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Development of a New Graphical Tool for Calculation of Exergy Losses in Sub-Ambient Processes

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This paper presents new graphical tools, which can quickly identify all thermal exergy losses occurring in process design particularly in condensers/evaporators of low-temperature processes. Although the Omega -H diagram is a powerful tool for getting insights about exergy loss in a heat exchanger network (HEN), the calculation of the enclosed area is not straightforward due to non-linearity of the curves. The Omega Composite Curves (OCCs) and Omega Grand Composite Curve (OGCC) developed in this research are new graphical tools that can be applied to any process, including sub-ambient processes. These curves are linear, and all enclosed areas have a rectangular shape. So, all thermal exergy losses can readily be calculated and also necessary modifications to enhance the efficiency of refrigeration systems, either in new design or retrofit study can graphically be suggested. To demonstrate the capability of the new graphical tools, two ammonia refrigeration cycles (one single-stage and one three-stage) have been designed to fulfil the cooling demand of a sub-ambient process and achieve minimum shaft work requirements. The exergy loss associated with each unit in the refrigeration cycle is directly calculated from the OGCC diagram. This is a convenient tool for calculation of exergy losses and can be used to compute the enclosed areas between the OGCC and the condenser/evaporator horizontal lines. The enclosed areas show that exergy loss for 3-stage compression is much less than that in the 1-stage cycle. Also, for the throttling valve, the exergy loss in the 3-stage refrigeration is considerably less than that in the 1-stage cycle. The new linear curves can easily be plotted and implemented to show the share of inefficiencies occurring in different unit operations.

1. Introduction

Several graphical representations for combined Pinch and Exergy Analysis (CPEA) have already been presented such as Exergy Composite Curves (ECC), Exergy Grand Composite Curve (EGCC), Column Exergy Grand Composite Curve (CEGCC), and Omega-H Diagram. The area enclosed by the two hot and cold composite curves of ECC / EGCC can illustrate the exergy losses within the heat exchanger network (HEN) of a process. Linnhoff and Dhole (1992) proposed a method for the design of low-temperature processes to yield shaft work targets directly from basic process data using EGCC. ECC and EGCC cannot show the exergy losses due to pressure and composition changes, as they use the Carnot factor as vertical axis. This limitation may miss possible process improvement opportunities when the process includes pressure changing equipment (e.g. compressor, expander and throttling valve). Later, the Omega-H diagram was presented to display both thermal and mechanical exergy losses within the process and target the exact scope for improvements (Feng and Zhu, 1997, Kim et al., 2002). In this graph, Ω indicates the energy level and H states the enthalpy. The Omega-H diagram for HEN consists of two curves as source (hot streams) and sink (cold streams) such that the area enclosed by the two curves reflects the exergy loss, which is associated with the finite temperature difference within the HEN. The exergy loss in a compressor, expander, throttling valve, mixer, etc. can be calculated using the Ω-H diagram as the difference between the exergy delivered by the source and exergy accepted by the sink. Marmolejo-Correa and Gundersen (2013) introduced a diagram for exergy targeting using an energy quality parameter called exergetic temperature. Hamsani et al. (2018) presented a numerical approach to calculate exergy targets and losses in sub-ambient processes.

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Several researchers have used the CPEA tools for sub-ambient processes. Panjeshahi et al. (2008) applied CPEA for modification of the cold section of an ammonia plant. They suggested some new refrigeration levels to reduce power consumptions. Tahouni et al. (2013) presented a comprehensive retrofit study for an olefin plant to increase overall energy efficiency using EGCC. Sahafzadeh et al. (2013) integrated a gas turbine with an ammonia process and reduced the amount of exergy losses within the existing plant. Thasai and Siemanind (2015) applied the CPEA for a case study of LNG to reduce the shaft work. Sardarmehni et al. (2017) presented a new benchmarking model for energy consumption in olefin plant cold-end processes based on CPEA. Kalantar Neyestanaki et al. (2017) proposed a method using EGCC for optimization of in-use refrigeration cycles considering the operational limitations and reduced the specific power consumption. This paper demonstrates two new simple tools (OCC and OGCC) for calculating exergy losses. The main objective is to estimate the condenser/reboiler exergy losses in sub-ambient processes in a simple and accurate way.

