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Sub-ambient heat exchanger network design including expanders

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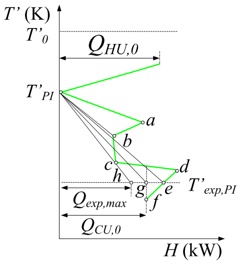
HIGHLIGHTS

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

GRAPHICAL ABSTRACT



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ABSTRACT

This paper presents a study on the integration of heat and work. A systematic design methodology for the integration of expanders into sub-ambient heat exchanger networks is developed. The objective is to minimize exergy consumption (or maximize exergy production). Four theorems are proposed and used as the basis of the design methodology. Pinch Expansion, i.e. expansion starts at pinch temperatures, is proven to be a preferred scheme under certain well-defined conditions. Stream splitting is used to maximize the use of Pinch Expansion. An important conclusion is that minimum exergy consumption (or maximum exergy production) can be achieved when expansion starts at pinch temperatures or ambient temperature.

1. Introduction

Heat recovery is a common way to increase energy efficiency in process plants. Pinch Analysis (PA) is a well-established methodology for the synthesis of heat exchanger networks (HENs) (Linnhoff and Hindmarsh, 1983). For a given set of hot and cold streams, the pinch temperatures are fixed by the minimum temperature difference ($\Delta T_{\min}$) for heat transfer. Both hot and cold utilities increase if any heat is transferred across the pinch. A distinguished advantage of PA is that the target for minimum utility consumption can be established in an early stage of process design. The Grand Composite Curve (GCC) is developed for targeting and selection of utilities. However, PA is less frequently applied in sub-ambient processes since work (not only heat) is involved for the production of refrigeration and traditional PA only sets heat load targets (Linnhoff and Dhole, 1992). Using the Carnot factor instead of temperature as the ordinate, the GCC was transformed into the Exergy Grand Composite Curve (EGCC) (Dhole and Linnhoff, 1994; Linnhoff and Dhole, 1992). The EGCC was used for targeting shaftwork in sub-ambient processes by converting the heat target into an exergy target. The exergy target was then converted into a shaftwork target using an exergetic efficiency.

This study investigates the integration of heat and work. The starting point is based on the following two observations for sub-ambient processes: (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

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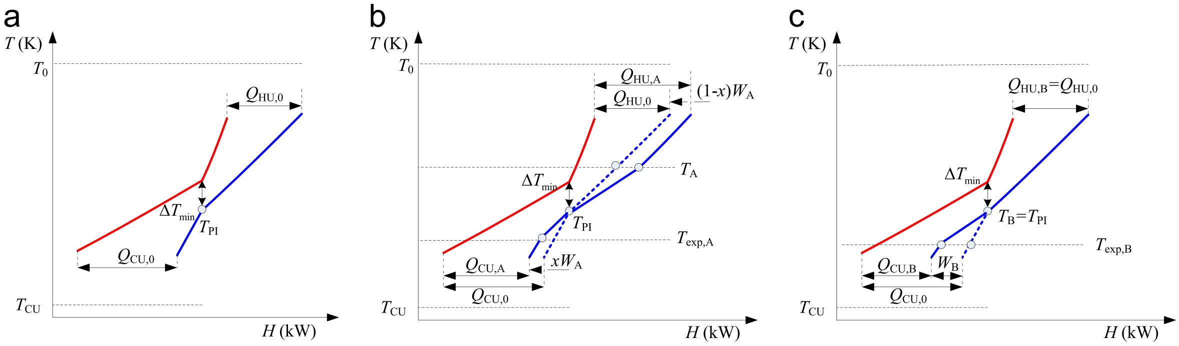

Fig. 1. CCs for Theorem 1: (a) Case O, (b) Case A, (c) Case B.

work consumption/production when pressure changing equipment such as compressors and expanders are included. An application example illustrating 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) that uses compression to upgrade heat (the temperature of heat is increased). A key 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 principle (Linnhoff and Parker, 1984; Linnhoff and Vredeveld, 1984).

