CHEMICAL ENGINEERING TRANSACTIONS

VOL. 63, 2018

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

Guest Editors: Jeng Shiun Lim, Wai Shin Ho, Jiří J. Klemeš

ISBN 978-88-95608-61-7; **ISSN** 2283-9216

DOI: 10.3303/CET1863048

Compressor Shaft Work Targeting using New Numerical Exergy Problem Table Algorithm (Ex-PTA) in Sub-Ambient Processes

Muhammad Nurheilmi Hamsani[a], Peng Yen Liew[a,b,*], Timothy G. Walmsley[c], Sharifah Rafidah Wan Alwi[b,d]

[a]Malaysia – Japan International Institute of Technology (MJIIT), Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, 54100 Kuala Lumpur, Malaysia
[b]Process Systems Engineering Centre (PROSPECT), Research Institute for Sustainable Environment, Universiti Teknologi Malaysia (UTM), 81310 UTM Johor Bahru, Johor, Malaysia
[c]Sustainable Process Integration Laboratory (SPIL), NETME Centre, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2896/2, 616 00 Brno, Czech Republic
[d]Faculty of Chemical and Energy Engineering, Universiti Teknologi Malaysia (UTM), 81310 UTM Johor Bahru, Johor, Malaysia
pyliew@utm.my

One of the major challenges faced by energy intensive industries is an excessive greenhouse gas emission to the atmosphere due to high consumption of fossil fuels throughout the production processes. Due to high electricity usage in intensive industries, it is strongly advisable to all the engineers and other stakeholders to reduce the amount of energy needed for production, thus reducing carbon footprints. This is because the power generation industry emits approximately 37 % of total carbon dioxide emission to the atmosphere. Process improvement via Process Integration enhances the process energy efficiency, which contributes to the minimisation of fossil fuels and electricity consumption. Sub-ambient processes with refrigeration system are one of the highly energy intensive processes, which consumes a vast amount of electrical energy to run the compressors for fulfilling the process cooling demand. It is crucial to optimise the process-utility heat transfer in the system including the placement of compressors and expanders to minimise the exergy losses and shaft work consumption. This paper presents a combined energy analysis technique of Pinch Analysis and Exergy Analysis to determine exergy losses and compressor shaft work targeting in sub-ambient processes via a novel numerical approach known as the Exergy Problem Table Algorithm (Ex-PTA). The validity of the novel approach is demonstrated by using an illustrated case study. Based on the new numerical method, the total exergy loss in the process is 4.42 kW which is equivalent to 7.4 kW potential savings of compressor shaft work. In the economic analysis, the wasted potential shaft work costs a loss of approximately 19,926 MYR/y which should be avoided to minimise process operating cost.

1. Introduction

Chemical industrial sector requires extensive energy use throughout the manufacturing processes. Combustion of fossil fuels contributes to the emission of carbon dioxide to the atmosphere, which increases drastically from time to time. It is crucial for engineers and other stakeholders to conduct energy management efficiently in their own premises due to the increasing energy price and the impact of energy consumption on carbon dioxide emission, air pollution and climate change. One of the strategies to reduce energy consumption is heat recovery network via Process Integration.

Heat Exchanger Network (HEN) can be designed based on the energy target using Pinch Analysis technique. The Pinch Analysis technique was originally developed in the 1970s by Linnhoff and Flower (1978) and is proven to boost energy efficiency by up to 40 % (Hackl and Harvey, 2012). The technique has been extended to Total Site Heat Integration (TSHI), which considers heating and cooling supply and demand between

Please cite this article as: Muhammad Nurheilmi Hamsani, Peng Yen Liew, Timothy G. Walmsley, Sharifah Rafidah Wan Alwi, 2018, Compressor shaft work targeting using new numerical exergy problem table algorithm (ex-pta) in sub-ambient processes, Chemical Engineering Transactions, 63, 283-288 DOI:10.3303/CET1863048

several processes or plants (Dhole and Linnhoff, 1993), and has been the subject of a recent review by Liew et al. (2017). Early in its development, TSHI was successfully applied to enhance the energy efficiency of large industrial sectors (Klemeš et al., 1997). A new graphical TSHI approach has been developed by Tarighaleslami et al. (2017) for recovering heat using non-isothermal utility in low temperature processes. Optimisation of the utility temperature selection can be applied to the graphical TSHI method for greater advantages (Tarighaleslami et al., 2016). Due to its graphical nature, it is difficult to construct when it deals with large and complicated problems and may encounter some inaccuracies. A novel numerical methodology for TSHI is then introduced by Liew et al. (2012) to improve the accuracy and efficiency of the method, which was later improved to account for stream variations (Liew et al., 2014).