2. Methodology

The first step to substitute Omega for Carnot factor as vertical axis is to investigate the equality of the exergy losses that are obtained by enclosed areas on EGCC and OGCC. This can be accomplished by comparing the enclosed areas between the line of a given stream and the horizontal (Enthalpy) axis, for η-H and Ω-H diagrams. Figure 1 and Table 1 clearly show that the calculated areas are exactly the same and hence one can use Omega instead of Carnot factor and easily calculate the exergy losses.

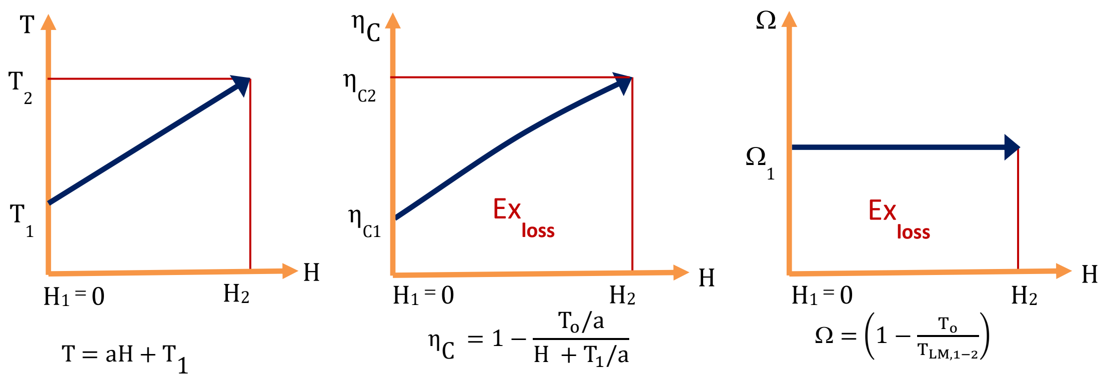

Figure 1: A given stream shown in three different diagrams

Table 1: Calculation of Enclosed Areas on η-H and Ω-H diagrams

η-H Diagram	Ω-H diagram
$T = aH + T_1, a = \frac{T_2 - T_1}{H_2 - H_1}$	$\Delta H = H_2 - H_1, H_1 = 0$
$\eta_C = 1 - \frac{T_o}{T} = 1 - \frac{T_o}{aH + T_1}$	$\Omega = \frac{\Delta Ex}{\Delta H} = \frac{H_2\left(1 - \frac{T_o}{T_{LM,1-2}}\right)}{H_2}$
$\eta_C = 1 - \frac{\frac{T_o}{a}}{H + \frac{T_1}{a}}$	$\Omega = \left(1 - \frac{T_o}{T_{LM,1-2}}\right)$
$Area = \int_0^{H_2}\left(1 - \frac{\frac{T_o}{a}}{H + \frac{T_1}{a}}\right).dH$	$Area = H_2\left(1 - \frac{T_o}{T_{LM,1-2}}\right)$
$Area = H_2 - \frac{T_o}{a}\left(ln\frac{H_2 + \frac{T_1}{a}}{\frac{T_1}{a}}\right)$	$Area = H_2 - \frac{T_o H_2\left(\ln\frac{T_2}{T_1}\right)}{T_2 - T_1}$
$Area = H_2 - \frac{T_o}{a}\left(\ln\frac{T_2}{T_1}\right)$	$Area = H_2 - \frac{T_o}{a}\left(\ln\frac{T_2}{T_1}\right)$

Also, Figure 2 shows how a typical Grand Composite Curve (GCC) can be translated to an OGCC, by converting each segment of the GCC to a piece of horizontal line (Ω) having a logarithmic mean value for the Carnot factor. By using a similar conversion technique to each segment of the hot and cold composite curves, one can obtain the Omega Composite Curves (OCC) and readily calculate the overall exergy losses of the HEN.

