CHEMICAL ENGINEERING TRANSACTIONS

VOL. 45, 2015

A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet

Guest Editors: Petar Sabev Varbanov, Jiří Jaromír Klemeš, Sharifah Rafidah Wan Alwi, Jun Yow Yong, Xia Liu

ISBN 978-88-95608-36-5; **ISSN** 2283-9216

DOI: 10.3303/CET1545108

Appropriate Placement of Compressors and Expanders in Above Ambient Processes

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The appropriate placement of compressors and expanders is studied in this paper. Since both heat and work are involved, the topic is extended from heat integration to the integration of both heat and work. The objective is to minimize exergy consumption for the integrated processes. A set of theorems have been proposed for assisting the design. A graphical design methodology using the Grand Composite Curve is developed that achieves the target of minimum exergy consumption.

1. Introduction

The concept of Appropriate Placement, also referred to as Correct Integration, is fundamental in Pinch Analysis, and a special case of the plus/minus principle (Linnhoff and Vredeveld, 1984). A quantitative approach is based on the Grand Composite Curve (GCC) that gives the amount of heat that can be correctly integrated. While this type of analysis is simple for reactors (Glavič et al., 1988), distillation columns (Linnhoff et al., 1983), evaporators (Smith and Linnhoff, 1988), heat pumps and heat engines (Townsend and Linnhoff, 1983), it is considerably more complicated for compressors and expanders since both heat and work are involved. The problem is extended to the integration of both heat and work. In addition, the shape of the GCC will change since the streams to be compressed or expanded are included when drawing the GCC. The placement of compressors was shortly discussed in the work by Glavič et al. (1988) with focus on reactor systems. Aspelund et al. (2007) formulated two heuristic rules for the placement of compressors and expanders in heat exchanger networks (HENs): (i) compression adds heat to the system and should preferably be done above Pinch, and (ii) expansion provides cooling to the system and should preferably be done below Pinch. The rules were stated more specifically by Gundersen et al. (2009) in the sense that both compression and expansion should start at the pinch temperature. An application example is the recuperative vapour recompression cryogenic air distillation process developed by Fu and Gundersen (2013). Another application is the N_2 Brayton cycle in oxy-combustion processes (Fu and Gundersen, 2014). On the basis of the heuristic rules proposed by Gundersen et al. (2009), Wechsung et al. (2011) presented an MINLP optimization formulation for the synthesis of sub-ambient HENs including compression and expansion. The work is further extended by Onishi et al. (2014) using a superstructure with the objective of minimizing total annualized cost.
The integration of compressors and expanders into HENs is not a straightforward task following the heuristic rules proposed by Gundersen et al. (2009). This paper presents a systematic methodology for such integration in above ambient processes. The objective is to minimize exergy consumption. A straightforward graphical design procedure is proposed on the basis of a set of theorems.

2. Problem statement

The following problem is to be solved: “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 and expanders in such a way that the exergy consumption is minimized or the exergy production is maximized”.

Please cite this article as: Fu C. , Gundersen T., 2015, Appropriate placement of compressors and expanders in above ambient processes, Chemical Engineering Transactions, 45, 643-648 DOI:10.3303/CET1545108

Table 1: Stream data

Stream	T_s, °C	T_t, °C	mc_p, kW/°C	ΔH, kW	p_s, bar	p_t, bar
H1	400	35	2	730	2	1
H2	320	160	4	640	-	-
H3	110	35	3	225	-	-
C1	15	380	3	1095	1	2
C2	190	250	10	600	-	-
Hot utility	400	400	-	-	-	-
Cold utility	15	15	-	-	-	-

As an illustrative example, the stream data 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 ΔT_{min} = 20 °C, (3) ambient temperature T_0 = 15 °C, (4) cold utility at T_{CU} =1 5 °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 κ = 1.4. The question to be addressed is at what temperatures C1 and H1 should be compressed/expanded so that the exergy consumption is minimised.

