Extending Pinch Analysis and Process Integration into Pressure and Fluid Phase Considerations

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An Extended Pinch Analysis and Design procedure (ExPAnD) has been under development for some years in our group. The methodology combines Engineering Insight in the form of Heuristic Rules, Thermodynamics in the form of Pinch & Exergy Analyses and Optimization in the form of Mathematical Programming and Stochastic Search algorithms. So far, focus has been on subambient processes such as LNG, where pressure and phase are stream qualities that can and have been used extensively to produce more efficient processes. This paper addresses the progress in establishing rules for manipulating stream pressure and phase as well as the optimal sequence of heating, cooling, expansion and compression. The scope is an extended heat recovery problem (including liquefaction/evaporation) where pressure and phase are considered together with temperature, and the rules are firmly based on Thermodynamics and the concept of the Heat Recovery Pinch. This is a significant extension to Pinch Analysis, and the new insight is also important in developing superstructures for Optimization. New insight about appropriate placement of compressors is illustrated by two examples.

1. Introduction and Background

Pinch Analysis is the core of Process Integration (see e.g. Smith, 2005), a design methodology that focuses on efficient use of resources (energy and raw material) and capital (equipment). During the last 25 years, these methods have made a real difference to industrial practice, and have been applied extensively across continents, industrial sectors and companies (operating, engineering & contracting, consulting and vendors). Despite this impressive success story, the methods have considerable scope for improvement, especially in subambient processes. Pinch Analysis uses temperature as the only quality parameter; however, in low temperature processes, pressure and phase are important design variables, even when only considering heat recovery problems. This is the motivation for developing ExPAnD (Aspelund et al., 2007).

1.1 The Core of Pinch Analysis
The single most important insight in Pinch Analysis is the decomposition effect of the Heat Recovery Pinch (Linnhoff et al., 1979). On this basis, rules were developed for grassroots design (Linnhoff and Hindmarsh, 1983), such as "do not transfer heat across

the Pinch" for Heat Exchanger Networks and "appropriate placement" for integration of distillation columns (Linnhoff et al., 1983), heat pumps and heat engines (Townsend and Linnhoff, 1983). Design modifications are guided by the "plus/minus" principle (Linnhoff and Vredeveld, 1984), which simply states that one should aim at reducing heat deficit above and heat surplus below Pinch.

1.2 Extending Pinch Analysis Rules to Pressure and Phase
The main objective of this paper is to present additional fundamental insight that can help the engineer in designing better heat recovery systems, in particular for subambient processes where pressure and phase are important additional design variables. Among the results are new rules for "appropriate placement" of compressors and expanders, new rules for phase considerations, possible replacement of mixed refrigerants by single components, and new ideas regarding cyclic utilities. The main and perhaps surprising conclusion is that the concept of the Pinch becomes vague and less important when manipulating pressures, since stream data are no longer fixed. Nevertheless, the results are extremely important when developing new superstructures for Optimization.

2. Special Needs in Subambient Processes

In subambient processes, stream pressure is important for a number of reasons. First, a pressurized cold stream can be expanded to provide additional cooling at a lower temperature. Secondly, the required work to increase pressure can be drastically reduced if this is done in liquid phase (pump) rather than gas phase (compressor). An extended problem definition was suggested by Aspelund et al., 2007:

"Given a set of process streams with a supply state (temperature, pressure and the resulting phase) and a target state, as well as utilities for power, heating and cooling; design a system of heat exchangers, expanders and compressors in such a way that the irreversibilities (or cost related objective functions) are minimized".

It should be noticed that this design problem is vastly more complex than traditional Heat Recovery problems. The single most important new property is the fact that the path from supply to target state is no longer fixed (not given by a unique temperature vs. enthalpy relation). By manipulating pressure and phase, virtually any path from supply to target state can be envisaged, and the target state may even be a soft specification.

3. Compression and Expansion in Heat Recovery Systems

When considering "appropriate placement" of various equipment in Heat Recovery systems, it is beneficial to think in terms of heat sources and sinks. A process consists of a heat sink above and a heat source below Pinch. On this basis, compression should be placed above Pinch, since it adds heat to the system. Similarly, expansion should be placed below Pinch, since it adds cooling to the system. This is in fact the opposite of common practice for minimizing/maximizing power requirements/production for compression/expansion, and only applies when Heat Recovery problems are involved.
As a straightforward consequence and extension of the insight and results from this paper, compression and expansion can be used to improve heat recovery even in cases where the target state has the same pressure as the supply state, and process streams can

be subject to both expansion and compression. In fact, process streams can undergo cyclic processes similar to reverse Rankine or Brayton cycles. This illustrates the fact that the distinction between process streams and utilities is vague in subambient processes, and our ExPAnD procedure may provide for a more holistic treatment of cyclic utilities, which is yet another limitation in basic Pinch Analysis.