In sub-ambient processes, a combined Pinch and Exergy Analysis technique has been developed by Linnhoff and Dhole (1992) to enable targeting for compressor shaft work savings. Exergy Analysis is performed to determine exergy losses in the processes which is then used to target for reduction of the compressors shaft work consumption. Aspelund et al. (2007) introduced a novel methodology, known as the Extended Pinch Analysis and Design (ExPAnD) as a new procedure to design sub-ambient processes. The methodology discussed on how utilisation of heating and cooling capacity can be done by manipulating the stream pressure. A new parameter known as the exergetic temperature was introduced by Marmolejo-Correa and Gundersen (2012). The new exergetic temperature was used to develop graphical representation which can be used in parallel with the ExPAnD methodology for determination of exergy targets. A new numerical approach in determining exergy targets and losses known as Exergy Problem Table Algorithm (Ex-PTA) has then been developed by Hamsani et al. (2017) as an improved method compared to the graphical method based on the ExPAnD methodology.

This paper aims to determine the target for compressor shaft work in sub-ambient processes using the Ex-PTA. In this paper, the targeted shaft work saving potential is quantified in a cost function for highlighting the importance of exergy losses towards sustainable process economy. This is due to a large amount of electricity being consumed to run the compressor in a refrigeration system, which is very costly.

2. Methodology

A summary of the proposed numerical approach for exergy losses and targets determination is given in this section. The methodology is then demonstrated in detail using a case study in the next section. The methodology is summarised as follows:

Step 1: Data Extraction

The process data for hot and cold streams in the refrigeration process are determined. This procedure includes extracting supply temperature (T_s), target temperature (T_t) (both in Celsius and exergetic form), heat capacity (CP), and enthalpy (ΔH). The temperature-based exergy ($\Delta\dot{E}^T$) and pressure-based exergy ($\Delta\dot{E}^P$) are determined using Eq(1) and Eq(2).

$$\dot{E}^T = \dot{m}C_p\left[T_o\left(\frac{T}{T_o} - \ln\frac{T}{T_o} - 1\right)\right] = \dot{m}C_pT^{E^T} = CP.T^{E^T} \tag{1}$$

$$\dot{E}^P = \dot{m}C_p\left[T_o\left(\ln\frac{P}{P_o}^{\frac{\kappa-1}{\kappa}}\right)\right] = \dot{m}C_pT^{E^P} = CP.T^{E^P} \tag{2}$$

where $\dot{m}$ is mass flow rate, C_p is specific heat capacity, T_o is ambient temperature, and P_o is ambient pressure.

Step 2: Energy Consumption Targeting

Energy targets in terms of Q_{Hmin} and Q_{Cmin}, are determined via the Problem Table Algorithm (PTA). The Pinch and enthalpy in each temperature interval for all streams are also identified.

Step 3: Removal of Heat Recovery Pockets in Grand Composite Curves (GCC)

The GCC is developed and heat recovery pockets are removed. Additional temperature intervals needed to remove the heat recovery pockets (Figure 1) are added using linear interpolation of existing temperature intervals.

Step 4: Construction of Dual Exergy Problem Table Algorithm (Ex-PTA)

Two Ex-PTA for the GCC pockets and pocket-less GCC are constructed (Hamsani et al., 2017). The temperature points determined from Step 3 are included in the Ex-PTA. Initial exergy cascade is performed from the highest temperature with 0 kW, while the adjusted exergy cascade is cascaded from top to bottom with the modulus of the negative value present at the heat Pinch in the initial exergy cascade.

