, the exergy power lost from the hot stream, $\Delta P_{\text{ex,H}}$ in the heat exchanger becomes:

$$\begin{aligned} \Delta P_{\text{ex,H}} &= P_{\text{ex,H1}} - P_{\text{ex,H2}} \\ &= m_{\text{H}} C p_{\text{H}} \left(T_{\text{H1}} - T_{\text{H2}} - T_0 \ln \frac{T_{\text{H1}}}{T_{\text{H2}}} \right) \\ &= m_{\text{H}} C p_{\text{H}} \left(\theta_{\text{H1}} - \theta_{\text{H2}} - T_0 \ln \frac{T_{\text{H1}}}{T_{\text{H2}}} \right) \end{aligned} \quad (6)$$

Note that in all the cases mentioned above, the hot stream heat capacity, C_{PH} is assumed constant. Part of the exergy that is lost from the hot side is gained by the cold side of the heat exchanger. The exergy power received by the cold side fluid in the heat exchanger becomes (e.g., water as the cold side fluid, with mass m_{w} and heat capacity, $C p_{\text{w}}$):

$$\begin{aligned} \Delta P_{\text{ex,C}} &= P_{\text{ex,C1}} - P_{\text{ex,C2}} \\ &= m_{\text{w}} C p_{\text{w}} \left(\theta_{\text{C1}} - \theta_{\text{C2}} - T_0 \ln \frac{T_{\text{C2}}}{T_{\text{C1}}} \right) \end{aligned} \quad (7)$$

Thus, the exergy loss in the heat exchanger network, becomes:

$$\Delta P_{\text{ex}} = \Delta P_{\text{ex,H}} - \Delta P_{\text{ex,C}} \quad (8)$$

The exergetic efficiency of the heat exchanger network becomes:

$$\eta_{\text{ex}} = \frac{\Delta P_{\text{ex,C}}}{\Delta P_{\text{ex,H}}} \quad (9)$$

3.0 RESULTS OF THE EXERGY ANALYSIS STUDIES

Application of the exergy analysis equations on each heat exchanger (equations (1) through (9)) yields the overall exergy balance results as summarised in Table 1. The overall exergetic efficiency of *heat transfer for the entire process* can be obtained from the ratio of the total useful exergy increase (total exergy received by the cold stream) over the total exergy loss (total exergy rejected by the hot stream).

Exergy loss for the existing heat exchanger network,

$$\begin{aligned} \Delta P_{\text{ex}} &= \Delta P_{\text{ex,H}} - \Delta P_{\text{ex,C}} \\ &= 1795.3 - 579 \\ &= 1216.3 \text{ kW} \end{aligned}$$

Existing heat exchanger network exergetic efficiency,

$$\begin{aligned} \eta_{\text{ex}} &= \frac{\Delta P_{\text{ex,C}}}{\Delta P_{\text{ex,H}}} \\ &= \frac{579}{1795.3} \times 100\% \\ &= 32.3\% \end{aligned}$$

The exergy received by the cold streams in process heat exchangers and the nett steam production are examples of useful exergy increases. Examples of exergy losses include the hot streams' exergy that are not transferred to cold streams and the exergy content of flue gases. Figure 2 shows the process flow diagram for the existing plant. The heat recovery systems under study include the heat exchangers X-1 to X-13. The results shown in Table 1 demonstrate that two of the largest exergy losses occur in exchangers X-4 and X-3. Note that exchanger X-4, which is the condenser of a distillation column contributes to approximately 69% of the total heat exchanger exergy loss. The next largest loss occurs in heat exchanger X-3.