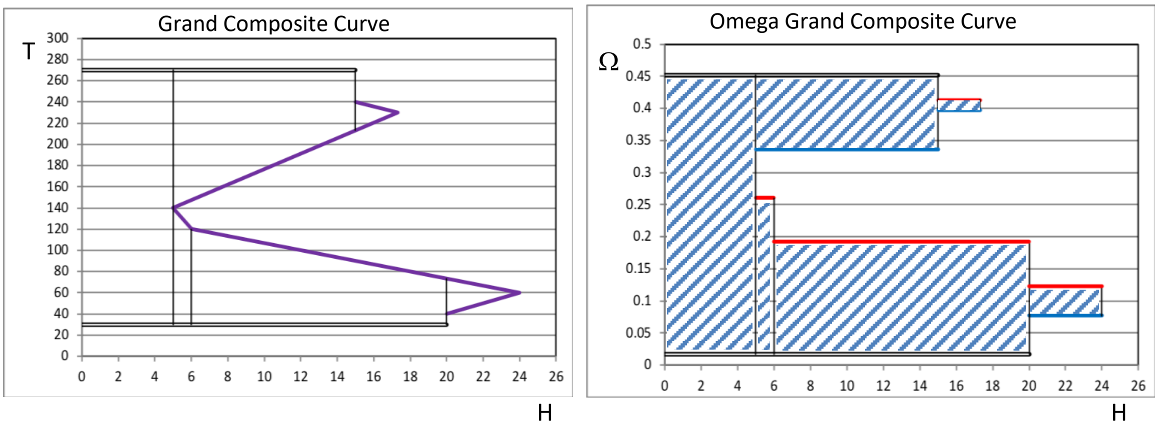

Figure 2: An example showing how the GCC can be translated to an OGCC

3. Case study

Table 2 shows the stream data for a process, which requires refrigeration cooling (Kim et al., 2002). The supply and target temperatures and heat capacity flowrates of the four process streams are shown. The task is to design a refrigeration cycle for the process to satisfy the cooling demand and achieve minimum shaft work consumption. The GCC based on the real temperatures for the process is shown in Figure 3 indicating minimum required hot and cold utilities of 130 and 190 MW at ΔT_{min} = 5°C.

Table 2: Stream data

Stream	T_S (°C)	T_T (°C)	CP (MW/°C)	ΔH (MW)
Hot 1	20	-45	5	-325
Hot 2	40	10	1	-30
Cold 1	-40	0	3	120
Cold 2	10	45	5	175

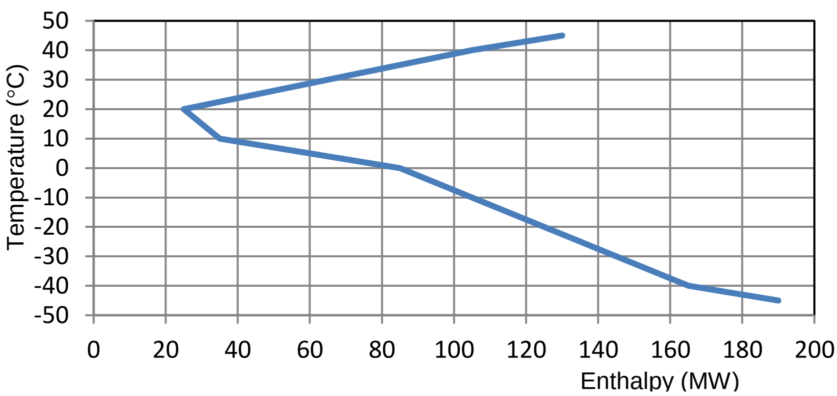

Figure 3: GCC of the process at ΔT_{min} = 5°C (based on the real temperatures)

First, a single-stage ammonia refrigeration cycle is installed to accommodate the cooling demand of the process, which is equal to 190 kW. Then, the amount of shaft work consumption will be reduced by increasing the number of refrigeration stages (Smith, 2016). The modification is carried out using the OGCC. Figure 4 illustrates the EGCC for the condenser and evaporator of the refrigeration cycles.

