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An algorithm for optimal waste heat recovery from chemical processes

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ABSTRACT

We describe a computer algorithm designed to calculate the optimal energy extraction in the form of heat used for steam raising from chemical processes. The concepts are illustrated using chemical plant stream data in a process with multiple distillation columns. Pinch analysis is first applied to find the grand composite curve (GCC) of the problem, which is then used by the algorithm to determine the maximum mass flow rate of steam that can be produced from process waste heat. An analysis of the effects of the minimum temperature of approach ΔT_{min} on the optimal steam raising result is also conducted, and it is found that, in general, a higher ΔT_{min} will reduce the percentage heat recovery from the process.

1. Introduction

Large-scale chemical processes require significant energy inputs to operate effectively. Reduction of these inputs, or recovery of waste heat, can therefore yield significant economic and environmental advantages. One way of improving the energy efficiency of a process is *pinch analysis* (Kemp, 2007), which involves the transfer of internal heat between process streams to reduce external heat requirements. Introduced by Hohmann (1971) and furthered in the work of Umeda et al. (1979), Linnhoff et al. (1983) and others (Linnhoff et al., 1982; Linnhoff and Hindmarsh, 1983; Kemp and Deakin, 1989; Ahmad and Linnhoff, 1989; Shenoy, 1995; Kemp, 1991; Smith, 2005), this approach allows the determination of the minimum external energy required to run a process. Inputs required for this approach include initial temperatures, final temperatures, flow rates and specific heat (*CP*) values of process streams. The pinch method has been used to successfully identify process inefficiencies and retrofit plants into more cost-effective and energy-efficient designs, including in industrial milk-powder production (Walmsley et al., 2013) and ethanol distillation (Gu et al., 2006). It forms part of the modern process design toolbox, as a complement, for example, to design approaches, like residue map analysis, for optimizing separation trains in flowsheets (Biegler et al., 1997).

Pinch analysis does not remove the need for external heating and cooling and, in general, waste heat at lower temperatures has to be rejected by the process. This introduces the possibility of waste heat recovery which has significant energy efficiency implications. If the waste heat is low-grade, it is difficult to recover and requires the use of complex heat transfer methods such as the organic Rankine cycle (Law et al., 2013; Little and Garimella, 2011). However, if high-grade heat is available within the process, it can potentially be extracted in the form of steam. In this paper, the maximum amount of steam that can be recovered from a pinch analysis-optimized process is calculated using a novel algorithm which shows that the optimal pathway for energy recovery involves countercurrent heat removal below the process pinch. Concerns related to the detailed design of heat exchangers and boilers used to produce steam are not addressed – the final heat exchanger network is not analyzed given that significant research has gone into such topics (Aegerter, 2005). Instead, our goal is to provide a method for calculating the optimum heat recovery which can then be used as a starting point for the detailed design of the particular heat exchanger network.

The optimization result from pinch analysis requires that only coolers are added below the pinch temperature. Since steam raising requires removing heat from the process, it becomes in the language of pinch technology analogous to placing a cooler below the

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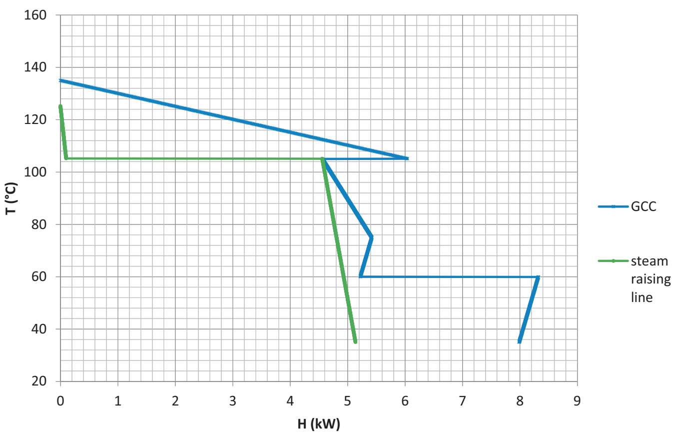

Fig. 1. Example of GCC and steam raising line. 1: (H_{start}, T_{start}); 2: (T_{gccmin}); 3: (H_{wsat}, T_{sat}); 4: (H_{ssat}, T_{sat}); 5: (0, T_{final}).

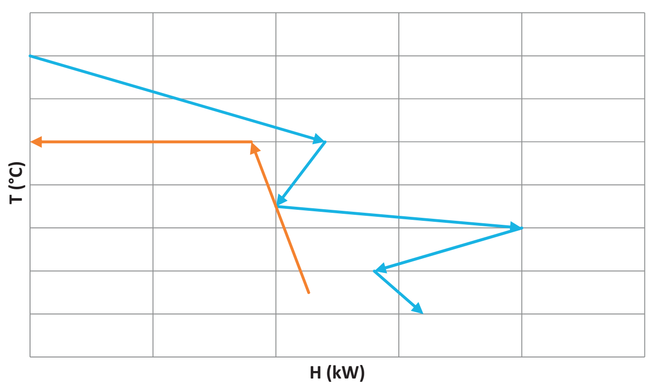

Fig. 2. Countercurrent pathway.

