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Integrating Compressors into Heat Exchanger Networks Above Ambient Temperature

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Heat from compression processes is normally wasted to cooling water due to its low temperature or concerns about operability. The recoverable amount of heat can be enhanced by increasing the operating temperature of compressors. However, the compression work also increases under this condition. The integration of compressors into heat exchanger networks (HENs) is complex since both heat and work are involved, and the role of streams (as hot or cold streams), the utility demand, and the location of pinch points may change. A systematic graphical design procedure for above ambient HEN design including compressors was presented. The objective is to minimize exergy consumption to balance the complex heat-work trade-offs involved. Four theorems are proposed as the basis of the design procedure with certain well-defined assumptions. It is found that the compression should be performed at pinch or ambient temperatures to achieve minimum exergy consumption. *AIChE J*, 61: 3770–3785, 2015
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Introduction

Pinch Analysis has been a well-known methodology for heat exchanger network (HEN) synthesis since the 1970s.[1–4] The pinch points are defined by the minimum temperature difference ($\Delta T_{\min}$) for heat transfer. The minimum consumption of hot and cold utilities is then established. Any heat transfer across the pinch increases utility consumption.[4] The concept of Appropriate Placement[5] is fundamental in Pinch Analysis and addresses how different pieces of equipment can be integrated with heat recovery processes to ensure it results in energy savings, also referred to as Correct Integration.[2,6] This concept is also closely linked to the so-called Plus/Minus principle[2,6] that is used to suggest process modifications that can improve the level of heat recovery. According to the Plus/Minus principle, one should try to increase the amount of heat provided by the hot streams (+) or decrease the amount of heat required by cold streams (−) in the above pinch region, and increase the amount of heat required by cold streams (+) or decrease the amount of heat provided by hot streams (−) in the below pinch region. The amount of heat that can be correctly integrated is calculated based on the Grand Composite Curve (GCC). The analysis on Appropriate Placement has been performed for reactors,[7] distillation columns,[8] evaporators,[9] heat pumps, and heat engines.[5] The integration of compressors and expanders is considerably more complicated due to the following reasons[10–16]: (1) both heat and work are involved, (2) the role of a stream (as hot or cold) may change with pressure manipulations, (3) the streams to be compressed or expanded are included in the HEN, thus, the heating and cooling demands for the streams are changing, and (4) the locations of pinch points may move as a result of the shape change of the GCC by including pressure manipulations of a stream. Heat pumps are used to upgrade low-temperature heat to higher temperatures at the expense of work consumed, thus, both heat and work are involved in heat pump design. However, the concept of Appropriate Placement of heat pumps[5] is mainly focused on evaporation and condensation processes, and is less related to compression and expansion.

The placement of compressors and expanders is defined by the inlet temperature of these units. The topic of operation of compressors was briefly discussed by Glavič and coworkers[7,17] with focus on reactor systems. Aspelund et al.[10] proposed the following heuristic rules for the appropriate placement of compressors and expanders:

- Compression adds heat to the system and should preferably be done above pinch.
- Expansion provides cooling to the system and should preferably be done below pinch.

Gundersen et al.[12] further clarified that both compression and expansion should start at the pinch temperature. As will be discussed in this article (Theorems 2–4), the heuristic rules[10,12] are not always correct and certain conditions should, thus, be defined. Fu and Gundersen[18] have developed a recuperative vapor recompression distillation scheme based on the new insight that compression and expansion should start at the pinch temperature. A single column is used instead of the traditional double-column for air distillation. An Extended Pinch Analysis and Design (ExPAnD) methodology was developed

Additional Supporting Information may be found in the online version of this article.

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by Aspelund et al.[10] that included a set of heuristic rules. A distinguished feature of this methodology is that pressure manipulations (compression and/or expansion) of streams are included in the problem statement for HEN design.

Following the ExPAnD methodology, Wechsung et al.[16] presented an mixed integer nonlinear programming (MINLP) optimization formulation for the synthesis of subambient HENs including compression and expansion with the objective of minimizing process irreversibilities. Stream pressures were included as variables in the heat integration problem, however, the pressure manipulations were based on the heuristic rules[10,12] which may not apply in some cases (as will be discussed in this article). In addition, the models did not include stream splitting that may result in significant energy savings. The topic was further investigated by Onishi et al.[13] using a superstructure with the objective of minimizing total annualized cost. The recovery of heat from air compression processes for boiler feedwater preheating was investigated by Fu and Gundersen[19] using Pinch Analysis. The topic was further studied by Fu et al.[20] using an MINLP model to optimize the pressure ratios of the compression stages.

In contrast to HENs, work exchange networks focus on the matching of compression and expansion so that pressure manipulations can be performed directly, for example, compressors and expanders can be located on a single shaft.[21] This topic was investigated by Razib et al.[21] using an MINLP model. The operating temperatures of compressors and expanders are included as variables and manipulated by utility exchangers. However, the heat exchange between process streams is not included. Liu et al.[22] investigated work exchange networks using a graphical method. The study does not include any heat exchange and the inlet temperatures of compressors and expanders are fixed. Onishi et al.[14] presented a comprehensive superstructure for work exchange networks that interact with HENs. The streams may be heated or cooled before and after each pressure manipulation stage. Stream splitting was included in each pressure manipulation stage, however, heating or cooling of stream branches within a stage was excluded. The superstructure was further extended by the same authors[15] for retrofit applications of HENs with pressure recovery of process streams. Dong et al.[11] presented an optimization study on heat, mass, and pressure exchange networks based on exergoeconomic analysis.

The heuristic rule that compression should start at pinch temperature was inadvertently used in previous work. A self-heat recuperation scheme was developed by Kansha et al.[23] In the scheme, a feed stream (a cold stream to be heated) undergoes a unit operation (e.g., reaction) after being heated. To avoid introducing any external heating, the effluent (product) stream is used to preheat the feed stream to its target temperature after being compressed to a temperature high enough, and then expanded after being cooled against the feed stream. As a result, the sensible heat of the effluent stream is recuperated and used for heating the feed stream. Incidentally, this scheme is perfectly in line with the thermodynamic insights (Theorem 1) developed in this article, that is, the compressor inlet temperature is at the pinch.

The above literature survey clearly shows increasing research interest in the integration of heat and work, however, these investigations have only to a limited extent been performed based on thermodynamic insights and mathematical analysis. Such studies are obviously important for understanding correct integration of heat and work, for example, assisting the building and solution of mathematical optimization models.[16] In this work, focus has been placed on above ambient heat recovery problems where compression is needed. Since both heat and work are involved, the objective has been changed from minimizing energy (hot and cold utilities) consumption as used in Pinch Analysis to minimizing exergy consumption. The insight obtained from various case studies has been generalized and formulated as a set of theorems. Analytical interpretations based on thermodynamics and mathematics are presented. The work results in a systematic methodology for HEN design targeting minimum exergy consumption. While establishing these targets, the optimal use of Pinch Compression (compressor inlet is at pinch temperature) and/or Ambient Compression (compressor inlet is at ambient temperature) will be identified and the corresponding possible split of streams into substreams (or branches) make the design task easy and straightforward. Figure 1 illustrates a superstructure for possible splits of a stream to be compressed at various temperatures that will be used in the theorems and examples.

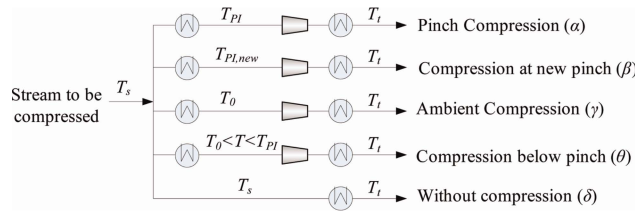

Figure 1. Illustration of stream splits for the theorems and examples.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

The article describes the following contributions to the area of process systems engineering: (1) correct integration of compressors in above ambient HENs has been investigated based on thermodynamic and mathematical analysis; (2) a graphical design procedure for such integration has been developed; and (3) exergy analysis has been used as a predesign tool, that is, minimum exergy consumption has been achieved at an early stage of process design. This study will be used as the basis of a comprehensive design methodology for heat and work integration in both above and below ambient processes. The results also provide useful insights and guidelines for further mathematical optimization studies. The work presented in this article has significant application potentials for improving energy efficiency and decreasing energy consumption and emissions in industrial processes where the conversion between heat and work is involved.

Problem Statement

The problem to be solved is stated as follows: "Given a set of process streams with supply and target states (temperature and pressure), as well as utilities for power, heating and cooling, design a network of heat exchangers, compressors, pumps expanders, and valves in such a way that exergy consumption is minimized." In this article, it is assumed that only compression is included. Cases including expansion will be presented in subsequent publications. The following assumptions are made for deriving Theorems 1–4 with the objective of minimizing exergy consumption: (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 hot utility (one temperature level) is

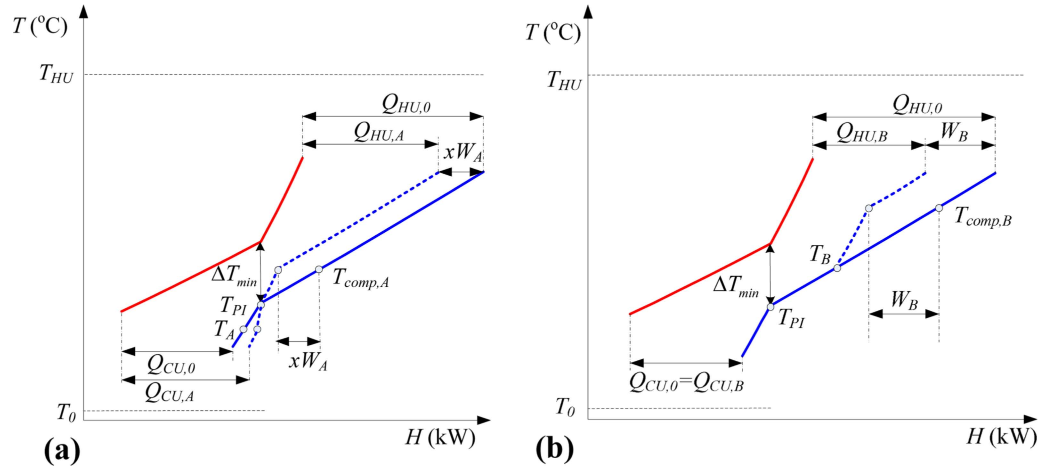

Figure 2. CCs for (a) compression below pinch and (b) compression above pinch.

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used, (3) the compressor polytropic efficiency $\eta_{\infty,\mathrm{comp}}$ is constant, (4) the gas to be compressed is ideal gas with a constant specific heat ratio of $\kappa \equiv c_p/c_v$, and (5) the exergy content of cold utility is negligible.