4.0 PROCESS IMPROVEMENT USING PINCH ANALYSIS

We describe the design of an optimal heat recovery (heat exchanger) network in order to demonstrate the use of Pinch Technology a systematic guiding tool for process

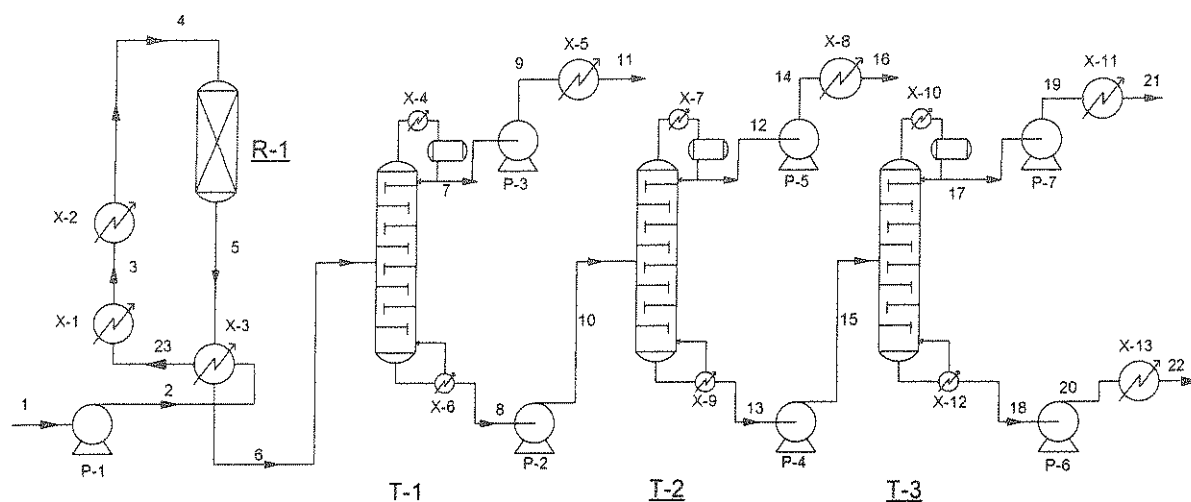


Figure 2 Process flow diagram for the existing aromatics plant

Table 1 Results of exergy calculations for individual exchangers

Heat Exchanger	$\Delta P_{ex,H}$ (kW)	$\Delta P_{ex,C}$ (kW)	mCp (kW/K)	ΔP_{ex} (kW)
X-1	84.6	39.6	21.94	45.0
X-2	172.9	140.5	12.61	32.4
X-3	265.8	141.5	49.04	124.3
X-4	917.9	78.7	484.22	839.2
X-5	44.6	8.5	36.27	36.1
X-6	76.6	72.6	23.56	4.0
X-7	33.9	3	18.48	30.9
X-8	18.5	2.5	15.37	16.0
X-9	86.6	83.5	26.63	3.1
X-10	40.7	2.2	13.67	38.5
X-11	42.7	4.1	25.37	38.6
X-12	1.8	1.7	0.31	0.1
X-13	8.7	0.6	3.61	8.1
Total	1795.3	579	-	1216.3

improvement through exergy analysis. The results show a high potential for energy recovery for the plant. A software developed in-house by Process Systems Engineering Group, Department of chemical Engineering, UTM is used to generate the composite hot and composite cold process streams on a temperature (T) versus enthalpy change (DH) diagram known as the *composite curves* (Figure 3). The software also generates accurate numerical values for the "pinch" temperatures and the minimum hot and cold heating requirements for the entire process (energy targets).