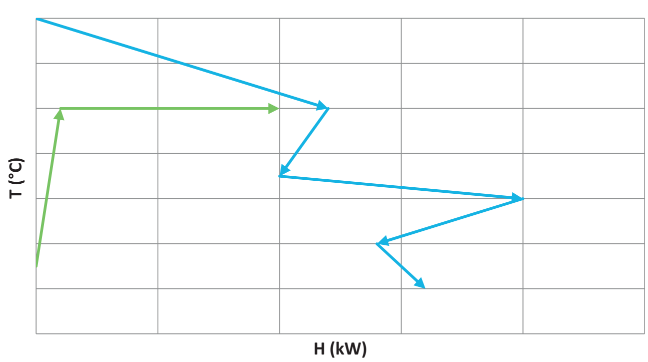

Fig. 3. Concurrent pathway.

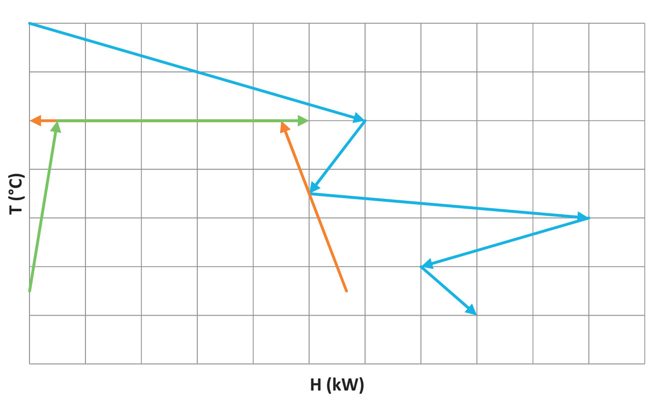

Fig. 4. Case I.

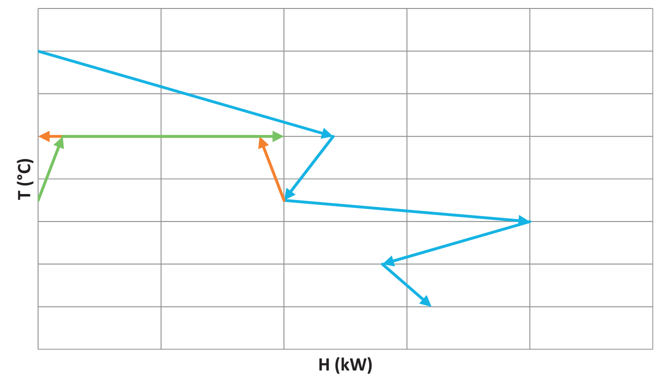

Fig. 5. Case II.

pinch. This is always possible to do without affecting the original pinch point. Herein, a novel algorithm is reported to calculate the maximum possible mass flow rate of steam at a given temperature and pressure that can be recovered from the process under these conditions.

Using this approach process engineers will be able to optimize the conditions for recovering waste energy from processes which also has a salutary environmental effect in that it reduces emissions generated by conventional power generation plants for the process use. The algorithm is designed to analyze complex processes including multiple streams, and steam generation at varied pressures and temperatures conditions

2. Methodology and corresponding algorithm

2.1. Summary of approach

A water mass balance shows that for the extraction of the maximum amount of heat in the form of steam the mass flow rate of water at all three heating stages (sensible, latent and superheating) must be the same. The algorithm we propose calculates a solution that fulfills this condition and the solution is checked to ensure that it does not create a new pinch.

2.2. Mathematical derivation

At each temperature level on the grand composite curve below the pinch, there is a maximum amount of energy that can be extracted while maintaining the optimal minimum energy requirement (MER) result. In order to use the maximum amount of energy without changing the pinch, it must be determined whether or not the steam raising lines intersect with any segment of the Grand Composite Curve (GCC) below the pinch. Any crossing of the GCC would violate the pinch temperature condition which is not allowed. All the variables used in the following analysis are shown in the schematic in Fig. 1.

In order to determine if the GCC and steam raising lines cross, the equations representing them need to be derived first. The straight line segments on the GCC can be represented using the following equation:

$$\frac{T - T_1}{H - H_1} = \frac{T_2 - T_1}{H_2 - H_1} \tag{1}$$

where (H_1, T_1) and (H_2, T_2) stand for the starting and ending point of any GCC line segments. The slope of the line segments along the GCC (in temperature-enthalpy, T–H coordinates) is given by

$$\frac{1}{C_{pw} \times M_w} = \text{Absolute value} \quad (\text{slope}) \tag{2}$$