Theorems

This section proposes four theorems that are used as the basis of a design methodology. Each theorem is illustrated with an example. The four theorems can be stated in the following simple form: (1) Pinch Compression should be used to its maximum if the outlet temperature of Ambient Compression is lower than hot utility temperature, (2) Ambient Compression is used after the heating demand has been satisfied by Pinch Compression, (3) the heat above pinch resulting from Ambient Compression should be used to reduce the portion with Pinch Compression, and (4) Ambient Compression should be used if its outlet temperature is higher than hot utility temperature.

Theorem 1. *For above ambient processes, a HEN design with Pinch Compression consumes the smallest amount of exergy if the following conditions are satisfied: (1) the outlet temperature of Ambient Compression is lower than hot utility temperature and (2) the compression heat is not more than required by the process, that is, Pinch Compression does not remove the original pinch point.*

Proof. A cold stream with heat capacity flow rate mc_p is assumed to be compressed from p_s to p_t. In the case that a hot stream is compressed, a similar proof can be established. The following two cases are compared: Case A—compression starts below pinch temperature, $T_A < T_{PI}$; Case B—compression starts above pinch temperature, $T_B \geq T_{PI}$ (note that Pinch Compression is included in this case). The composite curves (CCs) for the process streams are shown in Figure 2. The solid curves represent the case when pressure manipulation is not included, while the dashed curves show the change of the CCs when pressure manipulation is included. In the case without pressure manipulation, the heating demand is $Q_{HU,0}$. The hot utility temperature is T_{HU} and ambient temperature is T_0. ■

For Case A, the outlet temperature of compression at T_A, is calculated to be $T_{comp,A} = T_A (p_t/p_s)^{(n_c-1)/n_c}$, where $(n_c-1)/n_c = (\kappa-1)/(\kappa\eta_{\infty,comp})$. The compression work is then $W_A = mc_p(T_{comp,A} - T_A) = mc_p T_A[(p_t/p_s)^{(n_c-1)/n_c} - 1]$. Applying the Plus/Minus principle[2,6] (see Introduction for more details) to compression processes (above and below ambient), the enthalpy of the stream is increased by compression and the total heating demand of the process is, thus, reduced if the outlet temperature of compression is above pinch.[10,12] When compressing a cold stream from below to above pinch (Case A), the heating requirements are reduced above and below pinch. As a result, the total process needs less hot utility but more cold utility. This is illustrated in Figure 2a. The graphical explanation is that the mc_p contribution from the stream to be compressed has been removed from the cold CC between T_A and $T_{comp,A}$. Since the total mc_p is reduced in this temperature range, the slope of the cold CC is increased. For Case B, where the entire compression takes place above pinch, the need for hot utility is reduced while cold utility requirements remain the same. The work consumption is $W_B = mc_p(T_{comp,B} - T_B) = mc_p T_B[(p_t/p_s)^{(n_c-1)/n_c} - 1]$ and the heating demand is reduced to $Q_{HU,B}$.

For Case B, Pinch Compression ($T_B = T_{PI}$) consumes the smallest amount of exergy, since any compression above pinch ($T_B > T_{PI}$) consumes more work due to higher inlet temperature, and the increased work is directly converted into an equal (if the original pinch point is not removed) or even smaller (if the original pinch point is removed) amount of savings in the hot utility. Of course, converting work into heat on a 1:1 basis is not attractive referring to the second Law of Thermodynamics, thus, the comparison is performed between Pinch Compression ($T_B = T_{PI}$) and Case A. Assuming that the compression work above pinch is completely converted into savings in the hot utility (the original pinch point is not removed), then $Q_{HU,B} = Q_{HU,0} - W_B$ and $Q_{HU,A} = Q_{HU,0} - xW_A$, where x ($0 \leq x < 1$) is the fraction compressed above pinch for Case A. Note that the pressure ratio is not really split (i.e., compression is still done in one stage), and the fraction x only refers to the part of compression process where the stream's temperature increases from T_{PI} to $T_{comp,A}$. Since both heat and work are involved, exergy is used for the comparison. The exergy consumption for Case A is $E_A = E_{Q_{HU,A}} + W_A = Q_{HU,A}(1 - T_0/T_{HU}) + W_A$ and for Case B $E_B = E_{Q_{HU,B}} + W_B = Q_{HU,B}\ (1 - T_0/T_{HU}) + W_B$. The difference is found to be $E_B - E_A = (xW_A - W_B)(1 - T_0/T_{HU}) + (W_B - W_A)$.

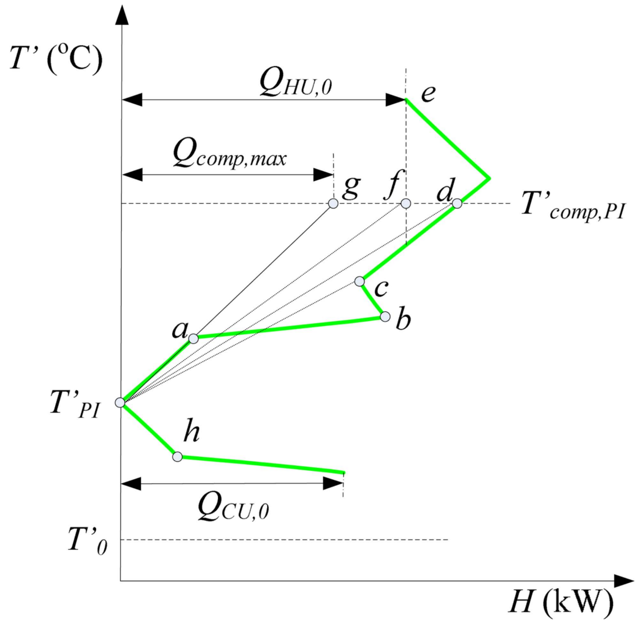

Figure 3. GCC for Pinch Compression.

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If $x=0$, that is, $T_{comp,A} < T_{PI}$, the difference in exergy consumption is derived to be $E_B - E_A = mc_p[(p_t/p_s)^{(n_c-1)/n_c} - 1][T_0T_B/T_{HU} - T_A]$. Since $(p_t/p_s)^{(n_c-1)/n_c} - 1 > 0$ and $T_0T_B/T_{HU} < T_0 \le T_A$, it is concluded that $E_B < E_A$, that is, Case B consumes less exergy.

If $x > 0$, that is, the compression in Case A crosses the pinch, $xW_A = mc_p(T_{comp,A} - T_{PI})$. The difference in exergy consumption is found to be

$$\begin{aligned} &E_B - E_A \\ &= [mc_p(T_{comp,A} - T_{PI}) - mc_p(T_{comp,B} - T_{PI})] \\ &(1 - T_0/T_{HU}) + [mc_p(T_{comp,B} - T_{PI}) - mc_p(T_{comp,A} - T_A)] \\ &= mc_p(T_{comp,B} - T_{comp,A})T_0/T_{HU} - mc_p(T_{PI} - T_A) \\ &= mc_p(T_0/T_{HU})(T_{PI} - T_A)(p_t/p_s)^{(n_c-1)/n_c} - mc_p(T_{PI} - T_A) \\ &= mc_p(T_{PI} - T_A)(T_{comp,0}/T_{HU} - 1) \end{aligned}$$

Since $T_{PI} > T_A$ and $T_{HU} > T_{comp,0}$ according to condition (1), again it is concluded that $E_B < E_A$. Theorem 1 has, thus, been proven. If $T_{HU} \le T_{comp,0}$, then $E_B \ge E_A$, which means that the hot utility temperature is relatively low and it is, thus, not worthwhile to save hot utility by consuming more work through Pinch Compression.

If the original pinch point is removed when Pinch Compression is used, the compression heat produced is more than the heat required. New pinch points are created at temperatures higher than the original pinch point. The compression heat can not be completely utilized. This case would be a violation of condition (2) in Theorem 1 and will be discussed in Theorems 2 and 3. Figure 3 shows the GCC for Pinch Compression without pressure manipulation. Modified temperatures (T') are used, which means that for cold streams $T' = T + 0.5\Delta T_{min}$, and for hot streams $T' = T - 0.5\Delta T_{min}$. The outlet temperature of Pinch Compression is $T'_{comp,PI}$. A temperature is defined as a Potential Pinch Point if it may create a new pinch point after a portion of the compression heat is included. The following temperatures are Potential Pinch Points: (1) the convex kink points (see definition below) on the GCC in the range between $T' = T'_{comp,PI}$ and $T' = T'_{PI}$ (such as points a and c); (2) the point $T' = T'_{comp,PI}$ on the GCC (point d) or the point on the line $T' = T'_{comp,PI}$ with $H = Q_{HU,0}$ if $T'_{comp,PI}$ is higher than the highest temperature on the GCC (not shown in Figure 3); and (3) the intersection point between the constant temperature line $T' = T'_{comp,PI}$ and a pocket (point f) in the GCC. A convex kink point on the GCC is defined as a point where either the slope decreases without sign change or the slope increases with sign change when referring to the positive y axis direction (i.e., modified temperature). According to this definition, points a, c, h, and the pinch point in Figure 3 are convex kink points.

The maximum portion of the stream that can be compressed at the pinch, $(mc_p)_{comp,PI,max}$, is determined by the following steps: (1) starting at the pinch point (T'_{PI}), draw lines between the pinch point and Potential Pinch Points and extend the line with the largest slope until it intersects with the constant temperature line ($T' = T'_{comp,PI}$), the corresponding heating demand at the intersection point (g in Figure 3) is then determined; (2) this heating demand $Q_{comp,max}$ is equal to the maximum work resulting from Pinch Compression that can be utilized, and $(mc_p)_{comp,PI,max}$ can, thus, be determined as $(mc_p)_{comp,PI,max} = Q_{comp,max}/(T'_{comp,PI} - T'_{PI})$. If the mc_p of the stream to be compressed is larger than $(mc_p)_{comp,PI,max}$, the original pinch point will be removed and the compression work can not be completely utilized. Stream splitting is, thus, used and the portion using Pinch Compression is $(mc_p)_{comp,PI,max}$.

