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A New Numerical Approach for Exergy Targets and Losses Determination in Sub-Ambient Processes

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Sub-ambient processes such as a refrigeration system are a highly energy intensive area in chemical industries. Refrigeration systems require a high level of process cooling using a combination of compression and expansion operations. It is, therefore, crucial to optimise heat transfer between the utility system and the process streams including the placement of compression and expansion operations to minimise the exergy losses and work as much as possible. This paper demonstrates how heat integration tools such as Pinch Analysis and Exergy Analysis can be applied to determine exergy losses and exergy targets for sub-ambient processes. In this study, a numerical approach, the Exergy Problem Table Algorithm (Ex-PTA), is proposed as an improved method compared to the graphical method based on the Extended Pinch Analysis and Design (ExPAnD) methodology. The methodology is applied to a literature case study of a refrigeration system to prove its validity. For the new numerical method, the minimum exergy requirement above the Exergy Pinch is 2.67 kW, while the maximum exergy rejection below the Exergy Pinch is 1.33 kW. The result shows that the total exergy loss for the process is 4.74 kW. In contrast, the maximum exergy rejection and minimum exergy requirement obtained in ExPAnD are 0.46 kW and 5.38 kW while the total exergy loss is 6.72 kW. These new targets assume so-called horizontal heat transfer is allowed between process and utility streams, whereas the ExPAnD method assumes vertical heat transfer between process and utility and, therefore, results in less optimistic targets.

1. Introduction

Energy demand in the chemical manufacturing sector is increasing drastically due to high production demand. Production cost is highly dependent on the energy price. The increased consumption of fossil fuels also gives negative impacts to the environment as a significant amount of greenhouse gases emit to the atmosphere. These critical issues have drawn the attention of engineers and other stakeholders to design effective corrective actions to address the environmental issues. One method is to reduce energy consumption through increased Process Integration and energy efficiency. There are many approaches to improve the industrial energy efficiency, such as energy audits. However, these audits seldom involve in-depth analysis of process design features and changes for optimum energy use (Fenwicks et al., 2014).

Pinch Analysis through improved Heat Exchanger Network design has been widely used to target and optimise the energy utilisation (Linnhoff and Flower, 1978). Pinch Analysis studies have been carried out for numerous chemical manufacturing and production plants to increase the energy efficiency in the order of 20 % to 40 % (Hackl and Harvey, 2012). One extension of Pinch Analysis is Total Site Heat Integration (TSHI), which integrates heating and cooling supply and demands of co-located processes via the site utility system (Dhole and Linnhoff, 1993). Heating or cooling deficit of a process may be indirectly satisfied by excess heating or cooling capacity of a different process through the generation and consumption of a common utility level. Klemeš et al. (1997) further developed TSHI methodology to enhance the energy efficiency of large industrial scale. Recently Tarighaleslami et al. (2017) further developed the graphical TSHI method for improved application to

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low temperature processes that require non-isothermal utility (e.g. hot water) and use these utility systems to indirectly recover heat. Total Site utility temperature selection can also be optimized to realise even greater benefits (Tarighaleslami et al., 2016). Although these graphical representations provide good visual insights, the approach may encounter some resolution difficulties and inaccuracies for large and complicated problems. Further development in terms of a novel algorithm for TSHI has been introduced by Liew et al. (2012), for better accuracy and efficiency than the graphical representation, and later improved to account for stream variations (Liew et al., 2014).

In sub-ambient processes, Pinch Analysis needed an extension to design networks with work and heat exchange. Compression and expansion of refrigerant are involved in the sub-ambient processes, which means that pressure is also an important design variable in addition to temperature and heat. A stream may be compressed to raise its temperature or expanded to reduce its temperature. A combined Pinch and Exergy Analysis methodology has been proposed by Linnhoff and Dhole (1992) as an extension of Pinch Analysis. Exergy Analysis is a systematic tool for calculating exergy content in the processes. Thus, reduction of compressors shaft work can be analysed. It is not only temperature variable that considers in this analysis but pressure of stream is also involved as design variables. The proposed Exergy Analysis illustrated graphical representation called Exergy Composite Curves (ECCs) and Exergy Grand Composite Curves (EGCCs) based on the Carnot factor. These exergy curves are like the conventional Composite Curves and Grand Composite Curves, except the Carnot factor replaces temperature for the y-axis. Aspelund et al. (2007) proposed a new methodology to design sub-ambient processes, known as the Extended Pinch Analysis and Design (ExPAnD) procedure. The main purpose of the methodology is to utilise heating and cooling capacity by manipulating the pressure of streams to reduce net shaft work. Marmolejo-Correa and Gundersen (2012) introduced a new parameter called Exergy temperature, which is proportional to exergy flow through the heat capacity flow rate. This new temperature scale enabled linear graphical representation of stream with a constant heat capacity flow rate as well as improved Exergy Composite Curves.