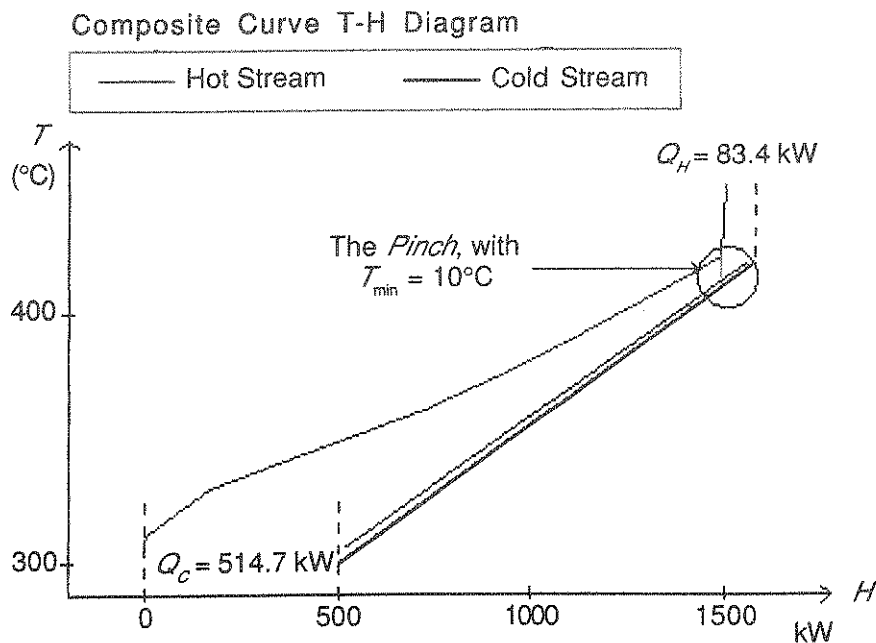


Figure 3 Composite curves showing the heat recovery 'pinch' and the energy targets for the aromatics process.

From the composite curves, we have identified:

- *The pinch point*, which is the point of closest approach between the composite hot and cold curves. Here is where the heat transfer is most constrained. The pinch temperatures are 150°C for the hot composite, and 140°C for the cold composite.
- the *minimum hot utility target*, $Q_{HMIN'} = 83.4 \text{ kW}$ represents the minimum external heating duty required by the process (the heating duty can be supplied by the use of steam, thermal oil or their equivalent).
- the *minimum cold utility*, $Q_{CMIN'} = 514.7 \text{ kW}$ represents the minimum external cooling duty required by the process (the cooling duty can be supplied by the use of cooling water, refrigerant or their equivalent). Finally, by using the pinch design procedure [1] on the existing plant, the heat exchanger network is successfully revamped to achieve the targeted energy consumption. As a result, more energy were recovered and exergy losses were minimized. Figure 4 shows a process flow diagram after process modifications. Note, that, exchangers X-19 and X-20 are the new exchangers installed to increase the process energy recovery.

Analysis of the figures obtained from Table 2, shows that potential energy savings of 60% for hot utility and 20% of cold utility are achievable for the aromatics plant. Such energy performance was achieved with the minimum heat exchanger approach