The identity of the stream (hot or cold) to be compressed and the locations of supply and target temperatures are not paid attention to the above procedure to determine the maximum fraction for Pinch Compression and the discussion about Potential Pinch Points. A detailed study on the effect of stream identity (hot/cold) and stream temperatures (supply/target) is presented in Supporting Information I. The study concludes that the heating demand is underestimated by $ymc_p\Delta T_{min}$ where $0 \le y \le 1$. Since modified temperatures are used, stream identities (hot or cold) are not distinguished in the GCC. Stream identities do not change in traditional heat recovery problems and the GCC can, thus, be used to accurately target utilities (levels and amounts). However, stream identities may vary with pressure manipulations and direct application of the GCC for utility targeting results in the error of $ymc_p\Delta T_{min}$. This amount normally has negligible influence on the total exergy consumption of process streams for two

Table 1. Stream Data for Example 1

Stream	T_s (°C)	T_t (°C)	mc_p (kW/°C)	ΔH (kW)	p_s (kPa)	p_t (kPa)
H1	400	60	2	680	–	–
C1	15	250	1	235	100	300
C2	200	380	4	720	–	–
Heat source	400	400	–	–	–	–
Cooling source	15	15	–	–	–	–

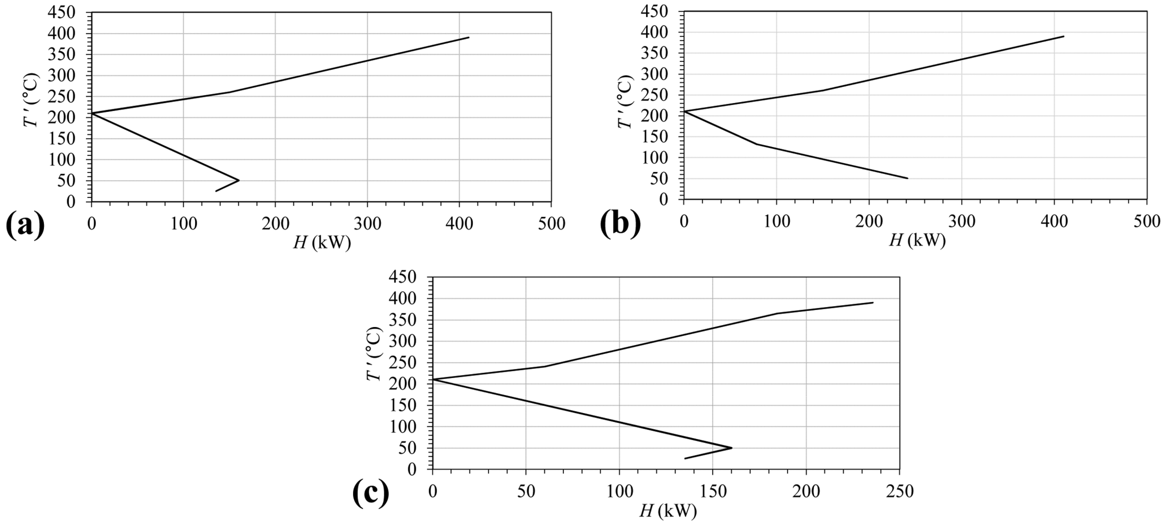

Figure 4. GCCs for Example 1: (a) Case O: without pressure manipulation, (b) Case A, and (c) Case B.

reasons: (1) $\Delta T_{\min}$ is normally small and $ymc_p\Delta T_{\min}$ is, thus, small compared to the heating demand and (2) the exergy content of the heat, $ymc_p\Delta T_{\min}(1-T_0/T_{HU})$, is even smaller. The advantage of excluding such negligible heat in the analysis is that GCCs can be used without distinguishing the identity of streams to be compressed and the locations of supply and target temperatures. The challenge that the identity of streams may change is then no longer a problem. Alternatively, a comprehensive procedure can be used to include all the cases presented in Supporting Information I when $\Delta T_{\min}$ is large and the underestimated heating demand ($ymc_p\Delta T_{\min}$) needs to be taken into account.

Theorem 1 is illustrated with Example 1. The following assumptions are made for all examples in this article: (1) $\eta_{\infty,\mathrm{comp}}=1$, (2) $\Delta T_{\min}=20°\mathrm{C}$, (3) $T_0=15°\mathrm{C}$, and (4) the fluid to be compressed is ideal gas with constant specific heat ratio $\kappa=c_p/c_v=1.4$.

Example 1. The stream data is shown in Table 1, indicating that a cold stream (C1) is compressed. The

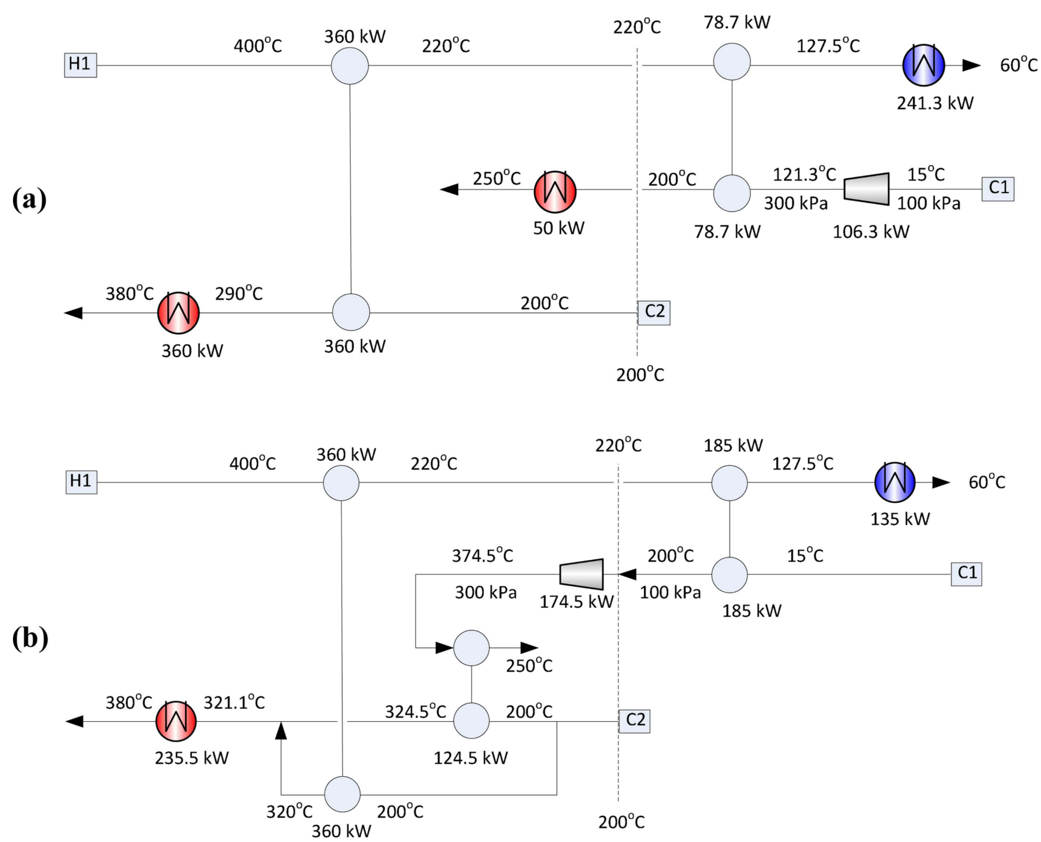

Figure 5. Heat exchanger networks for Example 1: (a) Case A and (b) Case B.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Table 2. New Stream Data for C1 in Example 1

Cases	T_s (°C)	T_t (°C)	mc_p (kW/°C)	ΔH (kW)	p_s (kPa)	p_t (kPa)
Case A						
C1	121.3	250	1	128.7	300	300
Case B						
C1_1	15	200	1	185	100	100
C1_2	374.5	250	1	124.5	300	300

outlet temperature of compression at T_0 is $T_{\text{comp},0}=T_0(p_t/p_s)^{(n_c-1)/n_c}=121.2°\text{C}<T_{\text{HU}}=400°\text{C}$, thus, according to Theorem 1, Pinch Compression can be used to reduce the exergy consumption.

The GCC without pressure manipulation (Case O) is shown in Figure 4a. The pinch temperature is 220/200°C. The following two cases are compared: Case A—compression at $T_0=T_s$ and Case B—compression at T_{PI} (200°C) for cold streams. Due to compression at different temperatures, the stream data for C1 changes as shown in Table 2. In Case B, stream C1 is compressed after being heated to T_{PI} and then cooled from $T_{\text{comp,PI}}$ to T_t, resulting in two new streams (C1_1 and C1_2). The role of stream C1 changes to a hot stream after compression. The GCCs are shown in Figures 4b, c. The pinch does not change in any of the two cases. The performance results are shown in Table 3. For Case A, the cooling demand increases by an amount equal to the compression work and the hot utility demand does not change since the entire compression process (both inlet and outlet temperatures) takes place below pinch. The heating demand in Case B is reduced by an amount equal to the compression work. Compared to Ambient Compression (Case A), the work consumption for Pinch Compression increases due to a higher compressor inlet temperature, however, the compression work has been completely utilized for heating purposes. As a result, the exergy consumption is reduced by 9.3% (Case B vs. Case A). The HEN designs are shown in Figure 5. The number of units is the same for the two cases.

Figure 6 shows compression work, hot utility and exergy consumption for various compressor inlet temperatures. The compression work of course increases with increasing inlet temperature. The hot utility demand remains constant (410 kW) when the inlet temperature is low and starts decreasing when the inlet temperature increases above 72.5°C whose corresponding outlet temperature for compression is the pinch temperature (200°C). The reason is that heat is introduced to the region above pinch by the compression with an inlet temperature above 72.5°C. This is in accordance with the plus/minus principle. The temperature of the cold stream C1 increases due to compression, and the amount of heat required by this cold stream is, thus, reduced in the above pinch region. For inlet temperatures below 72.5°C, Ambient Compression has the smallest exergy consumption, since compression work is at its minimum while the hot utility demand is constant (410 kW). The exergy consumption keeps decreasing when the inlet temperature exceeds 72.5°C since the portion of compression heat above pinch increases. Minimum exergy consumption is achieved when the inlet temperature is equal to the pinch temperature (200°C). More exergy is consumed when the inlet temperature is higher than the pinch temperature since the increased compression work is converted into heat on a 1:1 basis, thus, energy quality is reduced and exergy is lost.

Table 3. Performance Comparison for Example 1

Cases	O	A	B
Hot utility demand (kW)	410	410	235.5
Cold utility demand (kW)	135	241.3	135
Pinch temperature (°C)	210	210	210
Compression work (kW)	–	106.3	174.5
Exergy consumption (kW)	–	340.8	309.2
Number of heat exchangers	–	5	5
Number of compressors	–	1	1

Theorem 2. *For above ambient processes, the stream to be compressed should be split into two portions: the first portion (as large as possible until the heating demand is satisfied) is compressed at the pinch temperature and the remaining portion is compressed at ambient temperature, when the following conditions are satisfied: (1) the outlet temperature of Ambient Compression is lower than the pinch temperature and (2) the heat resulting from Pinch Compression is more than required.*

Theorem 2 is proven in Supporting Information II and is illustrated with Example 2.

