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A new Process Synthesis Methodology utilizing Pressure Exergy in Subambient Processes

Audun Aspelund and Truls Gundersen

Dept. of Energy and Process Engng, Norwegian University of Science and Technol., NO-7491 Trondheim, Norway – audun.aspelund@ntnu.no, truls.gundersen@ntnu.no

Abstract

A graphical representation using the concept of Attainable Region is developed to represent all possible Composite Curves for a pressurized cold stream below ambient to include the cooling effect when the stream is expanded to its target pressure. The Attainable Region is an addition to the ExPAnD methodology, a new tool for Process Synthesis extending Pinch Analysis by explicitly accounting for pressure and including Exergy calculations. The methodology shows great potential for minimizing total shaft work in subambient processes.

Keywords

Attainable Region, Process Design, Heat Recovery, Pinch, Pressure Exergy

1. Introduction and Problem Statement

Pinch Analysis (PA) has reached a very high level of industrial application over the years and has been successfully applied to improve heat recovery, to design better heat and power systems and utility systems, as well as many other aspects of process design [1]. The major limitation with this methodology is that only temperature is used as a quality parameter, neglecting pressure and composition. Exergy Analysis (EA) has the inherent capability of including all stream properties (temperature, pressure and composition); however, this methodology has its focus on the equipment units, rather than the flowsheet level [2]. In addition, there is no strong link between exergy and cost; in fact, there is often a conflict between reducing exergy losses and cost, especially above ambient.

In subambient processes, temperature is closely related to both pressure through boiling/condensation and power through expansion/compression. A pressurized stream can be expanded to produce thermal (cold) exergy from pressure exergy. Thus, it would be very convenient to have PA tools which include the effect of pressure. This calls for an updated problem definition suitable for the ExPAnD (Extended Pinch Analysis and Design) methodology [3]. With particular focus on subambient processes, the expanded problem definition is as follows:

"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 heating and cooling; design a system of heat exchangers, expanders and compressors in such a way that the irreversibilities are minimized".

In this paper, the concept of Attainable Region (AR) is used to represent all possible Composite Curves (CCs) for a pressurized cold stream below ambient to include the cooling effect of an expansion to its target pressure. The AR was introduced by Glasser et al. [4] to determine all possible chemical compositions one can get from a given feed composition in a network of CSTR and PFR reactors as well as mixers. The idea behind the AR concept was also used by Hauan and Lien [5] to design reactive distillation systems using composition vectors for the participating phenomena of reaction, separation and mixing.

2. Theoretical Background and Simplifying Assumptions

Exergy [2] can be divided into thermal and mechanical exergy. Thermal exergy is further divided into thermomechanical and chemical exergy. Since no change in composition occurs in the processes studied in this paper, focus is on thermomechanical exergy, which can be divided into temperature based exergy (relative to ambient temperature) and pressure based exergy (relative to ambient pressure). A detailed description of thermomechanical exergy and conversion between pressure based and temperature based exergy can be found in [3].

In the following, the ideal gas model with constant specific heat capacity C_p and adiabatic coefficient $k = C_p / C_v = 1.4$, is assumed. Further, isentropic expansion and reversible heat transfer (i.e. $\Delta P = \Delta T = 0$) is assumed. Expressions for temperature and pressure based exergy are then given by Equations (1) and (2):

Applying Equation (1) to a stream with fixed supply and target temperatures, the temperature based exergy of a stream to be heated from supply temperature (T_s) to target temperature (T_t) at constant pressure is given by Equation (3). When expanding a cold stream from pressure P_1 and temperature T_1 to pressure P_2, the outlet temperature (4), the work obtained (5), and the additional cooling duty (6) can be easily calculated. Equations (5-6) show that when assuming ideal gas, the work produced in an ideal expander is equal to the cooling effect obtained for the cold stream; however, the two terms have opposite signs.

$$e^{(\mathrm{T})} = C_p\left[T - T_0\left(1 + \ln\frac{T}{T_0}\right)\right] \qquad (1)$$

$$e^{(\mathrm{P})} = T_0 R \ln\frac{P}{P_0} = \frac{k-1}{k} C_p T_0 \ln\frac{P}{P_0} \qquad (2)$$

$$\Delta\dot{E} = \left(\dot{m}C_p\right)\left[T_t - T_s - T_0 \ln\left(\frac{T_t}{T_s}\right)\right] \qquad (3)$$

$$T_2 = T_1 \cdot \left(\frac{P_2}{P_1}\right)^{\left(\frac{k-1}{k}\right)} \qquad (4)$$