Step 5: Exergy Targeting

Exergy targets in terms of minimum exergy requirement and maximum exergy rejection are determined from the adjusted cascade in the Ex-PTA for the pocket-less GCC and exergy losses are determined from the adjusted cascade in the Ex-PTA for GCC pockets.

Step 6: Potential Shaft Work Determination

To determine compressor shaft work, the exergetic efficiency (η_{ex}) of the refrigeration system must be taken into account, which can be calculated using Eq(3).

$$W = \frac{\Delta Ex}{\eta_{ex}} \tag{3}$$

where ΔEx is the exergy losses and W is the compressor shaft work.

Step 7: Cost Analysis of Wasted Potential Shaft Work

Economic evaluation of the wasted potential shaft work is estimated. Some recommendation is suggested to reduce the cost of the refrigeration system.

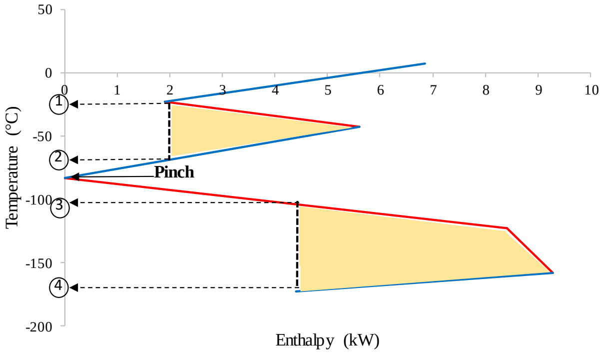

Figure 1: Grand Composite Curve including pockets

3. Case Study

The procedure is illustrated using a case study adopted from Marmolejo-Correa and Gundersen (2012).

3.1 Step 1: Data Extraction

The reference temperature and pressure in the system are 15 °C (T_o) and 100 kPa (P_o). A theoretical ΔT_{min} of 0 K is assumed for the process. The heat capacity ratios (κ) for hot streams, H1 and H2 are 1.30 and for cold streams, C1 and C2 are 1.41. Both initial and target temperatures are converted to exergetic temperature (T^E) using Eq(1) (Marmolejo-Correa and Gundersen, 2012). The negative sign of $\Delta\dot{E}^T$ for both cold streams and $\Delta\dot{E}^P$ for H1 and C1 indicate that the streams are exergy sources while the positive sign of $\Delta\dot{E}^T$ for both hot streams and $\Delta\dot{E}^P$ for C2 represent exergy sinks. Streams to be expanded are the exergy sources and, in sub-ambient processes, can provide cooling duty to the system. Shaft work generation from the expansion process increases with increasing fluid inlet temperature but the resulting cooling duty becomes a lower quality (i.e. higher temperature). This demonstrates the important trade-off between quantity and quality of the cooling duty and the amount of work generation when compression and/or expansion operations are involved (Fu and Gundersen, 2015). Table 1 shows the process stream data for the case study.

Table 1: Process stream data

	T_s (ºC)	T_t (ºC)	P_s (kPa)	P_t (kPa)	CP (kW/K)	ΔH (kW)	Ts^{E^T} (K)	Tt^{E^T} (K)	$\Delta\dot{E}^T$ (kW)	$\Delta\dot{E}^P$ (kW)
H1	6.85	-123.15	450	200	0.185	-24.05	0.12	50.01	9.23	-9.97
H2	-23.15	-158.15	120	120	0.350	-47.25	2.77	91.62	31.10	0.00
C1	-173.15	-43.15	700	250	0.325	42.25	116.93	6.80	-35.79	-28.02
C2	-83.15	6.85	120	300	0.350	31.50	21.87	0.12	-7.61	26.86

3.2 Step 2: Energy Consumption Targeting

The PTA is constructed to determine the minimum energy requirement. 6.85 kW of hot utility is consumed while cooling requirement of the process is 4.40 kW with a Pinch of -83.15 ºC (Hamsani et al., 2017). Enthalpy in the interval is then calculated using Eq(3) once all the heat capacities of the streams are summed up. Next, enthalpy of the lowest temperature of the hot stream is started with zero and cascaded upward. On the other hand, enthalpy of the lowest temperature of the cold stream is started with Q_{Cmin} value of 4.40 kW.