Example 2. The stream data is shown in Table 4, indicating that a hot stream (H1) is compressed. $T_{\text{comp},0}$ is calculated as $T_{\text{comp},0}=T_0(p_t/p_s)^{(n_c-1)/n_c}=184.8°\text{C} < T_{\text{HU}}$, thus, Pinch Compression can be used to reduce exergy consumption. The GCC without pressure manipulation (Case O) is the same as for Case O in Example 1 and is shown in Figure 4a. The following three cases are compared: Case A—Ambient Compression is used; Case B—Pinch Compression (α) is used to satisfy the heating demand and Ambient Compression is used for the remaining portion (γ); and Case C—compression at a temperature T_C below pinch ($T_0 \le T_C < T_{\text{PI}}$) is used and the heating demand is satisfied

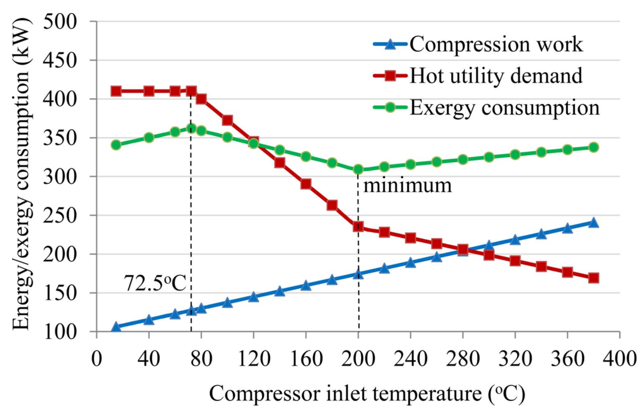

Figure 6. Energy and exergy consumption in Example 1 for various compressor inlet temperatures.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Table 4. Stream Data for Example 2

Stream	T_s (°C)	T_t (°C)	mc_p (kW/°C)	ΔH (kW)	p_s (kPa)	p_t (kPa)
H1	400	60	2	680	100	400
C1	15	250	1	235	–	–
C2	200	380	4	720	–	–
Heat source	400	400	–	–	–	–
Cooling source	15	15	–	–	–	–

by the compression. For Case A, H1 is compressed after being cooled from T_s to $T_0+\Delta T_{min}$ and then cooled to T_t. The design procedure is then straightforward.

For Case B, H1 is compressed after being cooled to T_{PI} and then cooled to T_t. The outlet temperature of Pinch Compression is $T_{comp,PI}=T_{PI}(p_t/p_s)^{(n_c-1)/n_c}=459.7°C$. If the entire stream (H1) is compressed at T_{PI}, the compression work is $W_{PI}=mc_p(T_{comp,PI}-T_{PI})=479.4$ kW, which is larger than the heating demand of 410 kW, see Table 3. Since $T_{comp,0}<T_{PI}$, according to Theorem 2, stream H1 is split into two portions: one portion (α) is compressed at T_{PI} and the compression work is equal to the heating demand of 410 kW, and the remaining portion (γ) is compressed at T_0. $(mc_p)_\alpha$ is calculated to be 1.71 kW/°C.

For Case C, H1 is cooled to temperature $T_C<T_{PI}$ before it is compressed, and then cooled to T_t. Assuming that $T_{comp,C}=T_{HU,min}=400°C$, the compression work above pinch is $W_{PI}=mc_p(T_{comp,C}-T_{PI})=2\times(400-220)$ kW$=360$ kW. This value is less than the heating demand (410 kW), thus, T_C should be increased so that the heating demand can be satisfied, and $T_{comp,C}$ is determined by $T_{comp,C}=(Q_{HU,0}/mc_p)+T_{PI}=(410/2)+220=425°C$. T_C is then calculated to be 196.7°C. Note that Case C is actually an example of Case A.i as discussed in the proof of Theorem 2.

The new stream data for H1 is shown in Table 5 and the GCCs are shown in Figure 7. The heating demand is satisfied by compression in both Cases B and C. The performance comparison is shown in Table 6. Compared to Ambient Compression (Case A), the exergy consumption is reduced by 14.7% using Pinch Compression (Case B). The exergy consumption for Case C is slightly higher than Case B, however, Case C may be more attractive since splitting of the stream to be compressed is avoided. This example illustrates that Pinch Compression is preferred with respect to minimum exergy consumption.

Theorem 3. *For above ambient processes, the heat from Ambient Compression should be utilized to reduce the portion using Pinch Compression, if the following conditions are satisfied: (1) the heat resulting from Pinch Compression is more than required and (2) the outlet temperature of Ambient Compression exceeds the pinch temperature but is lower than hot utility temperature.*

Theorem 3 actually indicates that the heat above pinch resulting from Ambient Compression should be utilized. This is reasonable since the heating demand can still be satisfied while the portion using Pinch Compression can be reduced. Otherwise, the heat above pinch resulting from Ambient Compression would be wasted. The proof of Theorem 3 is presented in Supporting Information III. Notice that some cases where compression at some intermediate temperature ($T_0<T<T_{PI}$) is used in combination with Ambient Compression (if necessary) may achieve the same minimum exergy consumption when the proposed scheme is used. Theorem 3 is illustrated with Example 3 where the stream to be compressed is split into the portions α and γ when Pinch Compression is applied.

Example 3. The stream data is shown in Table 7. Since $T_{comp,0}=321.8°C<T_{HU}$, the exergy consumption can be

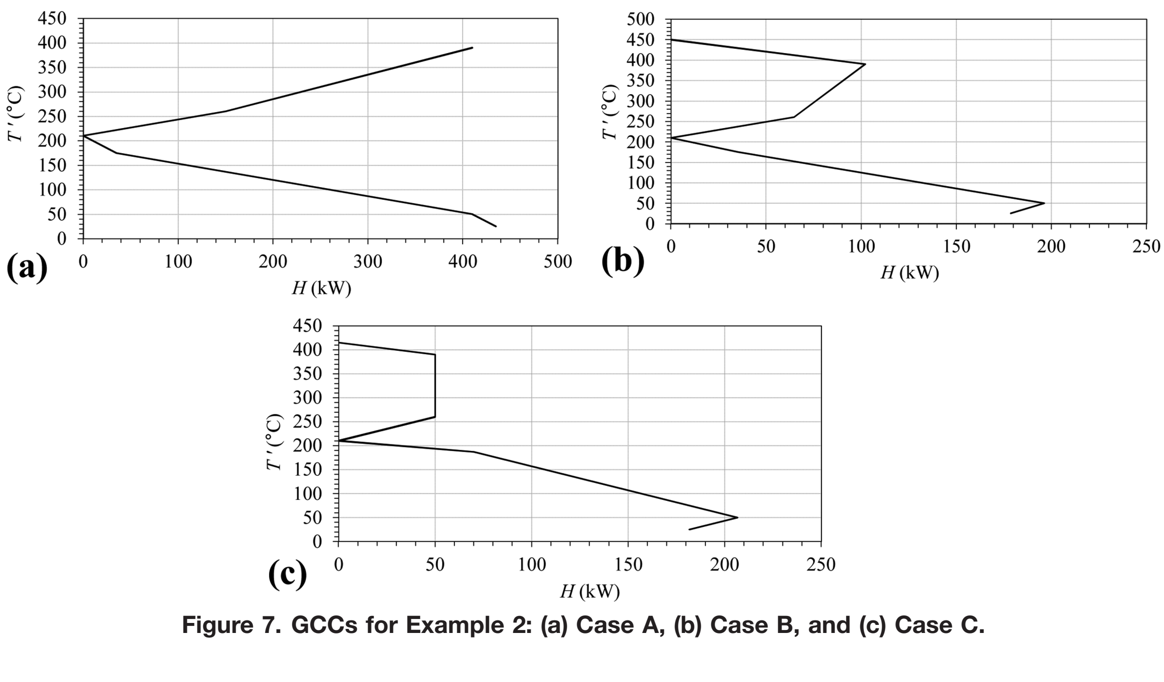

Figure 7. GCCs for Example 2: (a) Case A, (b) Case B, and (c) Case C.

Table 5. New Stream Data for H1 in Example 2

Cases	T_s (°C)	T_t (°C)	mc_p (kW/°C)	ΔH (kW)	p_s (kPa)	p_t (kPa)
Case A						
H1_1	400	35	2	730	100	100
H1_2	184.8	60	2	249.6	400	400
Case B						
H1_α1	400	220	1.71	307.8	100	100
H1_α2	459.7	60	1.71	683.5	400	400
H1_γ1	400	35	0.29	105.9	100	100
H1_γ2	184.8	60	0.29	36.2	400	400
Case C						
H1_1	400	196.7	2	406.6	100	100
H1_2	425	60	2	730	400	400

Table 6. Performance Comparison for Example 2

Cases	O	A	B	C
Hot utility demand (kW)	410	410	0	0
Cold utility demand (kW)	135	434.6	178.5	181.6
Pinch temperature (°C)	210	210	210	210
Compression work (kW)	–	299.6	453.4	456.6
Exergy consumption (kW)	–	531.4	453.4	456.6
Fractions of the stream (%)				
Pinch compression (α)	–	0	85.5	0
Ambient compression (γ)	–	100	14.5	0
Compression below pinch (θ)	–	0	0	100

reduced using Pinch Compression. The GCC without pressure manipulation (Case O) is shown in Figure 8a. The following three cases are compared: Case A—Ambient Compression is used; Case B—the compression is performed according to Theorem 3;and Case C—the heating demand is satisfied by compression at $T_C(T_0 < T_C < T_{PI})$, and Ambient Compression is used for the remaining portion if necessary. The design procedure for Case A is straightforward and not presented.

According to Figure 8a, the heating demand at $T_{comp,0}$ is $Q_{T_{comp,0}}=101.8$ kW. When Ambient Compression is used (Case A), a new pinch is created at $T_{comp,0}=321.8°C$ according to Figure 8b. The outlet temperature of compression at the original and new pinches are calculated to be $T_{comp,PI}=679°C$ and $T_{comp,T_{comp,0}}=875.5°C$. For Case B, the heating demand at $T_{comp,0}$ can be completely satisfied by Ambient Compression since the following values are obtained by solving the equations presented in Case 2 of Theorem 3 (see Supporting Information III): $(mc_p)_\alpha=0$, $(mc_p)_\beta=0.14$ kW/°C, and $(mc_p)_\gamma=1.86$ kW/°C.

