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Sub-ambient heat exchanger network design including compressors

Chao Fu*, Truls Gundersen

Department of Energy and Process Engineering, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway

HIGHLIGHTS

- The integration of heat and work is studied.
- Compressors are integrated with sub-ambient heat exchanger networks.
- Pinch Compression is proven to be preferred.
- The exergy consumption is minimized.

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ABSTRACT

Heat can be converted into work and vice versa, and this fact provides opportunities for the integration between them. This paper presents a systematic methodology for the integration of compressors into heat exchanger networks below ambient temperature. The objective is to minimize exergy consumption. Four theorems are proposed and used as the basis for the design methodology. Pinch Compression, i.e., compression starts at pinch temperature, is proven to be preferred under certain conditions. It is concluded that minimum exergy consumption can be achieved when compression starts at pinch temperatures, ambient temperature or the cold utility temperature.

1. Introduction

The synthesis of heat exchanger networks (HENs) is a central part of heat recovery problems. One of the well-established methodologies for HEN synthesis is Pinch Analysis (PA) (Linnhoff and Hindmarsh, 1983). The minimum utility consumption is established as a target using PA in an early stage of process design. For a given set of hot and cold streams (heat capacity flowrates, supply and target temperatures are fixed), the pinch temperatures are established by the minimum temperature difference (ΔT_{min}) for heat transfer. Both hot and cold utilities increase if any heat is transferred across the pinch. The Grand Composite Curve (GCC) is developed for targeting and selection of utilities. PA has achieved a notable success for above ambient process design. In sub-ambient processes, both heat and work (for producing refrigeration energy) are involved. However, traditional PA only sets targets for heat loads and was thus less used below ambient (Linnhoff and Dhole, 1992). Using the Carnot factor instead of temperature as ordinate, the GCC was transformed into the Exergy Grand Composite Curve (EGCC) (Dhole and Linnhoff, 1994; Linnhoff and Dhole, 1992), which was used for shaftwork targeting in sub-ambient processes. An exergetic efficiency factor was used to convert the exergy content of heat into shaftwork.

This study focuses on the integration of both heat and work. The following two observations in sub-ambient processes provide basic insights for the study: (i) compression consumes less work at lower temperatures but refrigeration is required to achieve the low temperature; and (ii) expansion produces more work at higher temperatures but less refrigeration is produced at lower temperatures. There is thus a trade-off between cold utility consumption and work consumption/production when pressure changing equipment such as compressors/expanders are included below ambient. One application example for the integration of heat and work is the utilization of compression heat for preheating the boiler feedwater in steam cycles (Fu and Gundersen, 2013a). Another example is the self-heat recuperation technology (Kansha et al., 2010) where heat is upgraded by compression, i.e., the temperature of heat is lifted. A challenging question related to the integration of heat and work is: at what temperatures should compression and expansion start? This question is related to the concept of Appropriate Placement (also referred to as Correct Integration) and the plus/minus

* Corresponding author. Tel.: +47 73592799; fax: +47 73593580.
E-mail addresses: chao.fu@ntnu.no, fuchao83@hotmail.com (C. Fu).

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principle (Linnhoff and Parker, 1984; Linnhoff and Vredeveld, 1984) in HEN design.

Aspelund et al. (2007) formulated the following two heuristic rules: (i) compression adds heat to the system and should preferably be done above pinch, and (ii) expansion provides cooling to the system and should preferably be done below pinch. The rules were stated more specifically by Gundersen et al. (2009): both compression and expansion should start at the pinch temperature. Following the rules, a recuperative vapor recompression cryogenic air distillation scheme was developed by Fu and Gundersen (2013b). The Extended Pinch Analysis and Design (ExPAnD) methodology developed by Aspelund et al. (2007) presents 10 heuristic rules for the integration of compressors and expanders into HENs. On the basis of the ExPAnD methodology, Wechsung et al. (2011) presented an MINLP optimization formulation for the synthesis of sub-ambient HENs including compression and expansion. The work was further extended by Onishi et al. (2014) using a superstructure with the objective of minimizing total annualized cost.

Rather than using mathematical optimization methodologies presented by Wechsung et al. (2011) and Onishi et al. (2014), this paper, with a focus on the integration of compressors into HENs below ambient temperature, presents a straightforward graphical methodology for HEN design including compressors. Since both heat and work are involved, the objective is to minimize exergy consumption. A set of theorems are proposed and proven to assist the design.

2. Theorems

The design methodology is developed based on four theorems that are introduced in this section. The following assumptions are made for the proof of Theorems 1–4: (1) supply and target states (temperature and pressure) for process streams and utilities for heating and cooling are given; (2) only one stream is compressed and only one cold utility (one temperature level) is used; (3) the compressor polytropic efficiency is constant, (4) the gas to be compressed is ideal gas with a constant specific heat ratio $\kappa \equiv c_p/c_v$, and (5) the exergy content of hot utility is negligible (assumed to be near ambient conditions).