3.3 Step 3: Removal of Heat Recovery Pockets

The heat Grand Composite Curve (GCC) is developed after completing the heat cascade. Next, the process-process heat recovery pocket is removed. This heat recovery pocket represents exergy losses in the system due to heat transfer. Points 2 and 3 in Figure 1 are known as additional temperature points where heat recovery occurs, while the light-yellow region is the heat recovery itself. It is worth noticing that point 2 and 3 have the same enthalpy value with point 1 and 4. Based on PTA, point 1 has an enthalpy of 1.90 kW while point 4 has an enthalpy of 4.40 kW. As shown in Figure 1, point 2 is located between temperature points of -43.15 °C and -83.15 °C. Linear interpolation is then performed to determine the exact temperature value of point 2 which is 69.58 °C. As for point 3, a similar step is done to determine the temperature value which results in -104.10 °C.

3.4 Step 4: Construction of Dual Exergy Problem Table Algorithm (Ex-PTA)

The dual Ex-PTA for the pocket-less GCC and GCC pockets are constructed as shown in Table 2 and 3. Point 2 and 3 which have determined in Step 3 are also added in temperature column in both Ex-PTA. For GCC pocket, the enthalpy cascade is determined by deducting the adjusted enthalpy cascade in PTA with pocket-less enthalpy cascade in Table 2. CP of the streams is then calculated using Eq(3). Exergy cascade for both Ex-PTA is then performed from high temperature to low temperature with an initial value of zero. The negative value at Pinch point of the previous cascade is then used to initiate the adjusted exergy cascade after first changing it to a positive value.

3.5 Step 5: Exergy Targeting

Maximum exergy rejection and minimum exergy requirement are determined from Table 2, while exergy loss is determined from Table 3. Exergy value at the lowest exergetic temperature (1.33 kW) represents the target for maximum exergy rejection, whereas exergy value at the highest exergetic temperature (2.67 kW) is the target for minimum exergy requirement. These values differ with the result obtained from ExPAnD method which gives a maximum exergy rejection of 0.46 kW and a minimum exergy requirement of 5.38 kW (Marmolejo-Correa and Gundersen, 2012). This difference is due to ExPAnd method assumes vertical process-process heat transfer within the process. If the exergy rejection of the process exceeds 1.33 kW, exergy transfer across the Pinch will occur and the exergy requirement will increase by the same amount of excess exergy rejection.

Exergy loss is directly proportional to the finite temperature difference of process-process heat transfer. If the exergy source utility supplies exergy greater than the minimum exergy requirement (assuming no exergy transfer across the Pinch), exergy loss occurs due to an increase in approach temperature for process-process and/or process-utility heat transfer above the exergetic Pinch. Cross-Pinch addition of exergy to below the exergetic Pinch or the rejection of exergy from above the exergetic Pinch causes the minimum exergy requirement for the process to increase. For a system with a ΔT_{min} of 0 K, the pockets on the GCC represent the heat transfer at approach temperatures greater than the ΔT_{min}. This heat transfer results in exergy loss. By converting the heat cascade of the GCC pockets, minimum exergy loss targets may be determined as 0.48 kW below the exergetic Pinch and 3.94 kW above the exergetic Pinch, which is a total of 4.42 kW.

3.6 Step 6: Potential Shaft Work Determination

After determining exergy loss in the system, the compressor shaft work is calculated using Eq(4). Exergetic efficiency (η_{ex}) is then used to estimate the shaft work of the compressor. The use of exergetic efficiency is significant in this study to measure the performance of sub-ambient processes (Marmolejo-Correa and Gundersen, 2011). Linnhoff and Dhole (1992) propose a value of 0.59 for η_{ex} while Smith (2005) proposes a similar value of 0.60. The previous work done by Linnhoff and Dhole (1992) showed that there was only 1.9 % difference between the proposed η_{ex} value and the simulation result. A value of 0.6 is used for η_{ex} to determine the potential compressor shaft work savings which is 7.4 kW. This means that 7.4 kW of compressor shaft work (wasted potential shaft work) could be reduced due to maximum work potential obtainable in the Exergy Analysis.