For Case C, assuming that $T_{comp,C}=T_{HU,min}=400°C$, the compression work above pinch is $W_{PI}=mc_p(T_{comp,C}-T_{PI})=2\times(400-220)=360$ kW, which is larger than the heating demand (180 kW). Stream H1 is, thus, split into two portions: one portion (θ) is compressed at T_C, which is determined to be 75.5°C from $T_{comp,C}=T_{HU,min}=400°C$, and $(mc_p)_\theta=180/(400-220)=1$ kW/°C; another portion (γ) is compressed at $T_0+\Delta T_{min}$ and $(mc_p)_\gamma=1$ kW/°C.

The new stream data for H1 is shown in Table 8 and the GCCs are shown in Figure 8. A new pinch point is created in Case B and the original pinch is removed due to a large portion compressed at T_0. The performance results are shown in Table 9. Compared to Ambient Compression, Case B has lower exergy consumption. However, the difference is small due to a very small portion that is compressed at the new pinch (portion β in Table 8). Case C has the same exergy consumption as Case B (neglecting the round-off errors). Stream splitting is used in both Cases B and C. The portion β in Case B is compressed at a high pinch temperature (321.8°C) that may

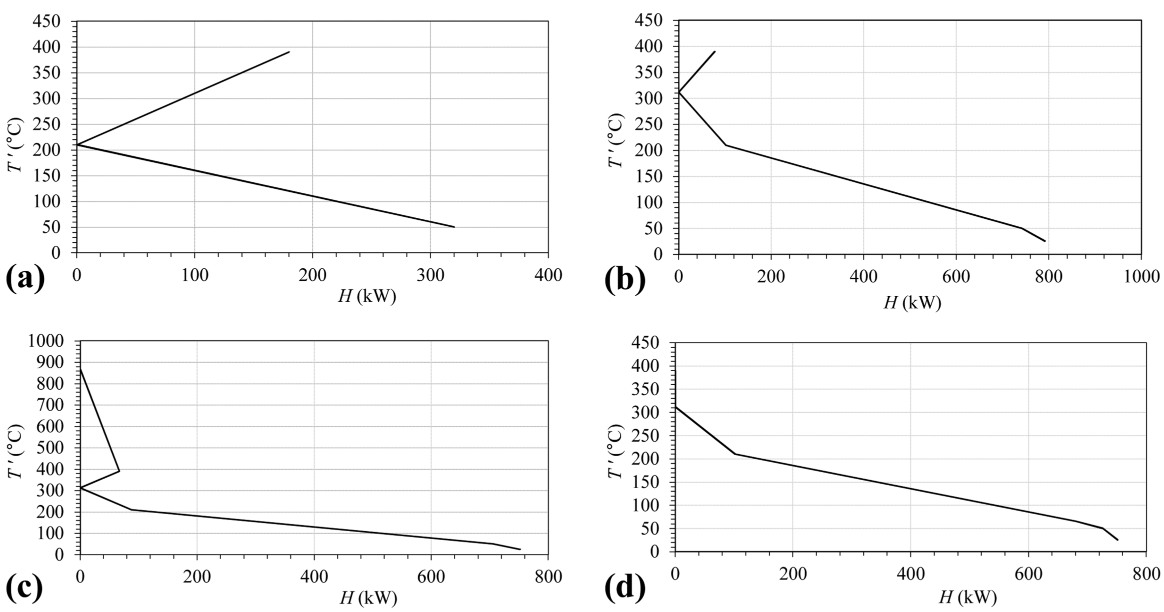

Figure 8. GCCs for Example 3: (a) Case O, (b) Case A, (c) Case B, and (d) Case C.

Table 7. Stream Data for Example 3

Stream	T_s (°C)	T_t (°C)	mc_p (kW/°C)	ΔH (kW)	p_s (kPa)	p_t (kPa)
H1	400	60	2	680	100	1000
C1	200	380	3	540	–	–
Heat source	400	400	–	–	–	–
Cooling source	15	15	–	–	–	–

Table 8. New Stream Data for H1 in Example 3

Cases	T_s (°C)	T_t (°C)	mc_p (kW/°C)	ΔH (kW)	p_s (kPa)	p_t (kPa)
Case A						
H1_1	400	35	2	730	100	100
H1_2	321.8	60	2	523.6	1000	1000
Case B						
H1_β1	400	321.8	0.14	10.9	100	100
H1_β2	875.5	60	0.14	114.2	1000	1000
H1_γ1	400	35	1.86	678.9	100	100
H1_γ2	321.8	60	1.86	487	1000	1000
Case C						
H1_θ1	400	75.5	1	324.5	100	100
H1_θ2	400	60	1	340	1000	1000
H1_γ1	400	35	1	365	100	100
H1_γ2	321.8	60	1	261.8	1000	1000

not be practical, however, this portion is small (0.14 kW/°C) and a large remaining portion (1.86 kW/°C) is compressed at T_0. In Case C, the portion θ is compressed at a low temperature (75.5°C), however, this portion (1 kW/°C) is much larger than the portion β in Case B.

Theorem 4. *For above ambient processes, Ambient Compression should be used if its outlet temperature is higher than hot utility temperature.*

Condition (1) in Theorem 1 requires that $T_{\text{comp},0} < T_{\text{HU}}$. Theorem 4 deals with the opposite situation when $T_{\text{comp},0} > T_{\text{HU}}$. In this case, the compression should not be done at or above T_{PI} (see proof for Theorem 1). The following two cases using compression below pinch are compared: Case A (compression at T_A) and Case B (compression at T_B). In both cases, the compression heat above pinch is assumed to be completely utilized. This means that compression heat above pinch is less than or equal to the heating demand for the case without pressure manipulation. In the opposite case, reducing temperatures (T_A and T_B) would reduce compression work, and the ultimate solution is Ambient Compression. For Case A, $Q_{\text{HU,A}} = Q_{\text{HU},0} - mc_p(T_{\text{comp,A}} - T_{\text{PI}})$, $W_A = mc_p(T_{\text{comp,A}} - T_A)$, and $E_A = Q_A(1 - T_0/T_{\text{HU}}) + W_A$. Similarly for Case B, $Q_{\text{HU,B}} = Q_{\text{HU},0} - mc_p(T_{\text{comp,B}} - T_{\text{PI}})$, $W_B = mc_p(T_{\text{comp,B}} - T_B)$, and $E_B = Q_B (1 - T_0/T_{\text{HU}}) + W_B$. The exergy consumption for the two cases can then be compared

$$\begin{aligned} E_B - E_A &= (Q_{\text{HU,B}} - Q_{\text{HU,A}})(1 - T_0/T_{\text{HU}}) + (W_B - W_A) \\ &= mc_p(T_A - T_B)p_r^{(n_c-1)/n_c}(1 - T_0/T_{\text{HU}}) \\ &\quad + mc_p(T_B - T_A)(p_r^{(n_c-1)/n_c} - 1) \\ &= mc_p(T_A - T_B)(1 - T_0 p_r^{(n_c-1)/n_c}/T_{\text{HU}}) \end{aligned}$$

Since $T_0 p_r^{(n_c-1)/n_c} = T_{\text{comp},0} > T_{\text{HU}}$, it can be concluded that $E_B > E_A$ when $T_B > T_A$. This means that the exergy consumption is smaller when the inlet temperature of compression is lower, and Ambient Compression should, thus, be used. In practice, the pressure ratio can be split (i.e., multistage compression) so that $T_{\text{comp},0} < T_{\text{HU}}$ and Pinch Compression can be used.

Example 4. The stream data is shown in Table 10. If ambient compression is used for H2, $T_{\text{comp},0} = 241°\text{C} > T_{\text{HU}}$. The following two cases are compared: Case A—Ambient Compression is used; and Case B—Pinch Compression is used. The new stream data for H2 is shown in Table 11 and the performance results are shown in Table 12 (O is the case without pressure manipulation). Pinch Compression does not create new pinch points, that is, the heating demand is not satisfied when the entire stream (H2) is compressed at T_{PI}, however, the exergy consumption for Pinch Compression is slightly higher than Ambient Compression. The reason is that the outlet temperature of Ambient Expansion exceeds hot utility temperature. This illustrates the guideline of Theorem 4 that Pinch Compression should not be used.

Design Procedure

On the basis of the four theorems, a design procedure is developed and is illustrated in Figure 9 for HEN design including compressors above ambient with the objective of minimizing exergy consumption. The first step is to compare $T_{\text{comp},0}$ with T_{HU}. If $T_{\text{comp},0} > T_{\text{HU}}$, according to Theorem 4, Ambient Compression is used, otherwise the exergy

Table 9. Performance Comparison for Example 3

Cases	O	A	B	C
Hot utility demand (Kw)	180	78.2	0	0
Cold utility demand (kW)	320	791.8	751.7	751.3
Pinch temperature (°C)	210	311.8	311.8	311.8
Compression work (kW)	–	573.5	610.9	611.3
Exergy consumption (kW)	–	618.2	610.9	611.3
Fractions of the stream (%)				
Pinch compression (α)	–	0	0	0
Compression at the new pinch (β)	–	0	7	0
Ambient compression (γ)	–	100	93	50
Compression below pinch (θ)	–	0	0	50

Table 10. Stream Data for Example 4

Stream	T_s (°C)	T_t (°C)	mc_p (kW/°C)	ΔH (kW)	p_s (kPa)	p_t (kPa)
H1	200	60	3	420	–	–
H2	200	70	1	130	100	600
C1	100	180	10	800	–	–
Heat source	200	200	–	–	–	–
Cooling source	15	15	–	–	–	–

Table 11. New Stream Data for H2 in Example 4

Cases	T_s (°C)	T_t (°C)	mc_p (kW/°C)	ΔH (kW)	p_s (kPa)	p_t (kPa)
Case A						
H2_1	200	35	1	165	100	100
H2_2	241	70	1	171	600	600
Case B						
H2_1	200	120	1	80	100	100
H2_2	382.8	70	1	312.8	600	600

consumption can be reduced using Pinch Compression. When Pinch Compression is used, $(mc_p)_{comp,PI,max}$ is determined using the concept of Potential Pinch Points. If the mc_p of the stream to be compressed is smaller than $(mc_p)_{comp,PI,max}$, according to Theorem 1, Pinch Compression is used for the entire stream, otherwise the stream is split into two portions and Pinch Compression is used for the portion $(mc_p)_{comp,PI,max}$, while the remaining portion of the stream will be handled subsequently. New GCCs can then be produced, adjusting for the effect of Pinch Compression, and a new $(mc_p)_{comp,PI,max}$ is determined. A new portion is split from the stream and compressed at the new pinch. The procedure is repeated until the entire stream has been compressed. If there is a remaining portion to be compressed after the heating demand has been satisfied using Pinch Compression, according to Theorem 2, this portion is compressed at T_0 if $T_{comp,0}$ is less than the original T_{PI}. Otherwise, according to Theorem 3, the portion with Pinch Compression should be reduced and an iterative procedure is required: A new GCC is produced by including pressure manipulation only for the portion with Ambient Compression, and the procedure for implementing Pinch Compression is used. The procedure stops if the entire stream has been compressed, otherwise the portion with Ambient Compression increases until the pinch points below $T_{comp,0}$ have been removed, and the remaining portion is then compressed at T_0.

