Thermal integration and energy loss minimization in refineries and polymerization units

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Abstract. Energy efficiency is vital for the competitiveness and sustainability of the refining and petrochemical sectors. This report focuses on the application of Pinch analysis, a thermodynamics-based methodology initially developed in response to the oil shocks of the 1970s, to maximize heat recovery (HR) in heat exchanger networks (HENs). The method allows for the precise setting of targets for minimum hot utility (Qh_{min}) and cold utility (Qc_{min}) consumption, as well as for the capital cost of the HEN, before the design phase. The work highlights the concept of the Pinch Point as the thermal constraint that governs the entire network, separating the process into independent thermal zones. Applications are illustrated through references to case studies in Crude Distillation Units (CDU) and Hydrocracking units.

Key Words: Pinch analysis, thermal integration, heat exchanger networks, refinery, delta T_{min}, heat recovery.

Introduction. The continuous growth of global energy demand, combined with increasing economic and environmental pressures on the process industry, necessitates a thorough reassessment of how energy is utilized and managed in refineries and petrochemical units (Budae 2025). In this context, energy losses associated with heat transfer operations and suboptimal equipment configuration represent a significant potential for improvement (Papp 2025; Muntean 2025). This paper addresses the issue of thermal integration as a strategic instrument for reducing energy consumption and environmental impact, with a focus on systematic approaches that enable the identification of the true limits of energy performance at the early stages of process analysis.

Importance of energy minimization. The refining and petrochemical industries are recognized as being among the largest energy consumers globally (Linnhoff 1993). In the absence of thermal optimization, much of the energy from process streams is wasted, leading to high operational costs and significant CO_2 emissions (Yusoff et al 2021).

Fundamentals of Pinch Analysis. The Pinch methodology was introduced by Linnhoff & Flower (1978), marking a paradigm shift from heuristic to systematic, thermodynamics-based design. The basic principle is that the energy performance of a system is limited by a single constraint: the Pinch Point. This technique transcends the First Law of Thermodynamics and aligns with Exergy Analysis (Second Law), providing a methodical distinction between unavoidable and avoidable exergy losses (Townsend & Linnhoff 1983ab).

Objectives of the paper. The objective of this paper is to present the Pinch Analysis methodology as a rigorous framework for energy minimization in refinery and petrochemical processes, with emphasis on its thermodynamic foundations and practical applicability. The work aims to clarify the key analytical stages involved in Pinch Analysis, including the construction and interpretation of Composite Curves and the application of the Heat Cascade Method for setting minimum energy targets. In addition, the study discusses how Pinch design rules govern the synthesis of heat exchanger networks and ensure the achievement of these targets. Finally, selected case studies, particularly from crude distillation and hydrocracking units, are used to demonstrate the potential of Pinch-based retrofitting strategies to significantly reduce utility consumption and improve overall energy efficiency.

Context and sustainability. Regulatory pressure (e.g., the European Energy Efficiency Directive - EED) mandates energy audits. Reducing Qh_{min} and Qc_{min} directly decreases fossil fuel demand in furnaces, having a measurable impact on CO_2 emissions. Thus, Pinch Analysis becomes a critical tool for compliance and decarbonization strategy.

Methodology: Pinch Analysis Principles

Data extraction and Heat Capacity flow rate (CP) calculation. The methodology begins with defining each stream by T_{in}, T_{out}, mass flow rate (m), and specific heat capacity (c_p). The key parameter, called Heat Capacity Flow Rate (CP), is fundamental:

$$\mathbf{CP=m*c_p}\ [\frac{kW}{K}]$$

where CP_{hot} refers to streams that release heat, and CP_{cold} refers to streams that absorb heat. For a phase change (isothermal), CP is considered infinite, and the thermal load (latent heat) is included directly in the enthalpy section. However, methodologically, phase-change streams are treated as isothermal segments with fixed enthalpy load rather than explicit CP values. The process stream data required for the Pinch Analysis, including stream classification (hot and cold), inlet and outlet temperatures, heat capacity flow rates, and corresponding heat duties, are summarized in Table 1.

Table 1

Process stream data for Pinch analysis

Flow	Type	T_{in} (C)	T_{out} (C)	CP (kW/C)	Task (Q)(kW)
H1	Hot	200	80	10	1200
C1	Cold	20	150	8	1040
C2	Cold	50	180	5	650

Composite Curves (CC) and the cascade method. Stream data are aggregated to build Composite Curves (CC) on a T-H (Temperature vs. Enthalpy) plot. CC_{hot} represents the total heat supply, and the total demand. The cold curve is shifted up by $\Delta\ T_{min}$ to account for the minimum driving force requirement.

The horizontal overlap area represents the maximum possible internal Heat Recovery (HR) (Linnhoff & Turner 1981). The Cascade Method is a rigorous tabular method to determine the Pinch and targets. The point where the cascading heat flow reaches its minimum (or zero) is the Pinch Point.

The Grand Composite Curve (GCC) is an alternative graphical representation essential for visualizing the Pinch and utility selection. The bulb above the Pinch shows the heat required from hot utilities (Qh_{min}). The bulb below shows the surplus heat to be removed by cold utilities (Qc_{min}) (Linnhoff 1993).