3. Theorems

The following four theorems are proposed for the integration of compressors in above-ambient HENs (the proof is not included due to space limitation):

(1) A HEN design with Pinch Compression (compression starts at pinch temperature T_{PI}) consumes the smallest amount of exergy if the following conditions are satisfied: (i) the outlet temperature of Ambient Compression (compression starts at T_0), $T_{comp,0}$, is lower than T_{HU}, and (ii) Pinch Compression does not produce more heating than required.

(2) If the heating demand has been satisfied by Pinch Compression, Ambient Compression is used for the remaining portion if $T_{comp,0} \le T_{PI}$.

(3) If the heating demand has been satisfied by Pinch Compression and $T_{comp,0} > T_{PI}$, Ambient Compression is used for the remaining portion and the corresponding heat (above pinch) should be utilized to reduce the portion using Pinch Compression.

(4) The compression is done at T_0 if $T_{comp,0} > T_{HU}$.

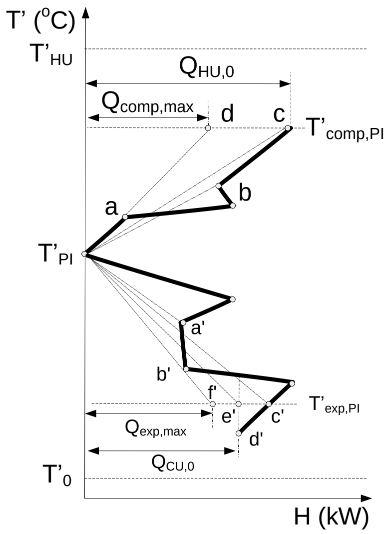

Figure 1: GCC without pressure manipulation

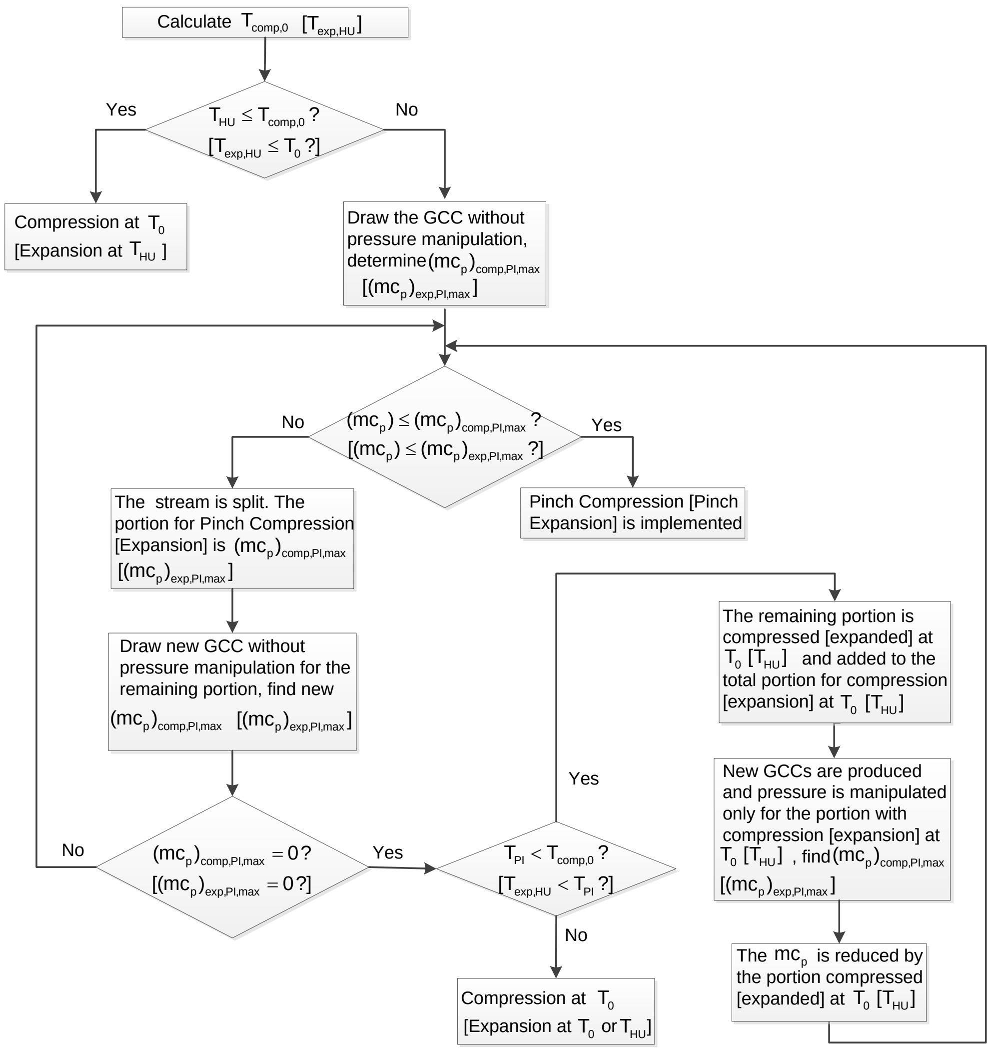

Figure 2: The design procedure

Similarly, the following four theorems are proposed for the integration of expanders in above ambient HENs:

(5) A HEN design with Pinch Expansion (expansion starts at T_{PI}) consumes the smallest amount of exergy if the following conditions are satisfied: (i) the outlet temperature of expansion at T_{HU}, $T_{exp,HU}$, is higher than T_0, and (ii) Pinch Expansion does not produce more cooling than required.

(6) If the cooling demand has been satisfied by Pinch Expansion, the remaining expansion should be done at T_{HU} or T_0 if $T_{exp,HU} \ge T_{PI}$.

(7) If the cooling demand has been satisfied by Pinch Expansion and $T_{exp,HU} < T_{PI}$, the remaining expansion should be done at T_{HU} and the corresponding cooling (below Pinch) should be utilized to reduce the portion using Pinch Expansion.

(8) Expansion should be done at T_{HU} if $T_{exp,HU} < T_0$.

4. Design procedure

Figure 1 shows the GCC for process streams without pressure manipulation. Modified temperatures (T') are used (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/Expansion is $T'_{comp,PI}$ and $T'_{exp,PI}$. A temperature is defined as a Potential Pinch