It can be observed that the streams should be compressed at pinch temperatures or ambient temperature to achieve minimum exergy consumption. In some cases, where compression at an intermediate temperature ($T_0 < T < T_{PI}$) is realized, the same minimum exergy consumption may be achieved, however, the determination of the compressor inlet temperature is not straightforward in more complex cases. When capital cost is taken into consideration, these cases may be more attractive.

Example 5. The stream data is shown in Table 13. If ambient compression is used for C1, $T_{comp,0} = 148.6°C < T_{HU}$, thus, the exergy consumption can be reduced by using Pinch Compression. The GCC without pressure manipulation (Case O) is shown in Figure 10a. The pinch temperature is 120/100°C. The outlet temperature of Pinch Compression is $T_{comp,PI} = 237.6°C$. The following cases are compared: Case A—Ambient Compression is used, Case B—compression is performed at T_s; Case C—the entire stream is compressed at T_{PI}; Case D—stream splitting is used: the portion with Pinch Compression is $(mc_p)_{comp,PI,max}$ and the remaining portion is compressed at T_0 (compression at the new pinch is, thus, not applied); Case E—stream splitting is used: compression at the original and new pinches are applied to satisfy the heating demand, and the remaining portion is compressed at T_0 (the heat above pinch resulting from Ambient Compression is not utilized); and Case F—the procedure presented in Figure 9 is used, that is, the heat above pinch resulting from Ambient Compression is utilized to reduce the portion with Pinch Compression in Case E. The design procedure for Cases A–C is straightforward. The new stream data for C1 is shown in Table 14 and the GCCs are shown in Figure 10.

For Case D, according to Figure 10a, the maximum work resulting from Pinch Compression is determined using the concept of Potential Pinch Points and $Q_{comp,max} = 60$ kW. The maximum portion with Pinch Compression is $(mc_p)_{comp,PI,max} = Q_{comp,max}/(T'_{comp,PI} - T'_{PI}) = 60\ \text{kW}/(247.6°C - 110°C) = 0.44\ \text{kW}/°C$. Stream C1 is, thus, split into two portions: Pinch Compression is used for the first portion ($\alpha = 0.44$ kW/°C) and Ambient Compression is used for the remaining portion ($\gamma = 2.56$ kW/°C).

For Case E, based on the results of Case D, the portion for original Pinch Compression is $\alpha = 0.44$ kW/°C. The new GCC (Case E1) without including pressure manipulation for the remaining portion ($\gamma = 2.56$ kW/°C) is produced and shown in Figure 10f. The new pinch is $T_{PI,new} = 280°C$ (for cold streams) and the outlet temperature of compression at the new pinch is $T_{comp,PI,new} = 484.0°C$. The maximum work resulting from compression at the new pinch is $Q_{comp,max,new} = 300$ kW and the maximum portion that can be compressed is

Table 12. Performance Comparison for Example 4

Cases	O	A	B
Hot utility demand (kW)	480	359	217.2
Cold utility demand (kW)	230	315	230
Pinch temperature (°C)	110	110	110
Compression work (kW)	–	206	262.8
Exergy consumption (kW)	–	346.4	347.7
Fractions of the stream (%)			
Pinch compression (α)	–	0	100
Ambient compression (γ)	–	100	0

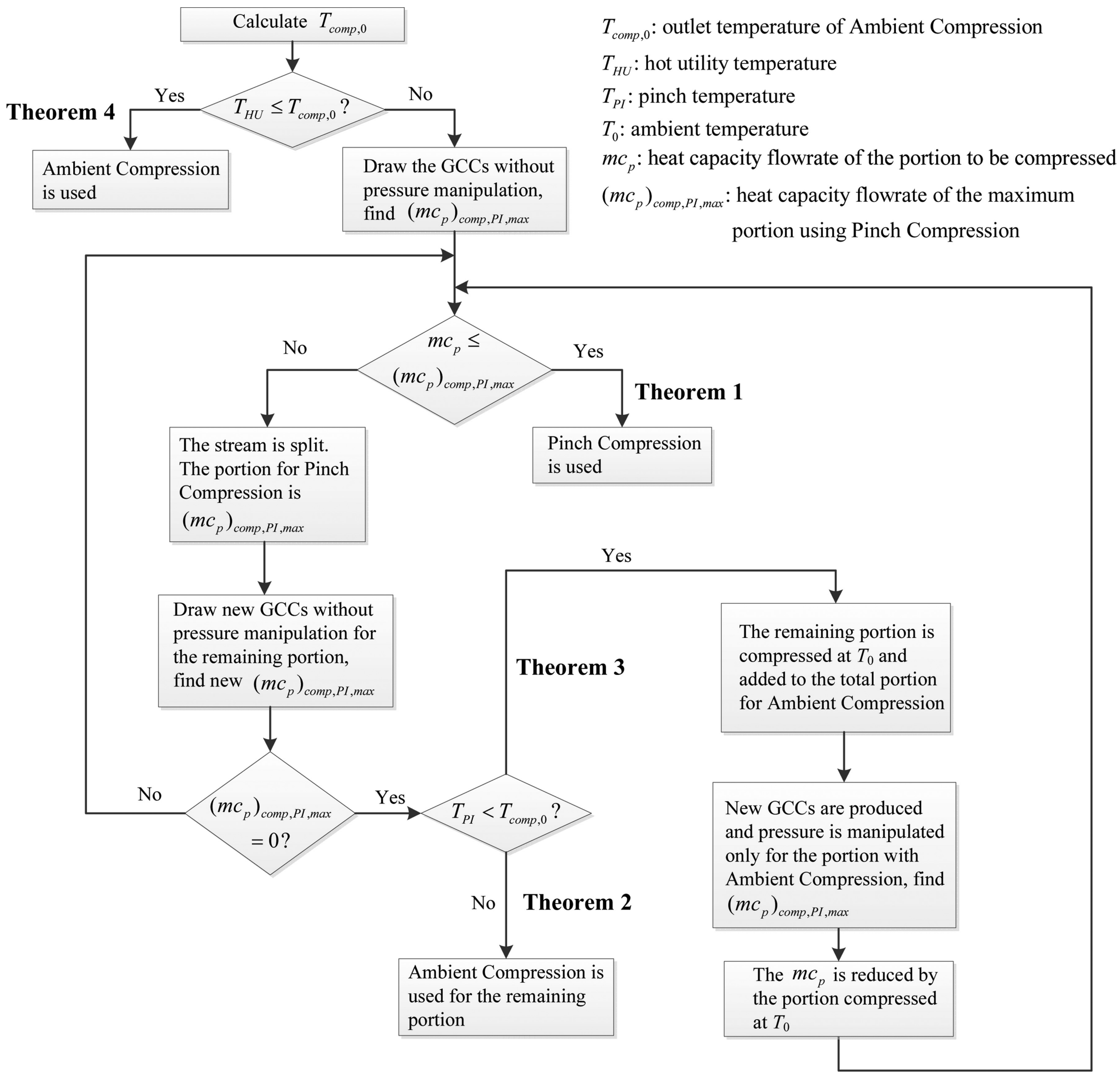

Figure 9. Design procedure for integrating compressors into above ambient HENs.

$\beta = (mc_\text{p})_{\text{comp,PI,max,new}} = 1.47$ kW/°C. The heating demand is then completely satisfied. The remaining portion ($\gamma = 3 - 0.44 - 1.47 = 1.09$ kW/°C) is compressed at T_0.

For Case F, since $T_{\text{comp},0} > T_{\text{PI}}$, the heat above pinch resulting from Ambient Compression should be utilized according to Theorem 3. The following iterative procedure is used to determine the compression scheme. Case E shows that the portion for Ambient Compression is 1.09 kW/°C, thus, a first case (F1) is studied by splitting C1 into two portions: one portion ($\gamma = 1.09$ kW/°C) is compressed at T_0 and the remaining portion ($\delta = 1.91$ kW/°C) is not compressed. The corresponding GCC is shown in Figure 10h. The maximum work resulting from compression at the pinch (110°C) is $Q_{\text{comp,max}} = 7$ kW and the portion that should be compressed is $(mc_\text{p})_{\text{comp,PI,max}} = 0.05$ kW/°C. The stream data for the second case (F2) is shown in Table 14 and the GCC is shown in Figure 10i. Note that there is a portion ($\delta = 1.91 - 0.05 = 1.86$ kW/°C) without compression. The maximum work resulting from compression at the new pinch (290°C) is $Q_{\text{comp,max}} = 300$ kW and the portion that should be compressed is determined to be $\beta = 1.47$ kW/°C. The heating demand is then completely satisfied. However, there is still a remaining portion to be compressed ($1.86 - 1.47 = 0.39$ kW/°C), and the portion for Ambient Compression, thus, increases to $\gamma = 1.09 + 0.39 = 1.48$ kW/°C. The GCC for the third case (F3) is shown in Figure 10j. A new iterative procedure is required since the original pinch has been removed and there is a portion ($\alpha = 0.05$ kW/°C) compressed at this pinch. Stream C1 is then split into two portions: one portion ($\gamma = 1.48$ kW/°C) is compressed at T_0 and the remaining portion ($\delta = 1.52$ kW/°C) is not compressed. The GCC for Case F4 is shown in Figure 10k. Obviously, a portion is necessary to be compressed at the new pinch (290°C) and the amount is $\beta = 1.47$ kW/°C. The remaining portion is then compressed at T_0. This new case (F5) is actually the final compression scheme for Case F. The GCC is shown in Figure 10l. Note that the original pinch has been removed since Ambient Compression produces enough heat that can be utilized above pinch. Also note that the new pinch is not created at $T_{\text{comp},0}$ since the point with $T = T_{\text{comp},0}$ on the GCC (Case O) is in a pocket.