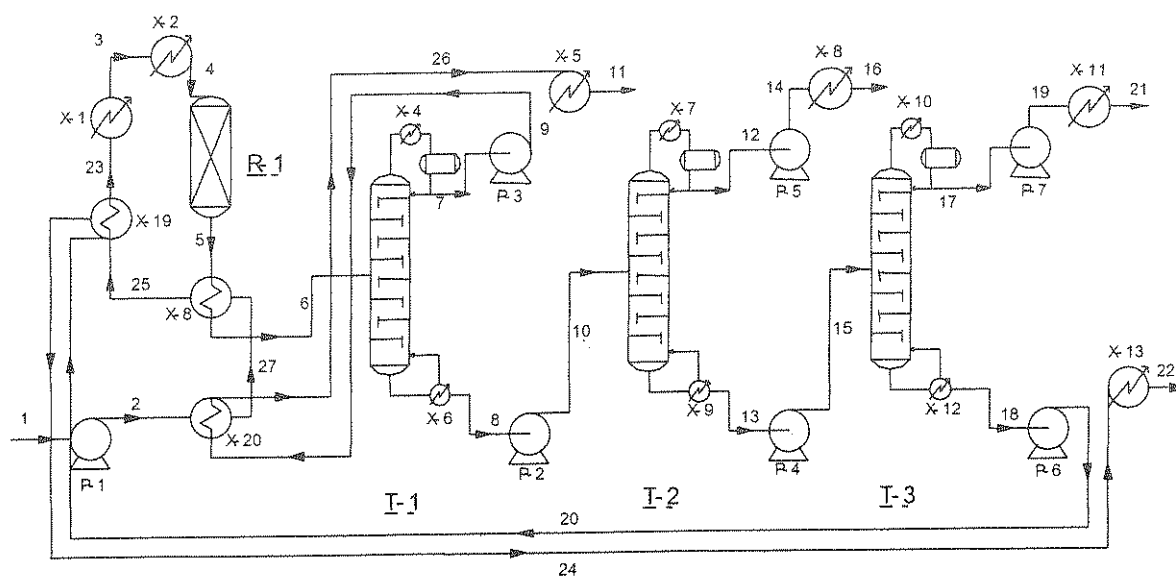


Figure 4 Process flow diagram for the aromatics plant after the addition of exchangers X-19 and X-20.

Table 2 Comparison between the utility consumption for the existing and proposed design

	Existing Consumption	Pinch Analysis	Energy Saving (%)
Q_{HMIN} (kW)	206.5	83.4	60%
Q_{CMIN} (kW)	640.8	514.7	20%

temperature, DT_{MIN} of 10°C . In all, only 2 additional process heat exchangers required for the existing plant (refer to Table 1 for the number of existing exchangers). Some repiping work is necessary to enable the new exchangers to be installed. Due to the need for a more flexible and a better control of the distillation column condenser and, hence, the product quality, we have excluded exchanger X-4 as a candidate for integration even though our exergy analysis shows X-4 to be the most promising candidate for heat recovery because of the highest exergy loss associated with it.

5.0 CONCLUSIONS

Exergy analysis studies performed on an aromatics plant allows us to assess the inefficiencies within the plants' existing network of heat exchangers. An exergy loss translates directly to wastage in primary fuel consumption. Based on the exergy analysis, an optimal grassroots design of heat exchanger network for the aromatics complex based on the systematic approach of Pinch Technology was produced and the potential improvement in the existing plant's performance was highlighted. The results show significant improvement in energy utilization from the existing plant performance leading to increased plant efficiency.

REFERENCES

- [1] Linnhoff, B., D. W. Townsend, D. Borland, G. F. Hewitt, B. E. A. Thomas, A. R. Guy, and R. H. Masland. 1982. *User Guide on Process Intergration for Efficient Use of Energy*. Rugby, England. Institution of Chemical Engineers.
- [2] Marshall, S. 1976. Aromatic Hydrocarbons Manufacture and Technology. *Chemical Technology Review*. No. 56.
- [3] Smith, R. and E. A. Petela. 1990. Minimization of Environmental Emissions Through Improved Process Integration. *Heat Recovery Systems and CHP*. 6(4): 329-339,.
- [4] Wall, G. 1998. *Exergetics, A Useful Concept*. Sweden: SE-431 44 Moldal.

NOTATION

A	Area [m ²]
C_p	Specific heat capacity [J/kg K]
E	Specific exergy [J/kg, Wh/kg] or exergy, availability or available work [J, Wh]
E/Q	Exergy factor [dimensionless, %]
m	Mass [kg]
P_{ex}	Exergy power [kW]
ΔP_{ex}	Exergy loss [kW]
Q	Specific heat [J/kg, Wh/kg] states used exergy [no unit or %]
T	Temperature [K] (0 K = -73.15°C)
T_0	Environment temperature [K] assumed to be 20°C or 293.15 K
T_{H1}	Hot stream inlet Temperature [K]
T_{H2}	Hot stream outlet temperature [K]
T_{C1}	Cold stream outlet temperature [K]
T_{C2}	Cold stream outlet temperature [K]
C_{PH}	Hot stream heat capacity [KW/kg.K]
CPW	Heat capacity for water in [KW/kg.K]
U_i	Overall heat transfer coefficient, gives the heat transfer rate per unit area of a substance, when the temperature difference is 1°C, i.e., 1 K [W/m ² K].
q_i	Temperature in degrees Celsius, see T
h_{ex}	Exergy efficiency [no unit, %]