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# Compression and Expansion at the Right Pinch Temperature

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Heat Integration is extended to the topic of Heat and Work Integration when pressure changing equipment such as compressors and expanders are included in heat exchanger network design. The latter topic is much more complex since heat and work have different energy qualities (exergy). Systematic graphical design methodologies have recently been developed for heat and work integration. The methodologies are based on a set of theorems that have been proven based on thermodynamic and mathematical analyses. The theorems show that minimum exergy consumption can be achieved in many cases when compression/expansion starts at the pinch temperature (Pinch Compression/Expansion). The Grand Composite Curve has been used to determine the maximum portions of streams using Pinch Compression/Expansion. However, the pinch temperatures for hot streams (hot pinch) and cold streams (cold Pinch) are different. They were not well distinguished in previous studies. Based on a recent mathematical optimisation study by the authors on the topic of heat and work integration, it is concluded that the pinch identity (hot or cold) should be the same as the identity of the stream at the inlet of compression/expansion. This paper introduces the new insight with an illustrative example. The insight is then verified by thermodynamic and mathematical analyses of various cases. A simple application of the insight to the self-heat recuperation scheme is investigated. An alternative scheme has been proposed. The total work consumption is reduced by 17.7 % in a thermal process with butane. The new insight is an important addition to the methodologies for heat and work integration that are established in previous studies.

## 1. Introduction

The concept of Appropriate Placement (Townsend and Linnhoff, 1983), also referred to as Correct Integration, is fundamental in Pinch Analysis. The appropriate placement of reactors, distillation columns, evaporators, heat pumps and heat engines in heat exchanger networks have been well identified (Smith, 2005). The placement of pressure changing equipment such as compressors and expanders is much more complex since both heat and work are involved. The following heuristic rule was formulated (Gundersen et al., 2009): both compression and expansion should start at the pinch temperature. Although it was not explicitly stated, both compression and expansion started at the pinch temperature in the self-heat recuperation scheme (Kansha et al., 2009). A set of fundamental theorems has recently been proposed for the integration of compressors (Fu and Gundersen, 2015a) and expanders (Fu and Gundersen, 2015b) into above ambient heat exchanger networks (HENs). Considerable symmetry has been found for the integration of expanders (Fu and Gundersen, 2015c) and compressors (Fu and Gundersen, 2015d) into sub-ambient HENs. The problem has actually been extended from Heat Integration to Heat and Work Integration. The objective has been to minimise exergy consumption. On the basis of these theorems, systematic graphical design procedures have been developed for heat and work integration (Fu and Gundersen, 2015e). It was concluded that compression/expansion should start at pinch, ambient, or cold/hot utility temperatures depending on the actual design problem. In many cases, compression/expansion at pinch temperature (referred to as Pinch Compression/Expansion) can significantly reduce hot and cold utilities as well as exergy consumption. In the

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graphical design procedures, the Grand Composite Curve (GCC) has been used for identifying the maximum portions of streams that can use Pinch Compression/Expansion.

Use of the GCC has considerably simplified the problem in the sense that stream identities as hot/cold and the relative locations of supply/target and pinch temperatures do not have to be considered. Modified Pinch temperatures can be directly determined from the GCC. However, choosing the right true (not modified) Pinch temperature where compression or expansion should start is an issue. This is related to the fact that stream identities (as hot/cold) may change during pressure manipulation. In previous work, the choice of true pinch temperatures for compression/expansion was suggested to follow the original identity of the stream to be compressed/expanded. This suggestion simplifies the choice of the right pinch temperature among various cases. However, small errors may be introduced when calculating the compression/expansion work. The choice of the best true pinch temperature has been formulated as an NLP optimisation problem to get more accurate results in more recent work (Maurstad Uv, 2015). The solvers DICOPT and BARON have been used. Exergy consumption can be reduced following the results from the optimisation formulation.

This paper presents the new insight on how to choose the right pinch temperature for compression/expansion. The insight is derived from thermodynamic and mathematical analyses for various cases. A simple application is presented to show the importance of compression and expansion at the right pinch temperature. The design methodologies for heat and work integration have thus been improved by this new insight.