The performance comparison is shown in Table 15. Ambient Compression (Case A) is used as the basis for comparison. The exergy consumption increases when the entire stream is compressed at the original pinch (Case C). In Case D, only a

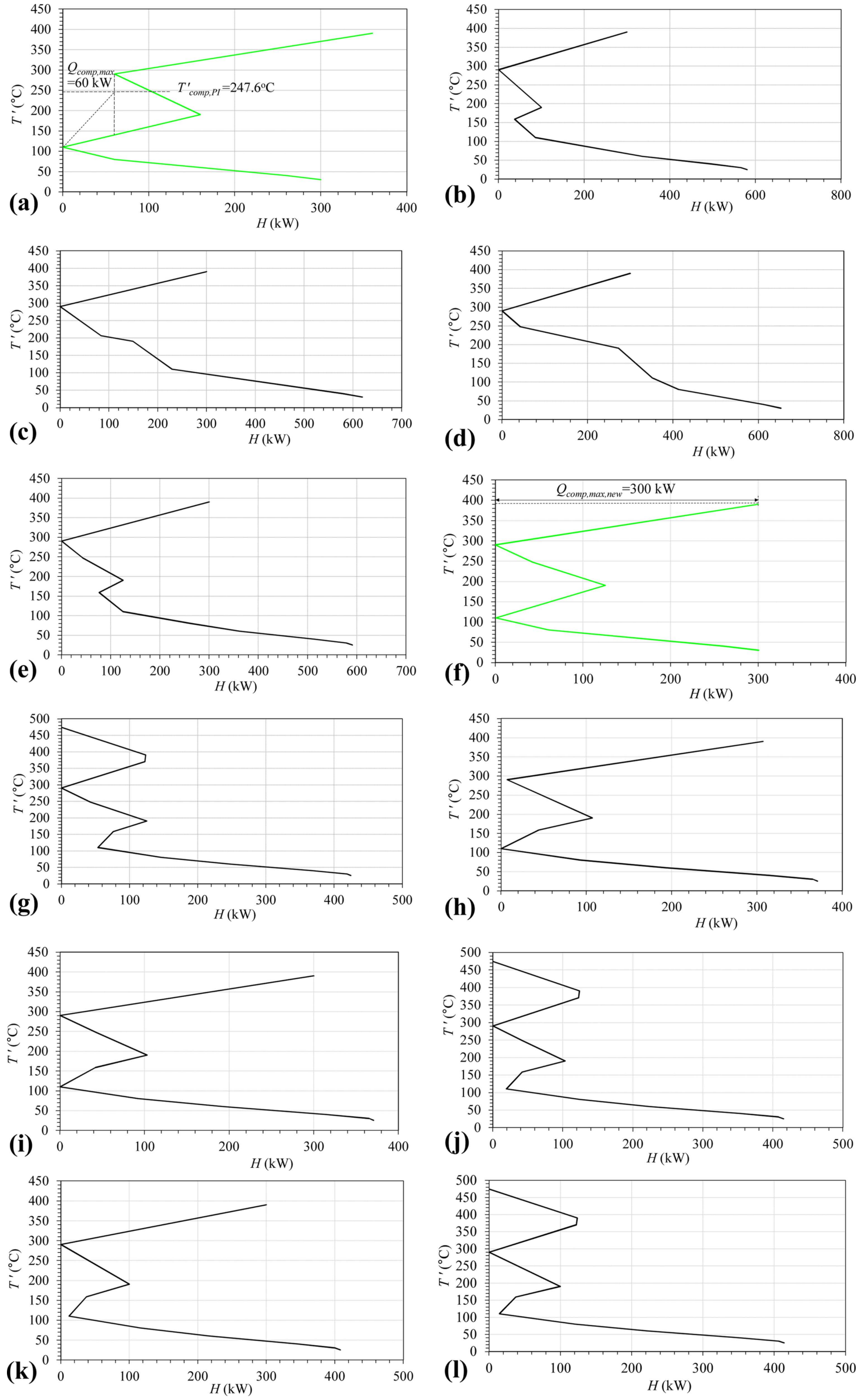

Figure 10. GCCs for Example 5: (a) Case O, (b) Case A, (c) Case B, (d) Case C, (e) Case D, (f) Case E1, (g) Case E2, (h) Case F1, (i) Case F2, (j) Case F3, (k) Case F4, and (l) Case F5.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

portion of the stream is compressed at the original pinch and the fraction is determined using the concept of Potential Pinch Points, however, the exergy consumption is still larger than Case A. The exergy consumption is reduced in Case E since compression at the new pinch is applied, and is further reduced in Case F since the heat resulting from Ambient Compression is utilized. The lowest exergy consumption is achieved in Case F following the design procedure presented in Figure 9.

Table 13. Stream Data for Example 5

Stream	T_s (°C)	T_t (°C)	mc_p (kW/°C)	ΔH (kW)	p_s (kPa)	p_t (kPa)
H1	300	50	4	1000	–	–
H2	120	40	4	320	–	–
C1	70	380	3	930	100	300
C2	30	180	3	450	–	–
Heat source	400	400	–	–	–	–
Cooling source	15	15	–	–	–	–

The HENs for Cases A and F are shown in Figure 11. As can be seen, two more heat exchangers and one more compressor are used in Case F, however, the exergy consumption is reduced by 7.6%. By increasing work consumption by 132.9 kW, the hot utility consumption is reduced by 300 kW while the cold utility consumption is reduced by 166.9 kW. Still, the energy savings may not be enough to compensate for the additional capital cost, however, this example illustrates the procedure to achieve a HEN design with the objective of minimum exergy consumption.

Discussions

The graphical design procedure developed in this article can be used as a targeting approach for HEN design including compressors. Minimum exergy consumption can be achieved

Table 14. New Stream Data for C1 in Example 5

Cases	T_s (°C)	T_t (°C)	mc_p (kW/°C)	ΔH (kW)	p_s (kPa)	p_t (kPa)
Case A						
C1_1	70	35	3	105	100	100
C1_2	148.6	380	3	694.2	300	300
Case B						
C1	196.5	380	3	550.5	300	300
Case C						
C1_1	70	100	3	90	100	100
C1_2	237.6	380	3	427.2	300	300
Case D						
C1_α1	70	100	0.44	13.2	100	100
C1_α2	237.6	380	0.44	62.7	300	300
C1_γ1	70	35	2.56	89.6	100	100
C1_γ2	148.6	380	2.56	592.4	300	300
Case E1						
C1_α1	70	100	0.44	13.2	100	100
C1_α2	237.6	380	0.44	62.7	300	300
C1_δ	70	380	2.56	793.6	100	100
Case E2						
C1_α1	70	100	0.44	13.2	100	100
C1_α2	237.6	380	0.44	62.7	300	300
C1_β1	70	280	1.47	308.7	100	100
C1_β2	484	380	1.47	152.9	300	300
C1_γ1	70	35	1.09	38.2	100	100
C1_γ2	148.6	380	1.09	252.2	300	300
Case F1						
C1_γ1	70	35	1.09	38.2	100	100
C1_γ2	148.6	380	1.09	252.2	300	300
C1_δ	70	380	1.91	592.1	100	100
Case F2						
C1_α1	70	100	0.05	1.5	100	100
C1_α2	237.6	380	0.05	7.1	300	300
C1_γ1	70	35	1.09	38.2	100	100
C1_γ2	148.6	380	1.09	252.2	300	300
C1_δ	70	380	1.86	576.6	100	100
Case F3						
C1_α1	70	100	0.05	1.5	100	100
C1_α2	237.6	380	0.05	7.1	300	300
C1_β1	70	280	1.47	308.7	100	100
C1_β2	484	380	1.47	152.9	300	300
C1_γ1	70	35	1.48	51.8	100	100
C1_γ2	148.6	380	1.48	342.2	300	300
Case F4						
C1_γ1	70	35	1.48	51.8	100	100
C1_γ2	148.6	380	1.48	342.2	300	300
C1_δ	70	380	1.52	471.2	100	100
Case F5						
C1_β1	70	280	1.47	308.7	100	100
C1_β2	484	380	1.47	152.9	300	300
C1_γ1	70	35	1.53	53.6	100	100
C1_γ2	148.6	380	1.53	354	300	300

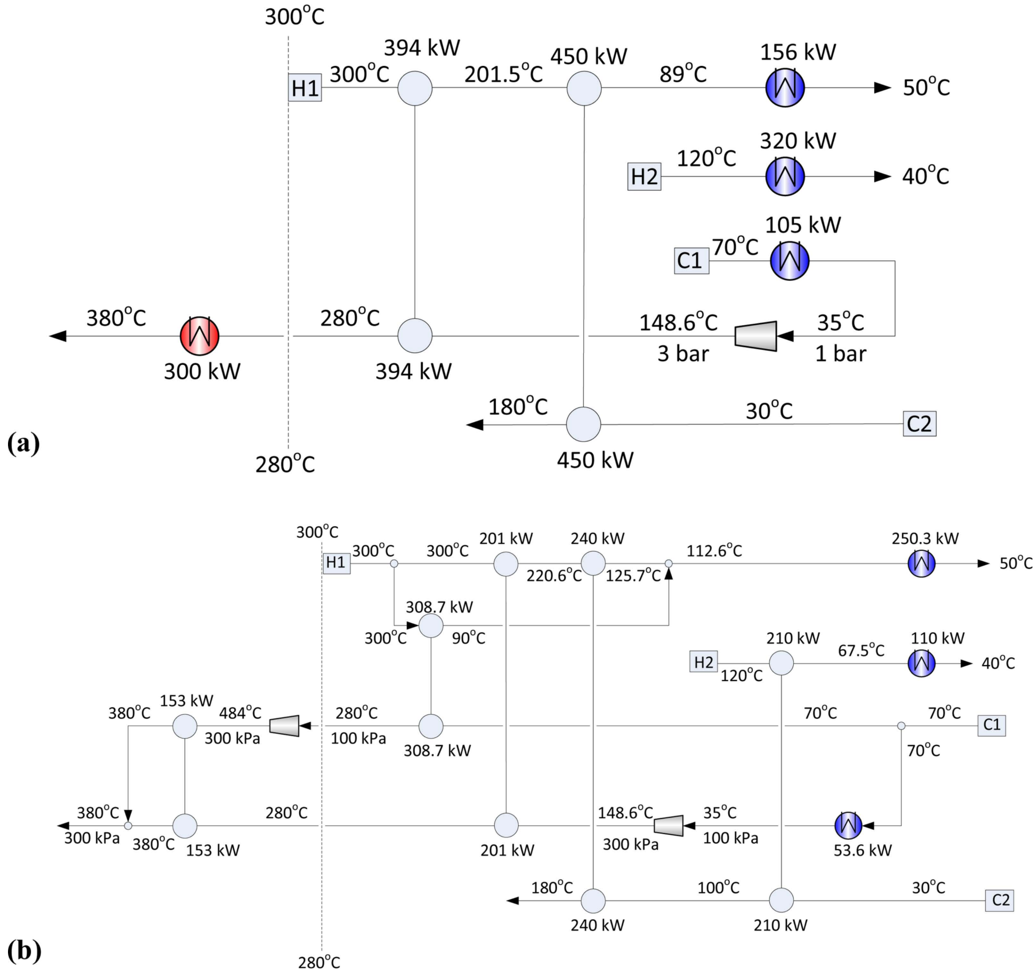

Figure 11. Heat exchanger networks: (a) Case A and (b) Case F.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

at an early stage of process design. The exergy of a given amount of heat is equal to the maximum amount of work that can be produced using reversible cycles. However, since the definition of exergy assumes reversible processes for the conversion of heat into work, exergy may not be a good parameter to balance the complex trade-off between heat and work in real processes. In addition, the relative prices of heat and work do not always follow the second Law of Thermodynamics. Nevertheless, the presented methodology is developed based on thermodynamic and mathematical analyzes and using exergy as a measure of design quality. Cost issues are beyond the scope of this study.