3.7 Step 7: Cost Analysis of Wasted Potential Shaft Work

Assuming the running hours of the compressor on a yearly basis is 7,920 h (330 d), the total energy consumption of the wasted potential shaft work is 58,608 kWh. The tariff for high voltage industrial sector is

0.34 MYR/kWh (TNB, 2014). As a result, 19,926 MYR/y is wasted due to the exergy loss in the system. One of the crucial ways to minimise the exergy loss within the system is reducing the approach temperature of the streams so that process-utility heat transfer is minimised. This can be performed by increasing the utility (refrigerant) temperature level as high as possible to reduce high temperature difference heat transfer of the streams and reduce the cost of the wasted potential shaft work.

Table 2: The Ex-PTA for the pocket-less GCC

T (ºC)	T^E (K)	Pocket-less Enthalpy Cascade kW	ΔT^E (K)	$\sum CP_H - \sum CP_C$ (kW/K)	$\Delta\dot{E}$ (kW)	Initial Exergy Cascade (kW)	Adjusted Exergy Cascade (kW)
6.85	0.12	6.85				0.00	1.33
			2.65	-0.17	-0.45		
-23.15	2.77	1.90				-0.45	0.88
(Point 1)			4.03	0.00	0.00		
-43.15	6.80	1.90				-0.45	0.88
			8.74	0.00	0.00		
-69.58	15.54	1.90				-0.45	0.88
(Point 2)			6.31	-0.14	-0.88		
-83.15	21.87	0.00				-1.33	0.00
(Pinch)			12.70	0.21	2.67		
-104.10	34.57	4.40				1.34	2.67
(Point 3)			15.40	0.00	0.00		
-123.15	49.97	4.40				1.34	2.67
			41.65	0.00	0.00		
-158.15	91.62	4.40				1.34	2.67
			25.31	0.00	0.00		
-173.15	116.93	4.40				1.34	2.67
(Point 4)							

Table 3: The Ex-PTA for the pockets of the GCC

T (ºC)	T^E (K)	Pocket Enthalpy Cascade kW	ΔT^E (K)	$\sum CP_H - \sum CP_C$ (kW/K)	$\Delta\dot{E}$ (kW)	Initial Exergy Cascade (kW)	Adjusted Exergy Losses Cascade (kW)
6.85	0.12	0.00				0.00	0.48
			2.65	0.00	0.00		
-23.15	2.77	0.00				0.00	0.48
(Point 1)			4.03	0.19	0.74		
-43.15	6.80	3.70				0.74	1.22
			8.74	-0.14	-1.22		
-69.58	15.54	0.00				-0.48	0.00
(Point 2)			6.31	0.00	0.00		
-83.15	21.87	0.00				-0.48	0.00
(Pinch)			12.70	0.00	0.00		
-104.10	34.57	0.00				-0.48	0.00
(Point 3)			15.40	0.21	3.23		
-123.15	49.97	4.00				2.75	3.23
			41.65	0.02	1.04		
-158.15	91.62	4.88				3.79	4.27
			25.31	-0.33	-8.21		
-173.15	116.93	0.00				-4.42	-3.94
(Point 4)							

4. Conclusion

Pinch and Exergy Analysis were used to analyse energy saving opportunities in sub-ambient processes through compressor work consumption minimisation. A novel numerical tool known as dual Exergy Problem Table Algorithm (Ex-PTA) has been introduced to determine the minimum exergy losses and compressor shaft work targets. This numerical tool results in more accurate and efficient findings as compared to the graphical method. Exergy cascade performed by Ex-PTA was aided by the traditional PTA as for heat cascade. The tool was then illustrated using an illustrative case study. The result showed that the minimum exergy loss and compressor shaft work targeting were 4.42 kW and 7.4 kW. Based on the economic evaluation, 19,926 MYR/y worth of potential compressor shaft work were lost throughout the process. The exergy losses could be avoided by increasing the utility (refrigerant) temperature level as high as possible to reduce heat transfer of the streams. In future research, the integration of heating and cooling capacity in above-ambient processes with sub-ambient processes with minimum approach temperature greater than zero can be further investigated. The usage of Ex-PTA in a Total Site Heat Integration (TSHI) is also worth to be explored.