Point if it may create a new pinch after the heating/cooling effect caused by Pinch Compression/Expansion is included. The following temperatures are Potential Pinch Points: (i) the convex kink points on the GCC in the region between $T = T'_{exp,PI}$ and $T = T'_{comp,PI}$ (such as points a, b, a' and b'); (ii) the points $T = T'_{comp,PI}$ and $T = T'_{exp,PI}$ on the GCC (points c and c'), or the point with the lowest temperature on the GCC (point d') if $T'_{exp,PI}$ is lower than this temperature and the point with the highest temperature if $T'_{comp,PI}$ is higher than the temperature; (iii) the intersection point between the constant temperature line $T = T'_{exp,PI}$ (or $T = T'_{comp,PI}$) and a pocket (point e') on the GCC.

The maximum portion of the stream that can use Pinch Compression, $(mc_p)_{comp,PI,max}$, is determined by the following steps: starting at the pinch point (T'_{PI}), draw lines between the pinch point and Potential Pinch Points (above pinch) 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 d in Figure 1), $Q_{comp,max}$, is equal to the maximum work resulting from Pinch Compression, and $(mc_p)_{comp,PI,max}$ can thus be determined as $Q_{comp,max} / (T'_{comp,PI} - T'_{PI})$. If the mc_p of the stream to be compressed is larger than $(mc_p)_{comp,PI,max}$, stream splitting is required and the fraction of the stream using Pinch Compression is $(mc_p)_{comp,PI,max}$. The maximum portion of the stream that uses Pinch Expansion, $(mc_p)_{exp,PI,max}$, is determined in a similar way: starting at the Pinch Point, draw lines between the pinch point and Potential Pinch Points (below Pinch) and extend the line with the largest negative slope until it intersects with the constant temperature line ($T = T'_{exp,PI}$). The corresponding cooling demand $Q_{exp,max}$ at the intersection (point f' in Figure 1) is equal to the maximum work resulting from Pinch Expansion, and $(mc_p)_{exp,PI,max}$ is determined as $Q_{exp,max} / (T'_{PI} - T'_{exp,PI})$. Stream splitting is required if $mc_p > (mc_p)_{exp,PI,max}$ and the fraction of the stream using Pinch Expansion is $(mc_p)_{exp,PI,max}$.