The compressor efficiency has been assumed to be $\eta_{\infty,\text{comp}} = 1$ for Examples 1–5. The design procedure can of course be applied for lower compressor efficiencies, since this assumption was *not* used in the theorems (see the proofs). However, compressor efficiency may vary with the operating temperature and the variation should be taken into consideration for practical designs. In addition, the operation of compressors above pinch temperatures can be a challenge for compressor design (operability). The development of compressors that can be operated at high temperatures is necessary to realize the energy savings presented in this article.

Although only one stream is assumed to be compressed in one stage in this article, the procedure can be extended to include multiple streams and compression stages. A challenging question then is related to the integration sequence of compression stages with the HEN. The temperature driving forces

Table 15. Performance Comparison for Example 5

Cases	O	A	B	C	D	E(=E2)	F(=F5)
Hot utility demand (kW)	360	300	300	300	300	0	0
Cold utility demand (kW)	300	580.8	619.5	652.8	591.3	424.4	413.9
Pinch temperature (°C)	110	290	290	290	290	290	290
Compression work (kW)	–	340.9	379.5	412.8	350.9	483.8	473.8
Exergy consumption (kW)	–	512.5	551.1	584.4	522.5	483.8	473.8
Fractions of the stream (%)							
Pinch compression (α)	–	0	0	100	14.7	14.7	0
Compression at new pinch (β)	–	0	0	0	0	49	49
Ambient compression (γ)	–	100	0	0	85.3	36.3	51
Compression at T_s	–	0	100	0	0	0	0

for heat transfer between compressed streams and other process streams can be reduced by manipulating the pressure ratio. Energy savings can, thus, be achieved by splitting the pressure ratios. The pressure ratios are assumed to be given in this article. The optimal distribution of pressure ratios among multiple compression stages will be investigated in future work. In addition, similar studies can of course be performed for integrating expanders and compressors into HENs for both above and below ambient processes. The results will be presented in other publications.

This article focuses on fundamental insights about above ambient HEN design including compressors. The following work is to be performed in the future for a more comprehensive study of the topic:

1. Multiple utilities are included. It has been assumed that one hot utility with constant temperature is used for heat recovery problems in this article. In many applications, nonconstant temperature utilities as well as multiple utilities are used. Further studies are required to include these utilities.

2. Cost should be considered. Minimum exergy consumption has been achieved following the design methodology. However, cost was not included in the study. The possibilities of removing small units at the expense of increased energy consumption should be investigated.

3. Mathematical optimization models can be built. The design methodology presented in this article can easily be applied to small size problems. For large scale industrial applications, mathematical optimization models may be more efficient to find the optimum (minimum energy consumption or the most cost-effective alternatives). This study provides useful insights for the building and solution of such optimization models.

Finally, it should be noted that the design methodology can be applied to many industrial heat recovery processes where compression is involved, for example, membrane separation of CO_2 from N_2 and natural gas liquefaction processes. Detailed industrial applications are presented in other publications.

Conclusions

The integration of compressors into HENs is a challenging task for the following reasons: (1) Both heat and work are involved and they have different energy qualities (exergy), (2) the identity of streams (as hot or cold) may change with pressure manipulations, (3) the heating and cooling demands for the streams are changing since the streams to be compressed are included in the heat recovery systems, and (4) the location of pinch points may change when pressure manipulations of a stream is included.

A systematic methodology for HEN design including compressors above ambient temperature has been developed. To assist the design, four theorems are proposed with well defined assumptions, and the insight obtained that is the basis for these theorems can be expressed by the following three simplified statements:

1. Pinch Compression should be used if the outlet temperature of Ambient Compression is lower than hot utility temperature (Theorem 1), otherwise Ambient Compression is used (Theorem 4),

2. ambient Compression is used after the heating demand has been satisfied by Pinch Compression if the outlet temperature of Ambient Compression is lower than the pinch temperature (Theorem 2); otherwise

3. the heat resulting from Ambient Compression should be utilized to reduce the portion with Pinch Compression (Theorem 3).

A straightforward graphical design procedure based on the GCC is presented. It is concluded that compression should be done at pinch temperatures and/or ambient temperature to minimize exergy consumption. No other compression temperature reduces the exergy consumption.

When Pinch Compression is implemented without considering stream identity (hot/cold) and the location of temperatures (supply/target), the heating demand is underestimated by a small error of $ymc_p\Delta T_{min}$ where $0 \le y \le 1$. The result may, thus, move slightly away from the optimum (i.e., minimum exergy consumption), however, the advantage is that the GCC can be used directly. The complexity of the design procedure is, thus, reduced considerably.

For the heat recovery problems considered in this article, it has been assumed that only one constant temperature utility is used. An extension study with multiple utilities (including nonconstant temperature utilities) is underway. In addition, the variation of compressor efficiency with temperature should be considered in practical designs. This work provides useful guidelines for further optimization studies on large scale problems. The splitting of pressure ratios by using multiple compression stages should also be investigated to further reduce energy consumption and/or cost.

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Notation

Roman letters

c_p = specific heat capacity at constant pressure, kJ/(kg °C)
c_v = specific heat capacity at constant volume, kJ/(kg °C)
E = exergy, kW
m = mass flow, kg/s
n_c = polytropic index for compression
p = pressure, kPa
Q = heat, kW
T = temperature, °C or K
T' = modified temperature, °C or K
ΔT_{min} = minimum temperature difference, °C
W = work, kW
x = fraction
y = fraction

Greek letters

α = portion of stream being compressed at the original pinch temperature
β = portion of stream being compressed at the new pinch temperature
γ = portion of stream being compressed at ambient temperature
δ = portion of stream without compression
θ = portion of stream being compressed at intermediate temperatures
$\eta_{\infty,comp}$ = compressor polytropic efficiency
κ = specific heat ratio

Subscripts

comp = compression
HU = hot utility
max = maximum

min = minimum
PI = pinch
s = supply
t = target
0 = ambient; original

Abbreviations

CC = composite curve
ExPAnD = extended pinch analysis and design
GCC = grand composite curve
HEN = heat exchanger network
MINLP = mixed integer nonlinear programming

Literature Cited

1. Gundersen T, Naess L. The synthesis of cost optimal heat exchanger networks: an industrial review of the state of the art. *Comp Chem Eng*. 1988;12(6):503–530.
2. Linnhoff B, Vredeveld DR. Pinch technology has come of age. *Chem Eng Prog*. 1984;80(7):33–40.
3. Smith R. *Chemical Process Design and Integration*. Hoboken, NJ: John Wiley and Sons, Ltd., 2005.
4. Linnhoff B, Hindmarsh E. The pinch design method for heat exchanger networks. *Chem Eng Sci*. 1983;38(5):745–763.
5. Townsend DW, Linnhoff B. Heat and power networks in process design. Part I: criteria for placement of heat engines and heat pumps in process networks. *AIChE J*. 1983;29(5):742–748.
6. Linnhoff B, Parker S. Heat exchanger networks with process modification. In: *IChemE Annual Research Meeting*. Bath, UK, 1984.
7. Glavič P, Kravanja Z, Homšak M. Heat integration of reactors—I. Criteria for the placement of reactors into process flowsheet. *Chem Eng Sci*. 1988;43(3):593–608.
8. Linnhoff B, Dunford H, Smith R. Heat integration of distillation columns into overall processes. *Chem Eng Sci*. 1983;38(8):1175–1188.
9. Smith R, Linnhoff B. The design of separators in the context of overall processes. *Chem Eng Res Des*. 1988;66:195–228.
10. Aspelund A, Berstad DO, Gundersen T. An extended pinch analysis and design procedure utilizing pressure based exergy for subambient cooling. *Appl Therm Eng*. 2007;27(16):2633–2649.
11. Dong R, Yu Y, Zhang Z. Simultaneous optimization of integrated heat, mass and pressure exchange network using exergoeconomic method. *Appl Energy*. 2014;136:1098–1109.
12. Gundersen T, Berstad DO, Aspelund A. Extending pinch analysis and process integration into pressure and fluid phase considerations. *Chem Eng Trans*. 2009;18:33–38.
13. Onishi VC, Ravagnani MASS, Caballero JA. Simultaneous synthesis of heat exchanger networks with pressure recovery: optimal integration between heat and work. *AIChE J*. 2014;60(3):893–908.
14. Onishi VC, Ravagnani MASS, Caballero JA. Simultaneous synthesis of work exchange networks with heat integration. *Chem Eng Sci*. 2014;112:87–107.
15. Onishi VC, Ravagnani MASS, Caballero JA. Retrofit of heat exchanger networks with pressure recovery of process streams at sub-ambient conditions. *Energy Convers Manag*. 2015;94:377–393.
16. Wechsung A, Aspelund A, Gundersen T, Barton PI. Synthesis of heat exchanger networks at subambient conditions with compression and expansion of process streams. *AIChE J*. 2011;57(8):2090–2108.
17. Homšak M, Glavič P. Appropriate placement of energors against local pinch temperatures. *Trans IChemE*. 1995;73(A):871–879.
18. Fu C, Gundersen T. Recuperative vapor recompression heat pumps in cryogenic air separation processes. *Energy*. 2013;59:708–718.
19. Fu C, Gundersen T. Exergy analysis and heat integration of a coal-based oxy-combustion power plant. *Energy Fuel*. 2013;27(11):7138–7149.
20. Fu C, Anantharaman R, Gundersen T. Optimal integration of compression heat with regenerative steam Rankine cycles in oxy-combustion coal based power plants. *Energy*. 2015;84:612–622.
21. Razib MS, Hasan MMF, Karimi IA. Preliminary synthesis of work exchange networks. *Comp Chem Eng*. 2012;37:262–277.
22. Liu G, Zhou H, Shen R, Feng X. A graphical method for integrating work exchange network. *Appl Energy*. 2014;114:588–599.
23. Kansha Y, Tsuru N, Sato K, Fushimi C, Tsutsumi A. Self-heat recuperation technology for energy saving in chemical processes. *Ind Eng Chem Res*. 2009;48(16):7682–7686.

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