Acknowledgments

The authors appreciate the financial support from Universiti Teknologi Malaysia through Research University Grant. The first author would like to express his gratitude to Malaysia-Japan International Institute of Technology (MJIIT) in providing the student incentive throughout the research project. This research has been supported by the EU project “Sustainable Process Integration Laboratory – SPIL”, project No. CZ.02.1.01/0.0/0.0/15_003/0000456 funded by EU “CZ Operational Programme Research and Development, Education”, Priority 1: Strengthening capacity for quality research.

Reference

Aspelund A., Berstad D.O., Gundersen T., 2007, An extended Pinch Analysis and design procedure utilizing pressure based exergy for subambient cooling, Applied Thermal Engineering, 27 (16), 2633-2649.

Dhole V.R., Linnhoff B., 1993, Total site targets for fuel, co-generation, emissions, and cooling, Computers and Chemical Engineering, 17, 101-109.

Fu C., Gundersen T., 2015, Sub-ambient heat exchanger network design including expanders, Chemical Engineering Science, 138, 712-729.

Hackl R., Harvey S., 2012, Total site analysis (TSA) and exergy analysis for shaft work and associated steam and electricity savings in low temperature processes in industrial clusters, Chemical Engineering Transactions, 29, 73-78

Hamsani M.N., Liew P.Y., Walmsley T.G., 2017, A new numerical approach for exergy targets and losses determination in sub-ambient processes, Chemical Engineering Transactions, 61, 1225-1230.

Klemeš J., Dhole V.R., Raissi K., Perry S.J., Puigjaner L., 1997, Targeting and design methodology for reduction of fuel, power and CO_2 on total sites, Applied Thermal Engineering, 17 (8-10), 993–1003.

Liew P.Y., Theo W.L., Wan Alwi S.R., Lim J.S., Manan Z.A., Klemeš J.J., Varbanov P.S., 2017, Total site Heat Integration planning and design for industrial, urban and renewable systems, Renewable and Sustainable Energy Reviews, 68, 964-985

Liew P.Y., Wan Alwi S.R., Varbanov P.S., Manan Z.A., Klemeš J.J., 2012, A numerical technique for total site sensitivity analysis, Applied Thermal Engineering, 40, 397–408.

Liew P.Y., Wan Alwi S.R., Klemeš J.J., Varbanov P.S., Abdul Manan Z., 2014, Algorithmic targeting for Total site Heat Integration with variable energy supply/demand, Applied Thermal Engineering 70 (2), 1073–1083.

Linnhoff B., Flower J.R., 1978, Synthesis of heat exchanger networks, Part I: systematic generation of energy optimal network, AIChE Journal, 24, 633-642.

Linnhoff B., Dhole V.R., 1992, Shaftwork targets for low-temperature process design, Chemical Engineering Science, 47 (8), 2081-2091.

Marmolejo-Correa D., Gundersen T., 2011, Low temperature process design: challenges and approaches for using exergy efficiencies, Computer-Aided Chemical Engineering, 29, 1909-1913.

Marmolejo-Correa D., Gundersen T., 2012, A new graphical representation of exergy applied to low temperature process design, Computer-Aided Chemical Engineering, 31, 1180-1184.

Smith, R., 2005, Chemical Process: Design and Integration, John Wiley, Chichester, UK.

Tarighaleslami A.H., Walmsley T.G., Atkins M.J., Walmsley M.R.W., Neale J.R., 2016, Optimisation of non-isothermal utilities using the unified total site Heat Integration method, Chemical Engineering Transactions, 52, 457–462.

Tarighaleslami A.H., Walmsley T.G., Atkins M.J., Walmsley M.R.W., Liew P.Y., Neale J.R., 2017, A unified Total Site Heat integration targeting method for isothermal and non-isothermal utilities, Energy, 119, 10–25.

TNB (Tenaga Nasional Berhad), 2014, Pricing & tariffs <www.tnb.com.my/commercial-industrial/pricing-tariffs1> accessed on 15.10.2017.