## 2. An illustrative example

The stream data is taken from Fu and Gundersen (2015b) and is shown in Table 1, where $T_s$ and $T_t$ are the supply and target temperatures, $p_s$ and $p_t$ are the supply and target pressures, $mc_p$ is the heat capacity flowrate, and ΔH is the enthalpy change due to temperature change. The following assumptions are made: (1) polytropic efficiency for compressors and expanders = 1, (2) minimum temperature difference for heat transfer $\Delta T_{min}$ = 20 °C, (3) ambient temperature and reference temperature for exergy $T_0$ = 15 °C, (4) cold utility at $T_{CU}$ = 15 °C and hot utility at $T_{HU}$ = 400 °C are available, and (5) the fluid to be compressed/expanded is ideal gas with constant specific heat ratio $\kappa$ = 1.4. The cold stream (C1) is to be expanded from 3 bar to 1 bar. Without including pressure manipulation of this stream, the problem is a simple heat integration task and Pinch Analysis can be used. The pinch temperature ($T_{PI}$) is found to be 220 / 200 °C. The hot and cold utilities are 700 kW and 480 kW respectively.

When pressure manipulation is included, the key question is: at which temperature should C1 be expanded? It can be expanded at $T_{HU}$ so that more work can be recovered, however, heat is consumed for preheating the stream to $T_{HU}$. Alternatively, C1 can be expanded at the cold utility temperature ($T_{CU} = T_0$) to avoid such heat consumption, however, less work is produced. Exergy was used for the trade-off between heat and work in the study by Fu and Gundersen (2015b). It has been proven that minimum exergy consumption can be achieved when the expansion is performed at the pinch temperature (Pinch Expansion). The Grand Composite Curve (GCC) has been used for identifying the maximum portions of streams that can use Pinch Expansion. However, the pinch temperatures for the hot and cold streams are not distinguished in the GCC. It is suggested that the pinch temperature to be used is determined by the original identity of the streams with pressure manipulation: (1) the pinch temperature for cold streams (cold pinch) is used for Pinch Compression/Expansion of a cold stream, and (2) the Pinch temperature for hot streams (hot Pinch) is used for Pinch Compression/Expansion of a hot stream. Small errors could be introduced in some cases when determining the heat and work duties. This example is used to illustrate such errors.

*Table 1: Stream data for the illustrative example*

| Stream | $T_s$, °C | $T_t$, °C | $mc_p$, kW/°C | ΔH, kW | $p_s$, bar | $p_t$, bar |
|---|---|---|---|---|---|---|
| H1 | 400 | 60 | 3 | 1,020 | - | - |
| C1 | 300 | 380 | 2 | 160 | 3 | 1 |
| C2 | 200 | 380 | 6 | 1,080 | - | - |
| Hot utility | 400 | 400 | - | - | - | - |
| Cold utility | 15 | 15 | - | - | - | - |

The new data for stream C1 with Pinch Expansion is shown in Table 2. Due to pressure manipulation, the stream is divided into two stream segments: C1_1 before expansion and C1_2 after expansion. The supply temperature $T_s$ for C1_2 corresponds to the outlet temperature of Pinch Expansion ($T_{exp,PI}$). The stream is expanded at the cold Pinch (200 °C) in Case A. This corresponds to the suggestion by Fu and Gundersen (2015b): the original identity of the stream (without pressure manipulation) is cold and the cold Pinch is thus used. Alternatively, the stream is expanded at the hot pinch (220 °C) in Case B. The stream is cooled from $T_s$

(300 °C) to $T_{PI}$ before expansion. It is thus a hot stream before expansion and a cold stream after expansion. The performance comparison is shown in Table 3. The hot utility is the same for the two cases. More expansion work is recovered in Case B due to a higher inlet temperature. The cold utility is reduced by an amount equal to the extra work from expansion. As a result, the total exergy consumption is smaller in Case B.