On the basis of the theorems, a graphical design procedure has been developed and is illustrated in Figure 2. The case for the integration of expanders is presented in brackets and not explained in detail. The first step is to calculate $T_{comp,0}$ and compare it with T_{HU}. According to Theorems 1 and 4, compression should start at T_0 if $T_{comp,0} > T_{HU}$ and at T_{PI} if $T_{comp,0} \leq T_{HU}$. When Pinch Compression is used, according to Theorem 1, the entire stream is compressed at T_{PI} if its mc_p is less than $(mc_p)_{comp,PI,max}$, which is determined using the concept of Potential Pinch Points. Otherwise, the stream is split and Pinch Compression is used for the portion $(mc_p)_{comp,PI,max}$. A new GCC is then produced, where the pressure manipulation of the portion with Pinch Compression, i.e. the heating or cooling of the portion from T_s to T_{PI} before compression and from $T_{comp,PI}$ to T_t after compression are included. The pressure manipulation of the remaining portion should not be included. The portion available for compression at new pinch temperatures can then be determined. The procedure is repeated until either the entire stream has been compressed or the heating demand has been completely satisfied (i.e. the pinch problem has become a threshold problem, $(mc_p)_{comp,PI,max}$ =0). In the latter case, according to Theorem 2, the remaining portion of the stream is compressed at T_0 if $T_{comp,0} \leq T_{PI}$. Otherwise, and according to Theorem 3, the portion for compression at the original T_{PI} should be reduced and an iterative procedure is required: A new GCC is produced by including pressure manipulation only for the portion of the stream with compression at T_0 (the other portion of the stream is included in the GCC without pressure manipulation), and the procedure for implementing Pinch Compression is repeated. The procedure stops if the entire stream has been compressed, otherwise the portion for compression at T_0 increases until $T_{comp,0}$ is lower than the new Pinch temperatures (which means that the Pinches below $T_{comp,0}$ have been removed). When the heating demand has been completely satisfied by compression at the new pinch point(s) above $T_{comp,0}$, the remaining portion of the stream should be compressed at T_0.

