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Perspective

State-of-the-art and challenges of Pinch Analysis in energy systems

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Energy recovery and energy saving are critically important issues in industrial production. With the increasing scarcity of global energy resources and the heightened awareness of environmental protection importance, energy recovery and energy saving in industrial production have become significant factors driving the sustainable development of the industrial sector. Energy recovery technologies can reuse energy that might otherwise be wasted. For example, in industrial production, many processes generate large quantities of waste heat. By applying heat recovery technologies, this waste heat can be effectively recycled and utilised for heating or steam generation, improving energy utilisation efficiency.

Pinch Analysis, which emerged to tackle this problem systematically, was proposed by Bodo Linnhoff and his colleagues beginning in 1978 (Linnhoff and Flower, 1978) and growing in 1983 (Linnhoff and Hindmarsh, 1983) as an optimal design method for heat exchanger networks based on thermodynamic principles. This method introduced the concept of thermally feasible energy targets (referring to maximum heat recovery or minimum energy consumption) and these targets can be achieved by optimising heat recovery systems, energy supply methods, and process operating conditions.

Initially, Pinch Analysis was primarily applied to the synthesis and design of maximum recovery heat exchange systems in the petrochemical industry, guiding the optimisation of energy recovery and supply by identifying the Pinch Points and the thermodynamic limitations of the system. As new problems emerged and the method evolved, Pinch Analysis gradually developed into a chemical process integration methodology for heat exchange systems and energy distribution, energy planning under carbon emission constraints, and other fields.

Jiří J. Klemeš has been one of the pioneers and ardent promoter of this method. In the book he edited (Klemeš, 2022), it is shown how Pinch Analysis aids in optimisng Heat Exchanger Networks. The book thoroughly explains the applications of Pinch Analysis and its extended methods from the process to the Total Site level.

Pinch Analysis enables users to set corresponding energy targets based on various Process Integration scenarios and analyse the effectiveness of integration. It offers visualisation and insight into the problem and is easy to understand and utilise. Many have also expanded upon it, proposing improved methods such as Stream Temperature and Enthalpy Plot (Wan Alwi and Manan, 2010), Temperature Driving Force (Gadalla, 2015), Bridge Analysis (Bonhivers et al., 2014), Shifted Retrofit Thermodynamic Grid Diagram (SRTGD) (Yong et al., 2015) and its extended versions (Wang et al., 2021a) to achieve better energy matching and bottleneck

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Apart from the petrochemical industry, Pinch Analysis has also been widely applied in supply chain optimisation (Singhvi et al., 2004), carbon-constrained energy sector planning (Tan and Foo, 2007), energy distribution (Bandyopadhyay, 2011), environmental risk management (Wang et al., 2017), refinery hydrogen system (Alves and Towler, 2002), and other fields. For instance, in energy distribution under carbon emission constraints, Pinch Analysis is used to establish energy demand and supply synthesis curves and identify the Pinch point that achieves equilibrium between energy supply and demand. Carbon emission optimisation has attracted a lot of attention in academia to achieve carbon peaking and carbon neutrality goals. Carbon Emission Pinch Analysis (Tan and Foo, 2007) has produced many results, primarily to describe the relationship between energy demand and carbon emissions. Recently, there have been some new achievements in optimising food structure (Li et al., 2022), marine fuel structure (Hong et al., 2023) and carbon dioxide sequestration in coastal ecosystems (Yang et al., 2024).

However, like any tool or method, Pinch Analysis also has its limitations. The shortcomings of Pinch Analysis in solving large-scale problems can be discussed from the following perspectives.

Although Pinch Analysis can effectively analyse the data extraction from heat exchangers, including starting temperature, target temperature, and enthalpy changes, it may encounter challenges when dealing with large-scale data. One such challenge lies in visualisation. For large-scale problems, the Temperature-Enthalpy diagram becomes exceedingly complex, making it difficult to pinpoint the global optimal solution without the assistance of advanced algorithms. This highlights the need for further developments in the directions of problem decomposition, data/representation aggregation and hierarchical optimization.

Users may require more complex interaction methods and additional customisation options. If the available methods fail to meet these needs, user efficiency and experience could be reduced. Currently, the primary approach to addressing this issue involves seeking local optima and then using these results to find a global solution. Additionally, research focuses on developing methods that integrate Pinch Analysis with Mathematical Programming to identify optimal solutions for large-scale problems.