*Table 2: New stream data for C1*

| Stream | $T_s$, °C | $T_t$, °C | $mc_p$, kW/°C | ΔH, kW | $p_s$, Pa | $p_t$, Pa |
|---|---|---|---|---|---|---|
| Case A | | | | | | |
| C1_1 | 300 | 200 | 2 | 200 | 300,000 | 300,000 |
| C1_2 | 72.5 | 380 | 2 | 615 | 100,000 | 100,000 |
| Case B | | | | | | |
| C1_1 | 300 | 220 | 2 | 160 | 300,000 | 300,000 |
| C1_2 | 87.1 | 380 | 2 | 585.8 | 100,000 | 100,000 |

*Table 3: Performance comparison for the illustrative example*

| Cases | A | B |
|---|---|---|
| Hot utility consumption, kW | 740 | 740 |
| Cold utility consumption, kW | 265 | 254.2 |
| Expansion work, kW | 255 | 265.8 |
| Exergy consumption, kW | 168.2 | 157.4 |

This example shows that exergy can be saved by expansion at the right pinch temperature. The question is how to choose the right pinch temperatures among various cases in practice when Pinch Compression/Expansion is implemented. Maurstad Uv (2015) concludes with the following insights from a mathematical optimisation study of heat and work integration: The inlet temperature to compression/expansion should be equal to the pinch temperature corresponding to the identity of the stream before compression/expansion as opposed to using the original identity of the stream. This is obviously correct for the example just discussed: Stream C1 is a hot stream before expansion and should thus be expanded at the hot pinch (220 °C). However, is this conclusion correct for all cases? The next section answers this question.

## 3. Case Analyses

For the expansion of a hot stream, the relative locations of $T_s$, $T_t$, $T_{PI}$ and $T_{exp,PI}$ give (4 !) = 24 cases. The set is reduced to 24/2 = 12 cases since $T_{PI} > T_{exp,PI}$ and further to 12/2 = 6 cases since $T_s > T_t$. Similar arguments can be made for expansion of a cold stream as well as compression of hot and cold streams. All possible cases are listed in Table 4. For Case H.1.a where $T_{exp,PI} < T_t < T_s < T_{PI}$, the temperature variation of the stream due to Pinch Expansion is shown in Figure 1.

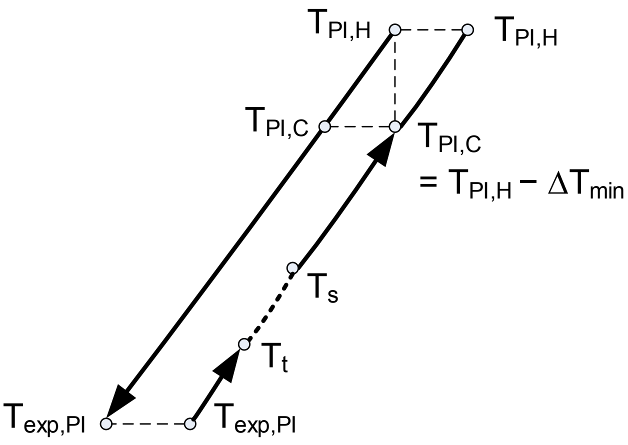

*Figure 1: Temperature variation due to Pinch Expansion in Case H.1.a*

The stream is expanded after being heated from $T_s$ to $T_{PI}$, and then heated from $T_{exp,PI}$ to $T_t$ after expansion. Assume that $\Delta T_{min}$ is small enough so that the relative location of the temperatures does not change when the temperatures change by $+\Delta T_{min}$ or $-\Delta T_{min}$. This assumption is made to reduce the number of sub-cases studied. For cases where this assumption is not valid, similar analyses can be performed. In the GCC without pressure manipulation, the excess heat (cooling demand) below the modified pinch temperature ($T'_{PI}$) is assumed to be more than the expansion work when Pinch Expansion is used. This means that the excess heat from other process streams is sufficient for heating the stream from $T_{exp,PI}$ to the cold pinch (hot pinch cannot be reached due to $\Delta T_{min}$). This assumption is used to avoid splitting the stream. In the opposite case where the excess heat below the modified pinch temperature is not sufficient, the same conclusion can be achieved using similar analyses.