The current study presents a numerical approach to determine the exergy losses and exergy targets of the processes via a conventional PTA for the heat cascade and a new Exergy PTA (Ex-PTA) for the exergy cascade. The new numerical approach is applied to a refrigeration system case study that operates below ambient temperature.

2. Methodology

The proposed numerical approach for determining the exergy losses in sub-ambient processes is defined as:

Step 1: Extract process stream data. Process data for all streams in the refrigeration system are extracted from the process design flowsheet such as heat capacity (CP), supply temperature (T_s) and target temperature (T_t) in °C and exergy form and enthalpy (ΔH). Temperature-based exergy ($\Delta\dot{E}^T$) is calculated using Eq(1). Exergy temperature have the same relationship to exergy as normal temperatures have to enthalpy.

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

Step 2: Construct the Problem Table Algorithm (PTA) for heat cascade. The conventional PTA is constructed to determine Q_{Hmin}, Q_{Cmin}, Pinch temperature, and enthalpy in each temperature interval for both hot and cold streams (Klemeš, 2013).

Step 3: Remove heat recovery pockets from the heat Grand Composite Curve (GCC). The heat GCC is created and heat recovery pocket is to be removed. Interpolation between temperature intervals is often required to determine two additional temperature intervals that are needed to remove the pockets.

Step 4: Construct Dual Exergy Problem Table Algorithm (Ex-PTA). Two Ex-PTA for the pocket-less GCC and GCC pockets are calculated separately. The first Ex-PTA of the pocket-less GCC represents the minimum exergy requirement and maximum exergy rejection that is possible for the problem. The second Ex-PTA of the GCC pockets represents exergy loss due to heat transfer within the process. The Ex-PTAs are calculated using the same method as the conventional PTA, except temperatures are converted to exergy form and the resulting cascade is exergy flows (not enthalpy). The additional temperatures from Step 3 are included as intervals in the Ex-PTA. For both Ex-PTA, the initial exergy cascade is started from the highest temperature with 0 kW. The modulus of the negative value present in the initial exergy cascade at the exergy temperature that corresponds to the heat Pinch from the PTA is used to initiate the adjusted exergy cascade.

Step 5: Target minimum exergy requirement, maximum exergy rejection, and exergy losses for the process. The adjusted cascade in the Ex-PTA for the pocket-less GCC provides targets for the minimum exergy requirement and maximum exergy rejection. The adjusted cascade in the Ex-PTA for GCC pockets targets exergy losses above and below the Pinch.

3. Case Study

The sub-ambient case study of Marmolejo-Correa and Gundersen (2012) is used to demonstrate the new method to determine exergy target. These targets are then compared to targets determined using the ExPAnD methodology.

3.1 Step 1: Extract process stream data

Table 1 shows the process stream data for a system that operates in sub-ambient conditions which is taken from Marmolejo-Correa and Gundersen (2012). Reference conditions are set as 15 °C (T_o) and 1 bar (P_o). H1 and H2 are notionally hot streams while C1 and C2 are cold streams. In the system, both H1 and C2 require expansion and C2 needs compression. Supply and target temperatures of the streams are converted to exergy temperature (T^E) using Eq (1). The heat capacity ratios (κ) for H1 and H2 are 1.30 and for C1 and C2 are 1.41. Notice that the highest T^E corresponds to the lowest temperature, which has the highest exergy, and vice versa. In sub-ambient processes, cold streams are the exergy sources and hot streams are the exergy sinks, opposite to above-ambient processes. The negative values of $\Delta\dot{E}^T$ for C1 and C2 and $\Delta\dot{E}^P$ for H1 and C1 indicate that the streams are exergy sources and the positive values of $\Delta\dot{E}^T$ for H1 and H2 and $\Delta\dot{E}^P$ for C2 represent exergy sinks. Furthermore, it is worth noticing that streams that undergo expansion are the exergy source and the exergy is transformed into temperature-based exergy and provide cooling duty to the system and minimise net shaft work. There is, therefore, a trade-off between utility cooling requirement and work consumption when compression and expansion operations of refrigerants are involved (Fu and Gundersen, 2015).

