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Simultaneous energy targeting, placement of utilities with flue gas, and design of heat recovery networks

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HIGHLIGHTS

- Simultaneous energy targeting, utility placement involving flue gas and HEN design.
- A graphical tool to design the utility flue gas-integrated HEN.
- Graphical guide for stream splitting in flue gas-integrated HEN design.
- Targeting the optimum utility flue gas temperature, FCp and performing heat allocation.

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ABSTRACT

Energy targeting and optimal utility placement are among the key steps in the cost-effective design of a process utility system. Composite Curves (CCs) and Grand Composite Curves (GCCs) are the popular Pinch Analysis tools for multiple utility targeting and placement. Although the CCs and GCCs can provide useful insights and yield acceptable utility targets, they could not be used to design a heat recovery network and to perform heat allocation involving the process and utility system. The Stream Temperature versus Enthalpy Plot (STEP) that was introduced in 2010 has the ability to overcome these limitations. Apart from giving the pinch points and energy targets, STEP can also graphically represent the maximum heat allocation (MHA) that can be converted into a maximum energy recovery (MER) network on a temperature versus enthalpy diagram. STEP has also been used for targeting closed-loop utilities having fixed supply and return temperatures that include steam, hot oil, refrigerants and cooling water circuits. However, the available STEP technique is unable to handle cases involving the “once-through” utility such as flue gas where the target temperature and flowrate needs to be simultaneously optimised in order to minimise fuel consumption. This paper presents a new approach to further extend STEP’s capability for the simultaneous energy targeting, optimal placement of process utility systems that include flue gas streams with variable-temperatures and flowrates, and design of heat recovery networks featuring such targeted utilities.

1. Introduction

There is typically large potential for energy savings from heat recovery from industrial processes. Hammond and Norman [1] have estimated that, between 15 and 23 PJ/yr of heat surpluses can potentially be recovered from industrial sites in the UK. Since the 1970s, Process Integration using Pinch Analysis has been an effective and reliable tool for the design of energy-efficient industrial processes. The technique has led to significant energy as well as capital-cost savings [2]. A popular Pinch Analysis graphical tool is the Composite Curves (CCs) which was introduced by Linnhoff et al. [3] to represent process streams on a Temperature versus Enthalpy (T–H) diagram. The hot (or cold) CCs are constructed from a composite of hot (or cold) streams that operate within a specified range of temperatures. The composite hot and cold streams can be horizontally moved to approach one another along the enthalpy (H) axis, until they are pinched to yield the maximum heat recovery potential and the minimum hot and cold utility requirements. Townsend and Linnhoff [4] introduced the Grand Composite Curve (GCC) for designing a multiple utility system. The GCC is a profile of the enthalpy difference between the shifted hot and cold CCs, plotted on a T–H diagram.

Various types of utilities of different qualities (temperatures) and quantities (enthalpy loads) can be drawn on the GCC. The point

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where the utility line touches the GCC is known as the "Utility Pinch". The temperature of the utilities can be constant (e.g. steam) or variable (e.g. cooling water, air preheat, boiler and furnace flue gas, and hot oil). The Balanced Composite Curves (BCCs) introduced by Townsend and Linnhoff [5] are utilised to locate a Utility Pinch when a utility level occurs in the range of temperatures of a heat recovery pocket. The BCC can clearly show the network design constraints, and is therefore useful in demonstrating the effects of multiple utilities and multiple Pinches on the temperature driving force of a HEN. The authors also proposed the Balanced Grid diagram for HEN design that includes multiple utilities.

Hall and Linnhoff [6] performed utility targeting for systems with variable-temperature utilities including air preheat and flue gas. The authors demonstrated the effect of varying the flowrate of air on flue gas targeting, and ultimately on fuel uptake. Various methods for flue gas targeting were presented, and their limitations highlighted. The GCC was preferred as the more precise graphical tool for utility flue gas targeting. However, it was also revealed that the combination of utility and process streams into one GCC might result in the loss of some vital information on the individual streams. The Utility Grand Composite Curves (UGCC) was the alternative introduced to provide a designer with better insights on the interface between a process and a utility system. The UGCC is a profile of the (negative) enthalpy difference between utility composites. Utility streams in the UGCC are represented as a single curve that is completely separated from the conventional GCC.

The heat recovery potential from flue gas streams in large-scale chemical process have been discussed by Novak Pintarič and Glavič [7]. The authors used a combination Pinch Analysis and Mixed Integer Non-Linear Programming (MINLP) to design an optimal heat exchanger network that resulted in significant savings of 47%. Xu et al. [8] analysed the potential of recovering exhaust flue gas from coal plant utility boilers. The thermal energy of boiler's exhaust accounts for approximately 3–8% of the total energy of fuel input.