*Table 4: All possible cases*

| Cases | Expansion | Compression |
|---|---|---|
| Hot stream | | |
| H.1 | H.1.a: $T_{exp,PI} < T_t < T_s < T_{PI}$ | H.1.b: $T_t < T_s < T_{PI} < T_{comp,PI}$ |
| H.2 | H.2.a: $T_t \le T_{exp,PI} < T_s < T_{PI}$ | H.2.b: $T_t < T_{PI} \le T_s < T_{comp,PI}$ |
| H.3 | H.3.a: $T_t < T_s \le T_{exp,PI} < T_{PI}$ | H.3.b: $T_t < T_{PI} < T_{comp,PI} \le T_s$ |
| H.4 | H.4.a: $T_t \le T_{exp,PI} < T_{PI} \le T_s$ | H.4.b: $T_{PI} \le T_t < T_s < T_{comp,PI}$ |
| H.5 | H.5.a: $T_{exp,PI} < T_t \le T_{PI} < T_s$ | H.5.b: $T_{PI} \le T_t < T_{comp,PI} < T_s$ |
| H.6 | H.6.a: $T_{exp,PI} < T_{PI} < T_t < T_s$ | H.6.b: $T_{PI} < T_{comp,PI} \le T_t < T_s$ |
| Cold stream | | |
| C.1 | C.1.a: $T_s < T_t < T_{exp,PI} < T_{PI}$ | C.1.b: $T_s < T_t < T_{PI} < T_{comp,PI}$ |
| C.2 | C.2.a: $T_s < T_{exp,PI} \le T_t < T_{PI}$ | C.2.b: $T_s < T_{PI} \le T_t < T_{comp,PI}$ |
| C.3 | C.3.a: $T_{exp,PI} \le T_s < T_t < T_{PI}$ | C.3.b: $T_s < T_{PI} < T_{comp,PI} \le T_t$ |
| C.4 | C.4.a: $T_s < T_{exp,PI} < T_{PI} \le T_t$ | C.4.b: $T_{PI} \le T_s < T_t < T_{comp,PI}$ |
| C.5 | C.5.a: $T_{exp,PI} \le T_s < T_{PI} < T_t$ | C.5.b: $T_{PI} \le T_s < T_{comp,PI} \le T_t$ |
| C.6 | C.6.a: $T_{exp,PI} < T_{PI} \le T_s < T_t$ | C.6.b: $T_{PI} < T_{comp,PI} \le T_s < T_t$ |

The following two cases are compared: (A) expansion at the cold pinch ($T_{PI,C}$), and (B) expansion at the hot pinch ($T_{PI,H}$). For Case A, the stream is heated from $T_s$ to $T_{PI,C}$ before expansion and is then heated from $T_{exp,PI,C}$ to $T_t$ after expansion. The excess heat below $T'_{PI}$ is assumed to be sufficient for heating the entire stream from $T_{exp,PI,C}$ to $T_{PI,C}$. The hot stream affects the heat balance in the following ways: (1) the heating from $T_s$ to $T_{PI,C}$ before expansion, (2) the heating from $T_{exp,PI,C}$ to $T_t$ after expansion, and (3) the original heat resulting from cooling the stream from $T_s$ to $T_t$ without including pressure manipulation. As a result, this expansion does not change the hot utility demand, $\Delta Q_A = 0$. The work produced is $W_A = mc_p T_{PI,C}[1-(p_t/p_s)^{(\kappa-1)/\kappa}]$. For Case B, the situation is identical to Case A except that hot utility is required to preheat the stream from $T_{PI,C}$ to $T_{PI,H}$, and the amount is $\Delta Q_B = mc_p\Delta T_{min}$. The work produced is $W_B = mc_p T_{PI,H}[1-(p_t/p_s)^{(\kappa-1)/\kappa}]$. For above ambient processes, the exergy consumption (E) for the two cases can be compared in the following way.