2.1. Theorem 1

Theorem 1. *For sub-ambient processes, a HEN design with Pinch Compression (compression starts at the pinch temperature) consumes the smallest amount of exergy if the following conditions are satisfied: (1) the outlet temperature of compression at cold utility temperature is lower than ambient temperature, and (2) Pinch Compression does not produce more heat than required, i.e., the original pinch point is not removed.*

2.1.1. Proof of Theorem 1

Proof of Theorem 1. A cold stream is assumed to be compressed from p_s to p_t. In the case of a hot stream being compressed, a similar proof can be established. The composite curves (CCs) for the streams without including pressure manipulation (Case O) are shown in Fig. 1(a). The heating and cooling demands are $Q_{HU,0}$ and $Q_{CU,0}$ respectively. The pinch temperature is T_{PI} for the cold streams. For compression above pinch, less work is consumed when the operating temperature is lower. Pinch Compression thus consumes the smallest amount of exergy if the original pinch point is not removed, i.e., the cooling demand does not increase. Comparison is then performed between Pinch Compression and compression below pinch. The following cases are compared: Case A – compression starts a temperature below pinch T_A ($T_{CU} \le T_A < T_{PI}$); Case B – Pinch Compression is used, $T_B = T_{PI}$.

For Case A, the work is $W_A = mc_p(T_{comp,\ A} - T_A) = mc_pT_A\ [(p_t/p_s)^{(n_c-1)/n_c} - 1]$, where $(n_c-1)/n_c = (\kappa-1)/(\kappa\eta_{\infty,comp})$, $\eta_{\infty,comp}$ is compressor polytropic efficiency, mc_p is the heat capacity flowrate of the stream being compressed, and $T_{comp,A}$ is the outlet temperature of compression at T_A. Since compression of the cold stream increases its temperature and enthalpy, the total cooling demand increases, $Q_{CU,A} = Q_{CU,0} + xW_A$ where x is the fraction compressed below pinch, $0 < x \le 1$. Although the compression process (pressure ratio) is not really split, the fraction compressed below pinch is referring to the temperature increase from T_A to T_{PI} and the fraction above pinch is referring to the temperature increase from T_{PI} to $T_{comp,A}$. When $T_{comp,A} \le T_{PI}$, i.e., the entire compression of the stream is performed below pinch, $x = 1$. The cooling provided by the cold stream is reduced since its enthalpy is increased by W_A, and the cooling demand is thus increased by the same amount (W_A). When $T_{comp,A} > T_{PI}$, the compression of the stream operates across the pinch. This case is shown in Fig. 1(b). The dashed curves represent the original CC without compression (Case O) and the solid curves represent the CC for Case A. The compression above pinch (from T_{PI} to $T_{comp,A}$) does not affect the cooling demand (cold utility) demand, but it reduces the heating demand (hot utility) due to the introduction of compression heat from T_{PI} to $T_{comp,A}$. The compression below pinch (from T_A to T_{PI}), however, increases the cooling demand by $mc_p(T_{PI} - T_A)$, which is written as xW_A where $0 < x = mc_p(T_{PI} - T_A)/mc_p(T_{comp,A} - T_A) < 1$. The corresponding cold CC in the temperature range from T_A to $T_{comp,A}$ has smaller heat capacity flowrate compared to Case O, as shown in Fig. 1(b). The exergy content ($E_{Q_{CU}}$) of a given cooling duty (Q_{CU}) at T_{CU} (sub-ambient) is derived by $E_{Q_{CU}} = Q_{CU}(T_0/T_{CU} - 1)$. The exergy content of a given amount of work is equivalent to the work. The total

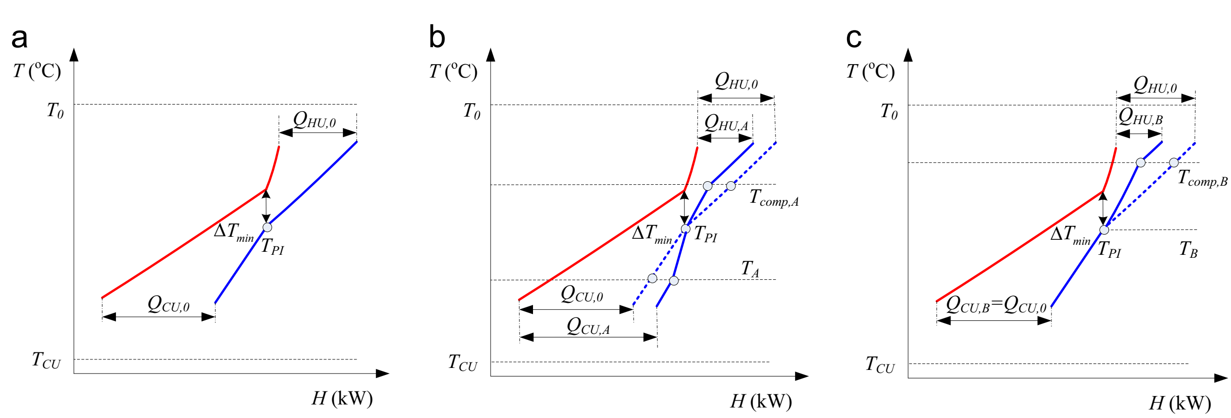

Fig. 1. CCs for Theorem 1: (a) Case O, (b) Case A, (c) Case B.