$$\dot{W} = \dot{m}C_p\left(T_1 - T_2\right) \qquad (5)$$

$$\dot{Q} = \dot{m}C_p\left(T_2 - T_1\right) \qquad (6)$$

3. Attainable Region for a pressurized cold stream

A simple example is used to illustrate how pressure exergy in a cold stream can be utilized for increased cooling duty at subambient conditions. A cold stream with heat capacity flowrate $\dot{m}C_p$ =2 kW/°C is heated from -120°C to 0°C, i.e. 240 kW. The supply and target pressures are 5 and 1 bar. Assuming ambient conditions to be 15°C and 1 bar, an exergy analysis shows that the change in temperature based exergy is -93.45 kW (from 94.26 to 0.81) while the change in pressure based exergy is -265.01 kW, giving a total change in thermomechanical exergy of -358.46 kW. Clearly, if there is a deficit in the duty of the cold streams, pressure exergy should be utilized to generate extra cooling duty. The question that remains is how to utilize this pressure exergy.

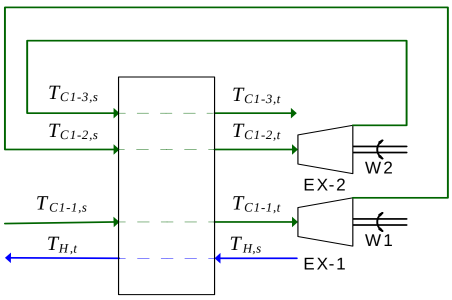

Figure 1 System with heat exchanges and expanders

Expansion of a gas will decrease its temperature and produce shaft work. By increasing the number of expanders and heat exchanges, see Figure 1, the cold stream Composite Curve (CC) can be designed to be as close as possible to the hot stream CC, thereby reducing the irreversibilities related to heat transfer. In the remaining part of the example, the possibilities for utilizing pressure exergy for cooling are shown and curves for the Attainable Region (AR) are developed.

Figure 2 shows the original cold stream heating curve between -120ºC and 0ºC as it would be in traditional Pinch Analysis, thus referred to as PA. Assuming no cooling or compression of the cold stream, there are two extreme cases for the utilization of pressure based exergy. If the stream is expanded at its coldest temperature ($T_{C1\text{-}1,t} = T_{C1\text{-}1,s}$), the lowest possible temperature will be achieved. In Figure 2, the total cold stream duty has increased with 112.91 kW to 352.91 kW with a cold end temperature of -176.45°C. The power produced is 112.91 kW, which is equal to the increase in cold stream duty, as mentioned in Section 2. The total temperature based exergy has increased with 152.10 kW (from 94.26 to 246.36 kW). Thus, pressure based exergy (265.01 kW) has been converted into work (112.91 kW) and temperature based exergy (152.10 kW).

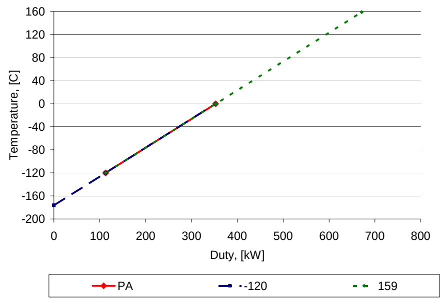

Figure 2 CC for PA and min/max temperature

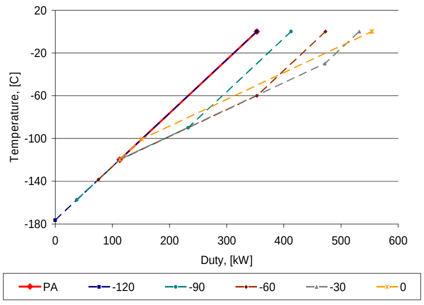

Figure 3 CCs for one expander

The highest temperature at which the stream can be expanded and still achieve its target temperature of 0°C, is 159.47°C. The corresponding CC is also shown in Figure 2. The total cold stream duty has increased with 318.94 kW to 558.94 kW. Note that 318.94 kW of power is produced, almost three times the power obtained when the stream is expanded at its supply temperature. Since the cold stream in this case is heated from below to above ambient, there is a decrease in temperature exergy below ambient of 94.26 kW and an increase above ambient of 54.74 kW, giving a net change in temperature based exergy of -39.52 kW.

3.1 Attainable Region for one expander

The next step is to heat the gas before expansion. By varying the amount of preheating, the Attainable Region for one expander is obtained. In temperature regions where the gas is heated two times, the heat capacity flowrate is doubled, leading to a less steep Composite Curve. In Figure 3, curves for heating the gas to -120ºC (no preheat), -90ºC, -60ºC, -30ºC and 0ºC before expansion are shown. Note that if the stream is heated to a temperature higher than -30ºC, the supply temperature of -120ºC can no longer be reached by expansion.