$$\begin{aligned}
&E_A - E_B \\
&= \{0 - mc_p T_{PI,C}[1-(p_t/p_s)^{(\kappa-1)/\kappa}]\} - \{mc_p\Delta T_{min}(1-T_0/T_{HU}) - mc_p T_{PI,H}[1-(p_t/p_s)^{(\kappa-1)/\kappa}]\} \\
&= mc_p\Delta T_{min}[T_0/T_{HU} - (p_t/p_s)^{(\kappa-1)/\kappa}] \\
&= mc_p\Delta T_{min}(T_0 - T_{exp,HU})/T_{HU}
\end{aligned} \tag{1}$$

where $T_{exp,HU} = T_{HU}(p_t/p_s)^{(\kappa-1)/\kappa}$ is the outlet temperature of expansion at $T_{HU}$. According to the study by Fu and Gundersen (2015b), Pinch Expansion should be used only when $T_{exp,HU} > T_0$. It can thus be concluded that $E_A < E_B$, i.e. expansion at the cold Pinch has less exergy consumption. Note that although the original identity of the stream is hot ($T_t < T_s$), the identity of the stream segment is cold at the inlet of Pinch Expansion. The expansion should be performed at the cold pinch in this case. The same conclusion can be achieved for sub-ambient processes.

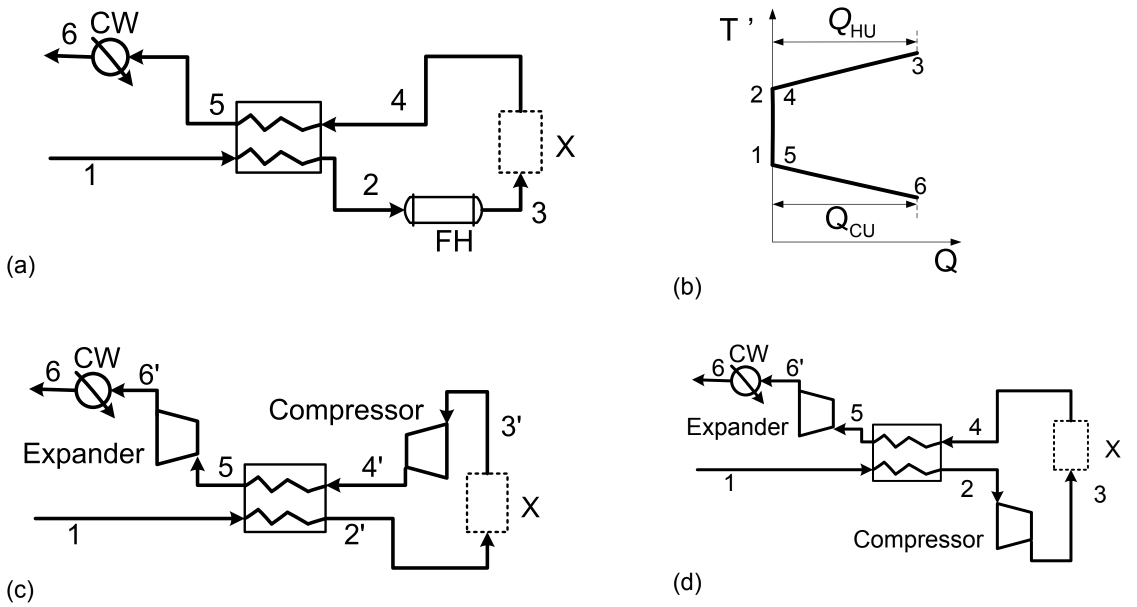

*Figure 2: The self-heat recuperation scheme (a) the reference heating process (redrawn from Kansha et al. (2009)), (b) GCC for the reference heating process, (c) the self-heat recuperation scheme (redrawn from Kansha et al. (2009)), (d) an alternative scheme*

Similar analyses have been performed for all the 24 cases in Table 4, however, these are not presented due to space limitations. The results show that the pinch identity (hot or cold) should be the same as the identity of the stream segment at the inlet of compression/expansion. This conclusion is the same as the insight obtained from the mathematical optimisation study by Maurstad Uv (2015).