Table 1: Process stream data (Marmolejo-Correa and Gundersen, 2012)

	T_s (ºC)	T_t (ºC)	P_s (bar)	P_t (bar)	CP (kW/K)	ΔH (kW)	Ts^{E^T} (K)	Tt^{E^T} (K)	$\Delta\dot{E}^T$ (kW)
H1	6.85	-123.15	4.5	2	0.185	-24.05	0.12	50.01	9.23
H2	-23.15	-158.15	1.2	1.2	0.35	-47.25	2.77	91.62	31.10
C1	-173.15	-43.15	7	2.5	0.325	42.25	116.93	6.80	-35.79
C2	-83.15	6.85	1.2	3	0.35	31.5	21.87	0.12	-7.61

3.2 Step 2: Construct Problem Table Algorithm (PTA) for heat cascade

Assuming a theoretical ΔT_{min} of 0 K for the process, which is the same as Marmolejo-Correa and Gundersen (2012), the system requires a minimum hot utility of 6.85 kW and a minimum cold utility of 4.40 kW with a Pinch temperature of -83.15 ºC, as shown in Table 2, which corresponds to exergy temperature of 21.87 K. Enthalpy in the interval for both streams is also determined in tabulated form. This methodology is an alternative way to represent the CCs in a numerical approach. For every stream present in an interval, the heat capacities of the streams are summed up. Then, enthalpy in each interval is calculated using Eq(3).

After determining the enthalpy in each interval, the enthalpy at the lowest temperature of the hot stream is then set to be zero. In the next temperature interval, enthalpy is added cumulatively in an upward manner based on enthalpy in the interval. As for cold stream, the initial enthalpy is started with Q_{Cmin} value of 4.40 kW at the lowest temperature and cascading upwards. In this case study, a theoretical ΔT_{min} is assumed to be 0 K. This means that both hot and cold CCs have identical enthalpy at Pinch temperature (Table 2) due to the intersection of composite streams.

3.3 Step 3: Remove heat recovery pockets from the heat Grand Composite Curve (GCC)

After completing the heat cascade, the heat GCC is constructed to illustrate the process-to-process heat recovery region. Next, the heat recovery pocket is removed to reduce area between hot and cold streams in GCC which is equivalent to exergy losses due to heat transfer. As shown in Figure 1, Points 2 and 3 are referred to as additional end temperatures where heat recovery occurs, while the light-yellow region bounded by the dashed vertical line is the heat recovery pocket.

Noted that Point 2 and 3 share the same value of enthalpy as Point 1 and 4. Since temperatures of Point 1 and 4 are known, enthalpy for the points can be also identified. From the adjusted enthalpy cascade in Table 2, Point 1 which is -23.15 °C has enthalpy of 1.90 kW while Point 4 (-173.15 °C) has enthalpy of 4.40 kW. From Figure 1, it clearly shows that Point 2 must be in a temperature range of -43.15 °C to -83.15 °C, since Point 1 and Point 2 have the same value of enthalpy. Interpolation is required to obtain the temperature of Point 2. As a result of the interpolation, Point 2 has a temperature of -69.58 °C. On the other hand, in below Pinch Region, Point 4 has the lowest temperature of -173.15 °C and its enthalpy is 4.40 kW. The interpolation is again performed to determine temperature of Point 3 which results in -104.10 °C.

Table 2: PTA for heat cascade

T (ºC)	CP (kW/K) H1	H2	C1	C2	ΔT (ºC)	$\sum CP_H - \sum CP_C$ (kW/K)	ΔH (kW)	Initial Enthalpy Cascade (kW)	Adjusted Enthalpy Cascade (kW)	Cold Stream Enthalpy (kW)	Cold Stream Enthalpy Cascade (kW)	Hot Stream Enthalpy (kW)	Hot Stream Enthalpy Cascade (kW)
6.85								0	6.85		78.15		71.30
	0.185			0.35	30	-0.17	-4.95			10.50		5.55	
-23.15								-4.95	1.90		67.65		65.75
	0.185	0.35		0.35	20	0.19	3.70			7.00		10.70	
-43.15								-1.25	5.60		60.65		55.05
	0.185	0.35	0.325	0.35	40	-0.14	-5.60			27.00		21.40	
-83.15								**-6.85**	**0 (Pinch)**		**33.65**		**33.65**
	0.185	0.35	0.325		40	0.21	8.40			13.00		21.40	
-123.15								1.55	8.40		20.65		12.25
		0.35	0.325		35	0.03	0.88			11.38		12.25	
-158.15								2.43	9.28		9.28		0.00
			0.325		15	-0.33	-4.88			4.88		0.00	
-173.15								-2.45	4.40		4.40		0.00