Marechal and Kalitventzeff [9] proposed another graphical tool called the integrated CCs to assess utility systems integration. They divided utilities into primary and secondary utilities. Primary utilities include water, fuels and air whereas secondary utilities include energy transformation and transfer media such as steam and refrigerant. The authors proposed an optimal utility system design by combining the Pinch Analysis and mathematical techniques. Their aim was to fulfil the process energy demand at the minimum cost using the "AGE" (Analysis, Generate, and Evaluate) 3-step approach. Pinch Analysis was used in the analysis step to determine the minimum energy targets. The optimum utility flowrates were calculated using the Mixed Integer Linear Programming (MILP) approach. The graphical tool proposed in their paper was used to analyse the integration of utilities with process streams.

Lakshmanan and Fraga [10] explains the limitations of Pinch Technology as well as the Problem Table Algorithm (PTA). They addressed the case involving a discontinuous composite line where there is no process stream within a temperature interval. In this case, the Problem Table Algorithm could not represent the gap in the CCs. They also demonstrate cases involving CCs that do not obey the Pinch rules. The authors identified the "critical point" where $\Delta T_{\min}$ reduction will not affect energy recovery.

Shenoy et al. [11] introduced the Cheapest Utility Principle (CUP) as an extension of the supertargeting approach for HEN multiple utility targeting. The key idea is to increase the total utility consumption while the amount of expensive utilities remain constant. The capital and utility costs were considered simultaneously. In targeting the minimum overall cost of heat exchanger networks, Hall et al. [12] considered both the capital and energy costs during the utility selection and optimisation. However, their method to determine the global optimum $\Delta T_{\min}$ may not necessarily result in an acceptable target. Since their Total Annual Cost (TAC) curves were almost flat near the optimum $\Delta T_{\min}$, it would be more beneficial to use a range of the optimum $\Delta T_{\min}$ instead of a single optimum $\Delta T_{\min}$. The method also enabled the small utility units to be eliminated by accepting a small TAC penalty in some cases. The authors also introduced a graphical plot known as the optimum load distribution (OLD) to identify the optimum utility load in the range of the optimum $\Delta T_{\min}$.

Jezowski and Jezowska [13] introduced a graphical approach for estimating the minimum cost at the minimum flowrate of non-point utilities that include flue gas, hot oil and cooling water. Note that the prices of utilities are dependent on their temperatures. Hot utilities at higher temperatures are typically more costly than those at lower temperatures. On the contrary, cold utilities at lower temperatures are more costly than those at higher temperatures. The work provided new insights on controlling the utilities' outlet temperatures in order to minimise utility flowrates during heat recovery. The utility limitation profile (ULP) from the GCC can be used to determine the magnitude of energy penalty levied when the utility flowrate is beyond the minimum. The GCC also shows the outlet temperature, the quantity of energy loss as well as the utility flow rate limitations.

An alternative to GCC is the Problem Table Algorithm (PTA) introduced by Linnhoff and Flower [14]. Castier [15] extended the Problem Table Algorithm (PTA) by presenting some new rules for utility targeting. The author used an algorithmic method to determine the minimum hot and cold utility requirements at a given interval temperature. The method emphasises on the appropriate utility placement to reduce the utility cost.

Salama [16] proposed the enthalpy flowrate technique for constructing the CCs of a heat exchanger network by using streams' cumulative enthalpy flowrate as an independent variable. The technique enables the construction of the Complement Grand Composite Curves (CGCC) introduced by the author. The CGCC was shown to be useful for (a) representing the profile of temperature difference between CCs, (b) estimating the heat exchanger (HEX) area, and (c) facilitating HEX area estimation in multiple–utility targeting. The cumulative enthalpy flowrate and temperature technique presented the GCC and CGCC in a single graph and provided vital information about the CCs to assist designers during the HEN targeting and design stages.

Costa and Queiroz [17] further extended the Problem Table Algorithm for multiple utility targeting as an alternative to the GCC. Their method is capable of identifying the possible temperature ranges of the utilities, and includes sub-tables of cascaded heat inputs and outputs. Some algorithms were introduced to determine the multiple utility targets. Liew et al. [18] proposed an algebraic method known as the Multiple Utility Problem Table Algorithm (MU-PTA). The method is capable of identifying heat recovery pockets, and of targeting the exact amount of utility needed within a given utility temperature interval. Liew et al. [19] has successfully applied the method to solve a Total Site Heat Integration retrofit problems.

Wan Alwi and Manan [20] introduced a graphical tool for simultaneous targeting and design of heat exchanger networks known as the Stream Temperature versus Enthalpy Plot (STEP). STEPs are continuous profiles of individual hot and cold streams on a shifted temperature versus enthalpy diagram. In addition to giving the pinch points and energy targets, STEPs show the maximum heat allocation (MHA) that can be graphically converted into a maximum energy recovery (MER) network, and represented on a Heat Allocation and Targeting (HEAT) diagram in terms of STEP temperature and enthalpy. STEP was shown to overcome the limitations of CCs and the Pinch Design Method (PDM). The HEAT diagram was