For example, Wang et al. (2020) developed a Mathematical Programming model for the structure of SRTGD and proposed a two-stage heuristic algorithm to solve the model. The results solved by the integrated method are better than those of the pure SRTGD method. Then, a novel iteration algorithm (Wang et al., 2021b) was developed to improve the solving efficiency. Chang et al. developed a serious work by proposing the concepts of minimal (Chang et al., 2020b) and non-minimal (Chang et al., 2020a) heat exchanger networks. Based on the proposed concepts, they developed smart and exhaustive enumeration algorithms to globally search for the optimal solutions of large-scale minimal and non-minimal heat exchanger network synthesis.

Later, Chang et al. (2021) studied non-isothermal mixing of large-scale minimal and non-minimal heat exchanger networks. They developed a global optimisation algorithm framework in which the Karush-Kuhn-Tucker (KKT) equations of a nonlinear programming (NLP) model were solved to find optimal solutions instead of solving the NLP model directly. As a result, their algorithm framework did not highly depend on nonlinear solvers. These works illustrate that Pinch Analysis and Mathematical Programming methods can be integrated together to search for high-quality solutions for large-scale heat exchanger network synthesis.

With the increasing adjustments in the energy sector, energy efficiency for reduction of demands and emissions have become primary goals. With its visualisation features, ease of analysis and display, and ability to conduct system-level planning under set objectives, Pinch Analysis holds tremendous potential to address these new challenges.

One aspect is the Cold Energy Integration of LNG. During the gasification process of LNG, the heat capacity also changes with the increase in temperature, resulting in a non-straight Temperature-Enthalpy line. One approach to tackle this issue is to simplify the heat capacity of LNG in different temperature zones. However, when it is crucial to consider this part of the heat capacity in detail, improvement methods should be developed.

Another issue concerns the application of CCUS (Carbon Capture, Utilisation, and Storage) in carbon emission analysis. In a traditional CEPA (Carbon Emission and Pinch Analysis) diagram, the lines representing different emission sources typically have positive slopes. However, when CCUS is integrated, negative slopes should be included in the CEPA diagram. In this scenario, optimising the system configuration to meet the carbon emission target requires careful consideration. The decision involves adjusting the emission sources or increasing the capacity of sinks.

Pinch Analysis also has the potential to be used in renewable energy system planning. By conducting a thermodynamic analysis of the input and output data of renewable energy systems (such as solar and wind energy), the system's minimum energy consumption or maximum energy recovery targets can be calculated under given conditions. By analysing and understanding the relationship between the heat load (kW) and temperature (°C) of energy flows and plotting a comprehensive curve of all hot and cold flows in the system, the energy utilisation efficiency of renewable energy systems can be enhanced. Based on the calculated energy targets and system characteristics, suitable energy supply methods, similar to the selection of heat utilities, can be chosen, such as energy storage systems and the integration of auxiliary energy sources (like natural gas and batteries).

By optimising energy supply strategies, the stable operation of renewable energy systems under different weather conditions and load demands can be ensured. Additionally, Pinch Analysis can be utilised to adjust and optimise process operating conditions in renewable energy systems, such as temperature, pressure, and flow rate, to improve system efficiency and energy utilisation. Thus, the use of Pinch Analysis in renewable energy system planning shows significant potential.

In the future, thinking about the following key issues is needed to further develop the Pinch Analysis method:

- Low-potential waste heat is available in huge quantities and is difficult to integrate. A method for efficiently recovering and integrating those waste heat streams is still pending.
- Pinch Analysis is based on Thermodynamics and, as such, must be used as a guidance tool and not an absolute optimisation tool. The only absolute results are the targets, which are upper or lower bounds to the related optimisation problems. Much light has to be shed on this topic to improve the understanding by students, lecturers, engineers and company managers.
- The process-level and site-level Pinch Analyses provide excellent integration recommendations for sites belonging to single companies. However, handling a multi-customer Total Site (Industrial Park) is hindered by, e.g., transactional and trust issues. This indicates the need to combine Pinch Analysis with trust-building tools (e.g., Blockchain) and transaction tools.

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Conflict of interest

The authors declare no competing interest.

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