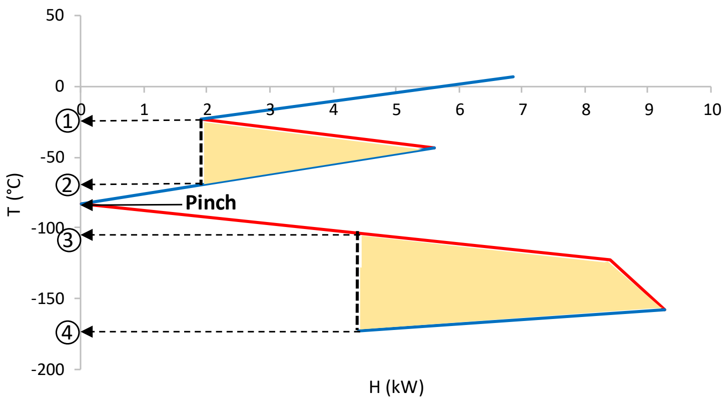

Figure 1: Grand Composite Curve including pockets

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

The Ex-PTA for exergy cascading for the pocket-less GCC is constructed as shown in Table 3. A second Ex-PTA for the GCC pockets is constructed as shown in Table 4. The additional temperatures determined in Step 3 are included in both Ex-PTA. To determine the enthalpy cascade of the pocket, the adjusted enthalpy cascade for heat cascade in Table 2 is subtracted with pocket-less enthalpy cascade in Table 3. CP of hot and cold streams are then calculated based on the change of pocket enthalpy and temperature difference in the temperature intervals using Eq(3). Like the heat cascade, the initial exergy cascade is cascaded from high temperature to low temperature, starting with an initial value of zero for both Ex-PTA. Once the initial exergy cascade is completed, the modulus of the negative values present at Pinch Point in the initial exergy cascade for the two Ex-PTA is used to initiate the adjusted exergy cascades.

3.5 Step 5: Target minimum exergy requirement, maximum exergy rejection, and exergy losses

From the adjusted cascade of Table 3, the exergy value corresponding with the lowest exergy temperature represents the target for the maximum exergy rejection, 1.33 kW, and the exergy value corresponding with the highest exergy temperature is the target for the minimum exergy requirement, 2.67 kW. Analysing the process according to the method of Marmolejo-Correa and Gundersen (2012) gives a maximum exergy rejection target of 0.46 kW and a minimum exergy requirement target of 5.38 kW. The difference is due to the assumption of Marmolejo-Correa and Gundersen (2012) of vertical heat transfer within the process.

In understanding these targets, some of the rules of heat Pinch apply, while others do not. If the process rejects more than 1.33 kW, it indicates Cross-Pinch exergy transfer (and heat transfer) is occurring such that the exergy requirement will increase by an amount equal to the excess exergy rejection. However, the process can reject less than 1.33 kW of exergy. In this case, exergy destruction below the Exergy Pinch increases due to an increase in approach temperatures for process-process and/or process-utility heat transfer. If the exergy addition from the exergy source utility is greater than the minimum process exergy requirement (assuming no Cross-Pinch exergy transfer), exergy destruction occurs due to an increase in approach temperatures for process-process and/or process-utility heat transfer above the Exergy Pinch. Cross-Pinch addition of exergy to below the Exegy Pinch or the rejection of exergy from above the Exergy 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 areas within the process that can transfer heat at approach temperatures greater than the minimum ΔT. This heat transfer results in exergy destruction. By converting the heat cascade of the GCC pockets, minimum exergy loss targets may be determined as 0.48 kW below the Exergy Pinch and 3.94 kW above the Exergy Pinch, which is a total of 4.74 kW.

Table 3: The Ex-PTA for the pocket-less GCC

T	T^E	Pocket-less Enthalpy Cascade	ΔT^E	$\sum CP_H - \sum CP_C$	$\Delta \dot{E}$	Initial Exergy Cascade	Adjusted Exergy Cascade
(ºC)	(K)	kW	(K)	(kW/K)	(kW)	(kW)	(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 4: The Ex-PTA for the pockets of the GCC

T	T^E	Pocket Enthalpy Cascade	ΔT^E	$\sum CP_H - \sum CP_C$	$\Delta \dot{E}$	Initial Exergy Cascade	Adjusted Exergy Losses Cascade
(ºC)	(K)	kW	(K)	(kW/K)	(kW)	(kW)	(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

Previous studies have shown that a combination of Pinch and Exergy Analysis is a significant tool in analysing integration opportunities in sub-ambient processes. In this paper, dual Exergy Problem Table Algorithm (Ex-PTA) are proposed for exergy cascades to target the minimum exergy requirement, maximum exergy rejection, and minimum exergy loss above and below the Pinch. The Ex-PTA is aided by the conventional PTA for heat cascade. The outcome of a case study shows that the minimum exergy destruction due to heat transfer is 4.74 kW while the exergy requirement and rejection are 2.67 kW and 1.33 kW. This new numerical tool enables the exergy targeting for sub-ambient processes to be carried out effectively which produces more accurate outcome compared to graphical method. Further studies related to numerical approaches are to be explored to investigate the opportunities for integrating heat and cooling capacity in above-ambient processes with sub-ambient processes with minimum approach temperatures greater than zero. The role of the Ex-PTA in Total Site Heat Integration (TSHI), which involves multiple processes and utility systems, will also be considered.

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