Based on the observations on the enthalpy change of streams with compression and expansion, 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. An application example is the recuperative vapor recompression air distillation processes developed by Fu and Gundersen (2013b). On the basis of 10 heuristic rules, an Extended Pinch Analysis and Design (ExPAnD) methodology was developed by Aspelund et al. (2007) 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 is 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 expanders into HENs below ambient temperature, presents a straightforward graphical methodology for HEN design including expanders. The design methodology is based on four theorems that are developed in Section 2. Since both heat and work are involved, the chosen objective is to minimize exergy consumption (or maximize exergy production). Here, exergy consumption or production is the sum of the exergy of utilities (heating, cooling and work). The exergy content (E) of a given amount of heat (Q) at sub-ambient temperature T is determined to be $E = Q(T_0/T - 1)$ where T_0 is ambient temperature. When the work resulting from expansion is more than the exergy content of hot and cold utilities, the exergy consumption is negative, i.e., exergy is produced.

The paper will also demonstrate that previously established insight about appropriate placement of expanders is too simplistic and does not take into account the fact that the Composite and Grand Composite Curves will change when expanders are integrated with heat exchanger networks. Pinch Expansion is often the preferred choice, but there are cases where it should be limited and even avoided.

2. Theorems

The following assumptions are made: (1) supply and target states (temperature and pressure) for process streams and utilities for heating and cooling are given; (2) only one stream is expanded and only one cold utility (one temperature level) is used; (3) the expander polytropic efficiency is constant, (4) the fluid to be expanded is an ideal gas with a constant specific heat ratio $\kappa \equiv c_p/c_v$, and (5) the exergy content of hot utility (near ambient temperature) is negligible. The following two terms are defined: (1) Pinch Expansion – expansion starts at the pinch temperature, and (2) Ambient Expansion – expansion starts at ambient temperature.

2.1. *Theorem 1*

For sub-ambient processes, a HEN design with Pinch Expansion consumes the smallest amount of exergy if the following conditions are satisfied: (1) the outlet temperature of Ambient Expansion is higher than cold utility temperature, and (2) the work produced from Pinch Expansion is completely converted into savings in cold utility, i.e. Pinch Expansion does not introduce a new pinch point.

2.1.1. *Proof of Theorem 1*

A cold stream is assumed to be expanded from p_s to p_t. In the case that a hot stream is expanded, a similar proof can be established. The composite curves (CCs) for a HEN without including pressure manipulation (Case O) are shown in Fig. 1(a). The cooling demand is $Q_{CU,0}$ and the pinch temperature is T_{PI} for the cold streams. The work resulting from expansion at a temperature T is determined to be $W = mc_pT[1 - (p_t/p_s)^{(n_e-1)/n_e}]$(Saravanamuttoo et al., 2009), where $mc_p$is the heat capacity flowrate, $(n_e - 1)/n_e = \eta_{\infty,\text{exp}}$ $(\kappa - 1)/\kappa$, and $\eta_{\infty,exp}$ is the expander polytropic efficiency. For expansion below pinch, more work and cooling are produced when the expansion starts at a higher temperature. The highest temperature where the expansion should start is the pinch temperature. Pinch Expansion is thus more favorable if no new pinch is created, i.e. the expansion work is completely converted into savings in cold utility. For expansion above pinch, two cases are compared: Case A – expansion starts above pinch temperature, $T_A > T_{PI}$; Case B – Pinch Expansion is used and thus, $T_B = T_{PI}$.

For Case B, the work produced is $W_B = mc_p(T_B - T_{exp,B}) = mc_pT_{PI}[1 - (p_t/p_s)^{(n_e-1)/n_e}]$. Since the cold stream temperature is reduced from T_B to $T_{exp,B}$ after expansion, the cooling demand is reduced by an amount equal to the work produced by expansion, unless new pinch points are created. The cooling demand is $Q_{CU,B} = Q_{CU,0} - W_B$. The hot utility demand does not change by the expansion. The CCs for Case B (solid lines) are shown in Fig. 1(c).