The Pinch Point and thermal constraints

Concept of optimum ΔT_{min} (supertargeting). The Pinch Point is defined by the minimum temperature difference (ΔT_{min}). Selecting this value is a crucial economic trade-off called supertargeting (Sarafa et al 2019; Shenoy et al 1998):

*Small $\Delta T_{min} \Rightarrow Qh_{min}$ and Qc_{min} results in low utility consumption but large heat exchanger areas (A) ⇒ leading to high capital costs ($C_{CAPITAL}$) (Sarafa et al 2019; Abubakar 2020).
*Large $\Delta T_{min} \Rightarrow$ results in small A (low capital costs) but high Qh_{min} and $Qc_{min} \Rightarrow$ leading to high operational costs (C_{OP}) (Sarafa et al 2019; Ulyev et al 2022). The total annual cost is calculated as:

$$TAC(\Delta T_{min}) = C_{CAPITAL}(\Delta T_{min}) + C_{OP}(\Delta T_{min})$$

Thermodynamic role of the Pinch. The Pinch corresponds to the location of the minimum temperature driving force, which constrains further reduction of global irreversibilities (Townsend & Linnhoff 1983ab). It separates the process into two independent thermal domains: region above the Pinch: A net heat consumer requiring Q_h and region below the Pinch: A net heat supplier requiring Q_c.

Heat exchanger network (HEN) synthesis. The objective of HEN design is to achieve minimum utility targets. The synthesis starts at the Pinch Point and moves away from it, as the thermal constraints are most restrictive at this point. To ensure feasibility immediately above the Pinch, the heat capacity flow rate of the hot stream must be less than or equal to that of the cold stream $CP_{hot} \leq CP_{cold}$ (for single-stream matching at the pinch); otherwise, the streams would violate the ΔT_{min} constraint. In cases where the number of streams does not allow for direct matching, stream splitting is employed to satisfy both thermodynamic and heuristic design criteria.

In-depth Pinch rules. Pinch rules represent fundamental thermodynamic constraints in the synthesis of heat exchanger networks. Violation of these rules leads to the formation of heat load loops, which result in a simultaneous increase in both hot and cold utility requirements. Therefore, strict adherence to Pinch rules is essential to achieve the minimum energy targets established by Pinch Analysis. The fundamental Pinch rules and their thermodynamic consequences are summarized in Table 2.

Table 2

Fundamental Pinch rules and their thermodynamic consequences

Pinch rule	Region	Consequence
No heat transfer across the Pinch	Entire network	Equal increase in Q_h and Q_c.
Above the Pinch: Do not cool!	Above Pinch	Unnecessary cooling of a hot stream, requiring more Q_h.
Below the Pinch: Do not heat!	Below Pinch	Unnecessary heating of a cold stream, requiring more Q_c.

Illustrative Applications

Retrofitting and fouling in CDU. Crude oil Distillation Units (CDUs) contain pre-heaters that frequently suffer from fouling, reducing the heat transfer coefficient (U) and efficiency. The study by Yusoff et al (2021) demonstrates the effectiveness of Pinch Analysis for retrofitting by:

- performance diagnostics: comparing the actual consumption (Q_{real}) with the theoretical Qh_{min} to quantify the energy loss caused by fouling;
- identifying solutions: proposing reconfigurations, such as installing bypasses, to reduce the deposition rate in critical sections (Yusoff et al 2021).

Hydrocracking unit case. Mrayed et al (2021) applied Pinch to a hydrocracking unit, achieving a significant saving of 67.5 MW, representing a reduction of approximately 45% of the initial utility demand (148.6 MW). The optimization included adding new exchangers and increasing the surface area of existing exchangers.

Advanced applications: Distillation and TSA

Integration of distillation columns. Pinch principles help in the efficient thermal coupling of reboilers and condensers with the main process. A reboiler can be integrated with a hot process stream only if its temperature is above the process Pinch (Shahruddin et al 2020). Heat Engine Method - this allows coupling a column's reboiler with another's condenser, leading to energy savings of 1.5% to 36% (Shahruddin et al 2018).

Total Site Analysis (TSA). Total Site Analysis extends Pinch to the entire industrial site to optimize utility generation (steam, cooling water). The key tool is the Total Site Curve (TSC). TSA allows for optimizing steam levels (High Pressure Steam - HP, Medium Pressure Steam - MP, Low Pressure Steam - LP) and integrating Cogeneration (CHP) (Linnhoff 1993).

Discussions and Limitations

Advantages of the methodology. Pinch analysis has retained its strength due to:

- thermodynamic objectivity: provides energy targets based on thermodynamic principles;
- separation of design from operation: separates the economic decision of ΔT_{min} (supertargeting) from the complex task of network (topology) design;
- powerful visualization: composite curves and GCC provide an intuitive understanding of process constraints.

Limitations of standard Pinch Analysis. The classic Pinch method has limitations that require supplementation with optimization techniques:

- constant CP assumption: treating CP as constant can lead to errors in fluids with high property variations;
- ignoring pressure drops: does not directly include pumping costs (electricity) in the supertargeting phase. A design that reduces Qh_{min} can increase the electrical C_{OP};
- space and flexibility constraints: does not consider physical space constraints or flexibility when changing flow rates.

To overcome these limitations, Pinch integration is used with Mixed Integer Linear Programming (MILP)-based models, which can simultaneously optimize cost, number of units, and geometric constraints.

Conclusions and Recommendations. Pinch Analysis remains a fundamental and rigorous tool for thermal integration in refineries and chemical process units. The methodology provides a coherent framework for systematic optimization, achieving energy targets that surpass traditional methods.

Recommendations for future research:

- integration of Pinch optimization with mathematical programming (MILP) to address operational requirements, fouling, and flexibility;

- application of advanced Pinch methods, such as Total Site Analysis (TSA), to extend optimization beyond individual units to the entire industrial complex;
- development of Pinch methods that incorporate carbon costs directly into the supertargeting objective function, making ΔT_{min} a decision based on Capital, Energy, and CO_2.

Conflict of interests. Authors declare that there is no conflict of interest.

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