3.1 Expansion in Subambient Processes

Thermomechanical exergy has two components; temperature based and pressure based exergy. In subambient processes, a pressurized cold stream can be expanded to provide additional cooling at lower temperatures. In the expansion process, pressure based exergy is transformed into temperature based exergy, while the produced power is regarded as a byproduct. This is contrary to expansion processes above ambient, where both pressure and temperature based exergy are reduced and converted to power.

3.2 Appropriate Placement of Compressors

The stream data for a heat recovery problem including LP steam and refrigerant (R) for a very simple Example 1 are given in Table 1. The hot stream is subject to a pressure increase from 1 to 2 bar, and the main purpose of the example is to illustrate the effect of alternative placements of the compressor, i.e. varying compressor inlet temperature.

Table 1 Stream Data for Example 1

Stream	T_s (°C)	T_t (°C)	$\dot{m} \cdot c_p$ (kW/°C)	$\dot{Q}$ (kW)	p_s (bar)	p_t (bar)
H1	130	-75	2.0	410	1.0	2.0
C1	15	140	5.0	625	-	-
C2	-50	140	1.0	190	-	-
LP	150	150	-	-	-	-
R	-85	-85	-	-	-	-

Ideal gas behavior and isentropic compression are assumed for simplicity. Exergy changes for the streams can be obtained by the following simple expression:

$$\Delta \dot{E}_x = \dot{m} \cdot c_p \cdot \left(T_t - T_s - T_0 \cdot \ln \frac{T_t}{T_s} \right) + \dot{m} \cdot c_p \cdot \frac{k-1}{k} \cdot T_0 \cdot \ln \frac{p_t}{p_s} \tag{1}$$

The value for k is arbitrarily set to 1.4, and the ambient temperature (exergy) T_0 is set to 298 K. In Figure 1, the compressor inlet temperature is varied from -75°C to 125°C, and values are plotted for compressor work, hot and cold utilities and exergy efficiency. Before considering compression of hot stream H1, minimum hot and cold utilities are 540 and 135 kW respectively, and the Pinch temperature is 25°C/15°C (ΔT_{min}=10°C). The Pinch point is caused by the supply temperature of cold stream C1 (15°C).

Figure 1 clearly indicates that the thermodynamic optimum is obtained when the compressor inlet temperature is equal to the hot Pinch temperature (25°C). This means that the "appropriate placement" of a compressor is just above the Pinch. As can be seen from Figure 1, there are typical regions between important "events" with respect to compressor inlet temperature. From -75°C to -28.5°C, compression takes place entirely

below Pinch. Thus, the only result from a heat recovery point of view is an increase in cold utilities. At -28.5°C, the compressor outlet temperature reaches 25°C, which is the hot Pinch temperature. For compressor inlet temperatures above -28.5°C, the compressor starts adding heat to the deficit region above Pinch, thus there is a saving in hot utility consumption. This trend continues with significant reductions in both hot and cold utilities until the point where the compressor inlet temperature is 25°C, the hot Pinch temperature. Cold utility consumption is then back to its minimum value of 135 kW, since compression now takes place entirely above Pinch. For compressor inlet temperatures above 25°C, hot utility consumption continues to decrease, however, this is only due to the increased heat provided by compressing at higher temperatures, thus there is a 1:1 conversion from mechanical energy (power) to thermal energy (heat), and since power is worth more than heat in this temperature region, this is not a good idea. In conclusion, "appropriate placement" of a compressor is above Pinch, since it then provides heat to a heat deficit region; however, it should be placed (i.e. compressor inlet temperature) exactly at the Pinch, since a higher inlet temperature simply converts power into heat, which from a thermodynamic point of view is not at all desirable.
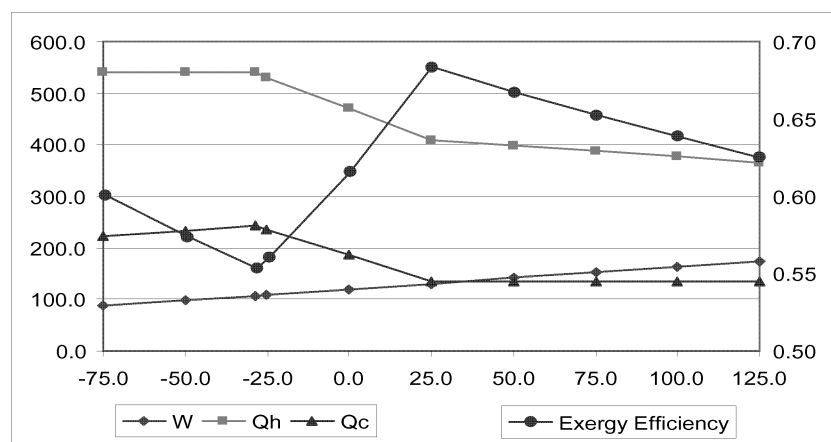

Figure 1   Compressor work, hot & cold utilities (left side y-axis) and exergy efficiency (right hand side y-axis) plotted as function of compressor inlet temperature.