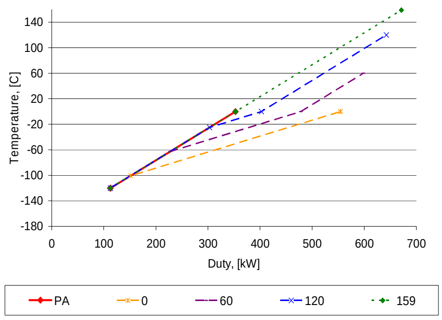

Figure 4 CCs for one expander

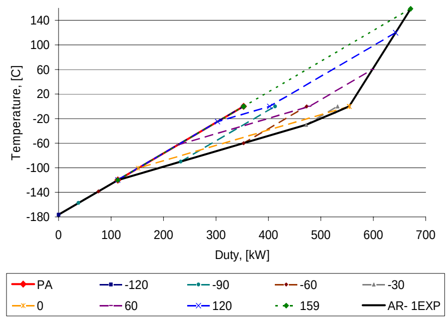

Figure 5 Attainable Region for one expander

If the cold stream can be heated to a temperature higher than its target, another set of curves can be generated. Figure 4 shows the curves for heating to 0°C, 60°C, 120°C and 159.47°C before expansion. The total Attainable Region for one expander, Figure 5, is given by combining the curves in Figures 3 and 4.

3.2 Attainable Region for two expanders

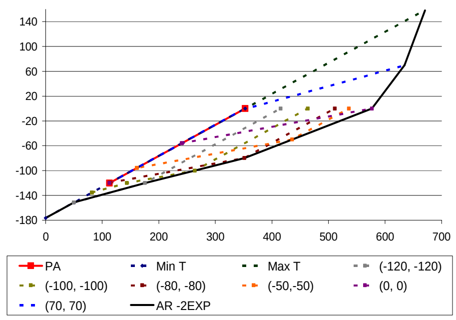

Figure 6 Attainable Region for two expanders

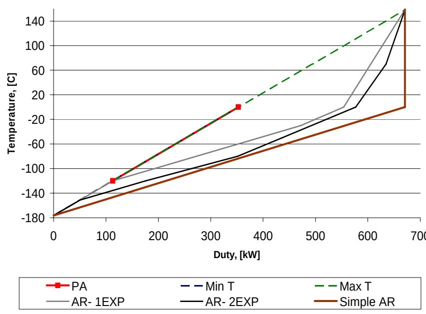

Figure 7 Various Attainable Regions

If two expanders, it is possible to have three times the heat capacity flowrate of the original stream as the stream may be heated through the same temperature region three times. In the calculations, an equal pressure ratio is used for the two stages. It is observed that the largest AR is found when the substreams are heated to the same temperature level before each expansion. Figure 6 shows the original stream, the individual CCs for the expanded stream and the AR for two stage expansion. Figure 7 shows the original stream, expansion at minimum (-120ºC) and maximum (159.47ºC) temperatures, as well as the AR for one and two expanders. As can be seen, the AR increases only slightly by adding a second expander. This increase is even less when adding a third expander.

As it is time consuming to develop the AR, a simplified version is developed. The simple AR (Figure 7) is defined as the triangle between the minimum and maximum temperatures and the maximum attainable duty at the original target temperature. This region will always be larger than the AR for two expanders.

4. Discussion and Conclusions

A simplified method for obtaining all possible Composite Curves, here referred to as the Attainable Region (AR), for a pressurized cold stream using one or two expanders has been developed. This graphical tool is an important addition to the ExPAnD methodology which shows great potential for minimizing total shaft work in the synthesis of subambient processes by utilizing pressure exergy for additional cooling. A limiting AR using an infinite number of expanders has also been developed, but space limitations prohibits its presentation here.

In order to simplify the construction of the AR, assumptions of ideal gas with constant C_p and isentropic expansion have been used, however, the major findings in this paper would not change if a process simulator with rigorous thermodynamics and real expansion had been used. The current version of the AR only includes expansion and heating, while industrial case studies have shown that even compression and cooling of a pressuirized cold stream may be beneficial in cases with surplus of shaft work and "local" cooling duty surplus.

A combined use of the graphical AR tool and numerical exergy calculations is expected to considerably reduce the need for heuristic rules developed as an integral part of the original ExPAnD methodology for subambient processes.

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