## 4. A simple application

In the self-heat recuperation scheme developed by Kansha et al. (2009), both compression and expansion actually start at the pinch temperature. The reference heating process is redrawn and shown in Figure 2(a). Stream 1 is preheated against the effluent stream (4) from a unit operation "X", and it is further heated in a fired heater (FH) before being fed to "X". For simplicity, it is assumed that $T_4 = T_3$. The GCC for this process is shown in Figure 2(b). Note that for modified temperatures, $T'_1 = T'_5$, $T'_2 = T'_4$ and $T'_3 = T_3 + 0.5\Delta T_{min} = T_4 + 0.5\Delta T_{min} = T'_4 + \Delta T_{min}$.

The self-heat recuperation scheme proposed by Kansha et al. (2009) is redrawn in Figure 2(c). In order to avoid consuming external heat in FH, the effluent stream 3' is compressed to a higher temperature (4') so that it can be used for preheating the feed stream (1) to the operating temperature (2') of "X". After the preheating process, the effluent stream 5 is expanded and further cooled by cooling water. According to the GCC shown in Figure 2(b), the compression start at the higher hot pinch temperature ($T_4 = T'_3$) and the expansion starts at the lower hot pinch temperature ($T_5$). The scheme thus coincides with the heuristic rule by Gundersen et al. (2009): both compression and expansion should start at the pinch temperature.

As concluded in Section 3, it is important to compress and expand at the right pinch temperature. Since stream 2 in Figure 2(a) is to be heated, it is thus a cold stream. Compression at the cold pinch is more thermodynamically efficient. An alternative scheme is thus proposed and presented in Figure 2(d). The compression starts at the cold pinch ($T_2$) in this case.

*Table 5: Performance comparison for the thermal process with butane*

| Cases | Self-heat recuperation scheme | Alternative scheme |
|---|---|---|
| Compression work, kW | 29.175 | 29.175 |
| Compression pressure ratio | 1.4396 | 1.4549 |
| Expansion work, kW | 25.126 | 25.843 |
| Total work consumption, kW | 4.049 | 3.332 |

The thermal process with butane as the fluid (Kansha et al., 2009) has been studied for comparing the two schemes. Calculation details about this process can be found in Kansha et al. (2009), and are thus not presented in this paper. The results are shown in Table 5. Since the temperature change due to compression is the same (=$\Delta T_{min}$) for the two cases, the compression work is also the same. However, the compression pressure ratio is higher in the alternative scheme due to lower inlet temperature (cold pinch). As a result, more expansion work is recovered considering that the inlet temperature for expansion is the same and the pressure ratio is higher. The total work consumption is reduced by 17.7 % in the alternative scheme. The energy savings seem to be considerable for this special case since $\Delta T_{min}$ is relatively large (10 K) compared to the overall temperature range (50 K). It should be noted that the operating pressure of "X" is higher in the alternative scheme, which may be an advantage or disadvantage for this unit operation. The lower operating temperature for the compressor is an advantage with respect to operability.

## 5. Conclusions

The placement of compressors and expanders in heat exchanger networks was formulated as the following heuristic rule in previous work: both compression and expansion should start at the Pinch temperature. The heuristic rule has been recently extended to a set of theorems that deal with the new topic of heat and work integration (i.e. simultaneous Work and Heat Exchange Networks - WHENs). Minimum exergy consumption has been chosen as the objective of process design. The Grand Composite Curve has been used in the graphical procedures, and as a result, the complexity of the topic has thus been considerably reduced. However, the hot and cold pinch temperatures were not well distinguished when using the Grand Composite Curve. A remaining question is at what pinch temperature should compression/expansion be performed? The following new insight is summarised from thermodynamic and mathematical analyses on various cases: The Pinch identity (hot or cold) should be the same as the identity of the stream segment at the inlet of compression/expansion. This insight was actually first concluded from a recent mathematical optimisation study about heat and work integration. The insight has been applied to the self-heat recuperation scheme. An alternative scheme has been proposed by using compression at the cold Pinch instead of the hot Pinch. When the scheme is applied to a thermal process with butane, a 17.7 % reduction in total work consumption has been achieved. The new insight is thus an important improvement of previous studies on the topic of heat and work integration.

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