3.3 Pinch Changes due to Pressure Manipulations

The stream data for another very simple Example 2 are given in Table 2. Before considering compression of hot stream H2, minimum hot and cold utilities are 165 kW and 100 kW respectively, and the Pinch temperature is -50°C/-60°C (ΔT_{min}=10°C). The Pinch point is caused by the supply temperature of cold stream C2 (-60°C). Otherwise, Example 2 uses the same assumptions as Example 1; however, exergy calculations are omitted, since the main purpose is to show Pinch changes caused by the compression. This is the reason why data for hot and cold utilities are not included in this example. In Figure 2, the compressor inlet temperature for hot stream H2 is varied from -120°C to 0°C. In this case, the Pinch point changes a number of times, and the question about the "appropriate placement" of the compressor becomes a bit more challenging.

Table 2 Stream Data for Example 2

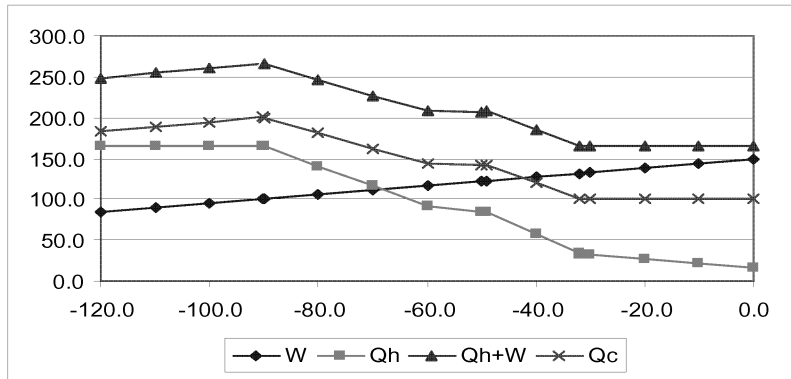| Stream	T_s (°C)	T_t (°C)	$\dot{m} \cdot c_p$ (kW/°C)	$\dot{Q}$ (kW)	p_s (bar)	p_t (bar)
H1	50	-160	1.5	315	-	-
H2	0	-120	2.5	300	1.0	2.0
C1	-180	-20	2.0	320	-	-
C2	-60	30	4.0	360	-	-

Figure 2   Compressor work, hot & cold utilities for Example 2.

For compressor inlet temperatures between -120°C and -90.1°C, compression takes place entirely below Pinch, thus the only effect is an increase in the use of cold utilities. At -90.1°C, the compressor outlet temperature is -50°C which coincides with the hot Pinch temperature.   For higher inlet temperatures, the Pinch point will follow the compressor outlet temperature (which is the supply temperature of the additional hot stream resulting from the compression).   Hot and cold utilities are considerably reduced in this region, which ends when the compressor outlet temperature reaches 0°C.   Then the supply temperature of hot stream H2 becomes Pinch.   The reduction in hot and cold utilities continues until the compressor inlet temperature is about -32°C, where the Pinch point returns to its original position at -50°C/-60°C.   From this point on, there is a 1:1 conversion from power to heat which is not desirable.   The "appropriate placement" of the compressor in this case is just before the Pinch swaps back to its original position. The explanation in this case is that the compressor is pushing the Pinch point gradually to a higher temperature, and before reaching the "just above Pinch" situation, the Pinch changes back to a lower temperature.   The savings in hot utility from its original value before compression (165 kW) to its final value (33 kW) when the compressor is optimally placed is 132 kW.   At the same time, compressor work has increased from 83.8 kW (inlet temperature -120°C) to 132 kW (inlet temperature -32°C).   Considering the compressor as an open heat pump, its Coefficient of Performance (COP) can be calculated to be (165-33)/(132-83.8) = 2.74.   While that is a fairly low COP for a heat pump, it should be noticed that in this case the compressor is required for the pressure increase of hot stream H2, and no other investment in heat pump equipment is needed.

4. Fluid Phase and Cyclic Processes

Due to space limitations, focus in this paper has been on pressure manipulations, however, the issues of fluid phase and cyclic processes for process streams and utilities are closely related to compression and expansion. As mentioned earlier, compression in liquid phase (pump) is preferable to gas phase (compressor). For single components, the two-phase region should be avoided, since condensation and evaporation then will take place at constant temperature resulting in large irreversibilities. Interestingly, single components will exhibit multicomponent behavior (gliding temperatures) when avoiding the two phase region, which is achieved by using compression and expansion.

5. A new Superstructure for Optimization

Section 3.3 showed that compression (and expansion) of process streams often results in Pinch changes. With multiple streams being subject to pressure manipulations, stream data will be floating, not fixed, thus a manual design procedure is prohibitive. The Pinch point becomes less important, and focus will be on obtaining close to parallel Composite Curves. The insight obtained, however, is used to develop superstructures that can be used for automatic synthesis of heat recovery systems with heat exchangers, compressors and expanders using Optimization. A brief overview of the emerging methodology and an application to a Liquefied Energy Chain based on LNG were recently presented by Gundersen et al. (2009) and Aspelund and Gundersen (2009).

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