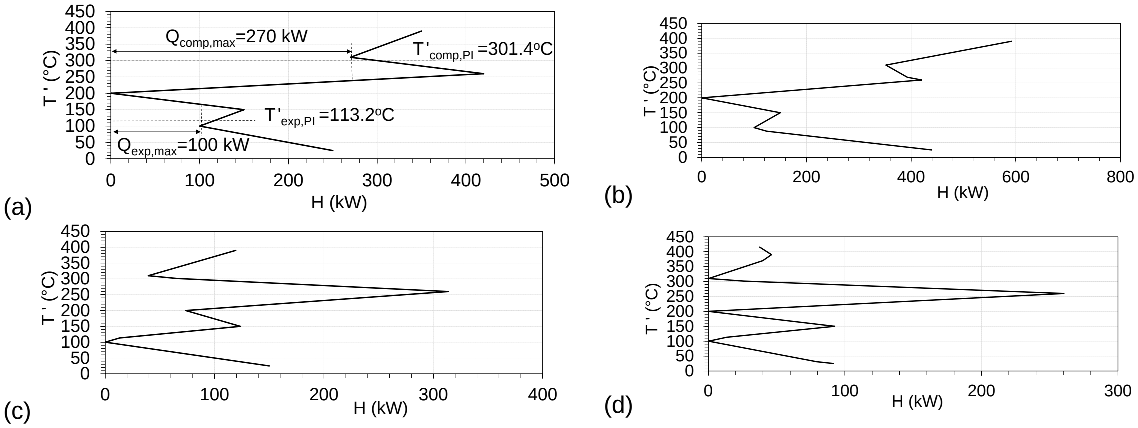

Figure 3: GCCs: (a) Case O; (b) Case I; (c) Case II; (d) Case III

5. Illustrative example

For the stream data presented in Table 1, the GCC for Case O without pressure manipulation is presented in Figure 3(a). The pinch temperature is 200 °C. The following three cases are studied: Case I - H1 is expanded at T_{HU} (the highest temperature) and C1 is compressed at T_0 (the lowest temperature); Case II - both compression and expansion start at T_{PI}; Case III - the proposed procedure is applied. For Cases I and II, the design is straightforward. For Case III, $T_{comp,0}$ = 78.1 °C $< T_{HU}$ and $T_{exp,HU}$ = 279.1 °C $> T_0$, Pinch Compression/Expansion should be used (Theorems 1 and 5). The work resulting from Pinch Compression/Expansion is determined to be $Q_{comp,max}$ = 270 kW and $Q_{exp,max}$ = 100 kW based on Figure 3(a). The maximum portions are determined to be $(mc_p)_{comp,PI,max}$ = 2.66 kW/°C and $(mc_p)_{exp,PI,max}$ = 1.15 kW/°C. Streams C1 and H1 should thus be split: the first portions (indexed α) are compressed/expanded at T_{PI} while the remaining portions are temporarily not compressed/expanded. A new GCC is then drawn and two new pinch points are created at 100 and 310 °C. The maximum portions compressed/expanded at the new pinch temperatures can thus be determined with a similar procedure using the concept of Potential Pinch Points: $(mc_p)_{comp,PI,max,new}$ = 0.64 kW/°C and $(mc_p)_{exp,PI,max,new}$ = 2.18 kW/°C. The remaining portions (indexed β) of streams H1 and C1 can thus be completely compressed/expanded at the new T_{PI}.

Table 2: New stream data for H1 and C1

Streams	T_s , °C	T_t , °C	mc_p , kW/°C	ΔH , kW	p_s , bar	p_t , bar
Case I						
H1	279.1	35	2	488.2	1	1
C1	78.1	380	3	905.7	2	2
Case II						
H1_1	400	210	2	380	2	2
H1_2	123.2	35	2	176.4	1	1
C1_1	15	190	3	525	1	1
C1_2	291.4	380	3	265.8	2	2
Case III						
H1_α1	400	210	1.15	218.5	2	2
H1_α2	123.2	35	1.15	101.4	1	1
H1_β1	400	110	0.85	246.5	2	2
H1_β2	41.2	35	0.85	5.3	1	1
C1_α1	15	190	2.66	465.5	1	1
C1_α2	291.4	380	2.66	235.7	2	2
C1_β1	15	300	0.34	96.9	1	1
C1_β2	425.5	380	0.34	15.5	2	2

Table 3: Performance comparison

Cases	O	I	II	III
Hot utility demand, kW	350	591.8	119.4	37.6
Cold utility demand, kW	250	439.3	150	91.7
Pinch temperature, °C	200	200	100	100; 200; 310
Compression work, kW	-	189.3	304.2	312.4
Expansion work, kW	-	241.8	173.6	158.3
Exergy consumption, kW	-	286.0	198.9	175.6

Due to pressure manipulation, the new data for streams H1 and C1 are shown in Table 2 and the corresponding GCCs are shown in Figure 3. The performance comparison is presented in Table 3. Compared to Case I (compression at T_0 and expansion at T_{HU}), the exergy consumption is reduced by 30.5 % when both compression and expansion start at T_{PI} (Case II) following the heuristic rules proposed by Gundersen et al. (2009). However, the original pinch has been removed according to Figure 3(c), indicating that too large portions have been compressed/expanded at T_{PI}. Minimum exergy consumption is achieved when the proposed procedure is applied (Case III). The exergy consumption is reduced by 38.6 % compared to Case I. The reason for exergy savings is that the heat resulting from both compression and expansion has been completely utilised. This fact can be observed by comparing Cases III and O. The heating/cooling demand in Case III is reduced by an amount equal to the compression/expansion work.

6. Conclusions

A systematic methodology for the integration of compressors and expanders into heat exchanger networks above ambient temperature has been developed. The objective has been to minimize exergy consumption since both heat and work are involved. The Grand Composite Curve has been used as a tool in the graphical design procedure. Considerable exergy savings (38.6 %) have been achieved in the illustrative example by maximum utilization of Pinch Compression/Expansion.

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