As the calculation of area between the process EGCC and levels of evaporators and condensers is not easy, the levels are shown on the process OGCC in Figure 5. Enclosed areas in Figure 5 show that exergy loss for 3-stage compression is much less than that for 1-stage cycle. Also, for the throttle valve, the amount of exergy loss in 3-stage refrigeration is significantly less than 1-stage cycle. Figures 6 and 7 depict the compressors and throttling valves for the single and triple stage refrigeration cycles. The exergy loss related to each unit in the refrigeration cycle is directly calculated from Figures 5, 6 and 7. Tables 3 and 4 summarize the value of exergy sink and exergy source as well as exergy losses in each part of refrigeration cycles. Note that for the single-stage refrigeration cycle, 130 MW of the condenser heat is used to heat up the process above the Pinch, and the remainder goes to ambient. Tables 5 and 6 compare the amount of exergy losses and shaft work consumption between the two proposals.

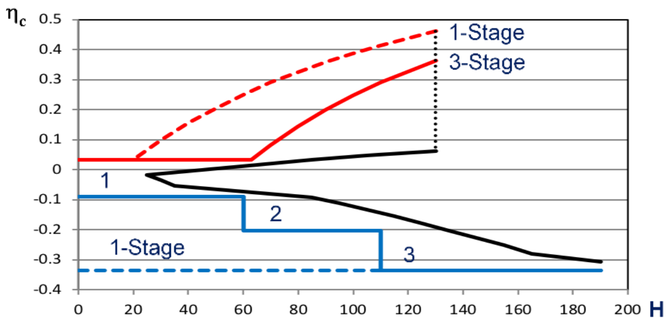

Figure 4: Condenser and evaporator in the EGCC (Single and Three-stage refrigeration cycle)

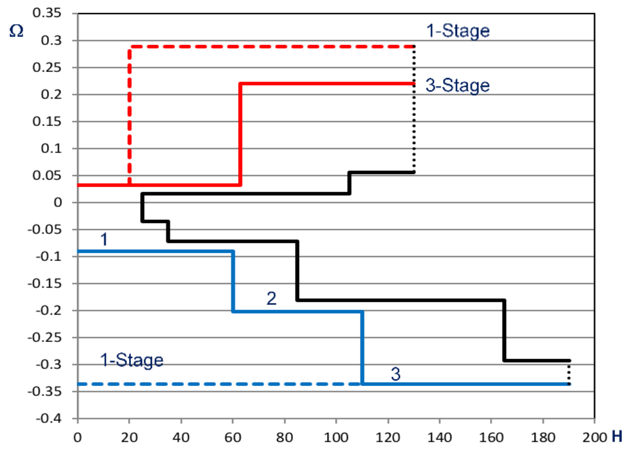

Figure 5: Condenser and evaporator in the OGCC (Single and Three- stage refrigeration cycle)

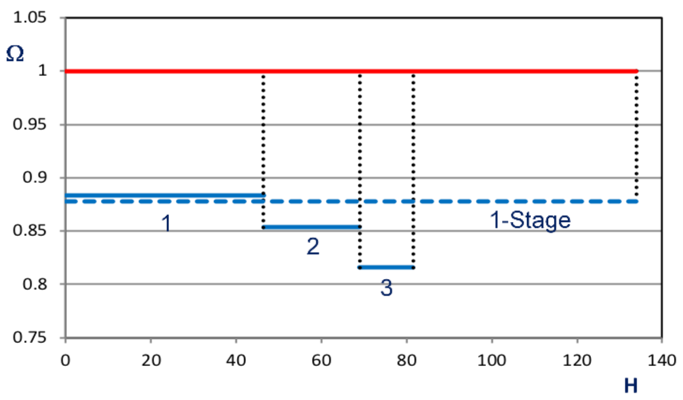

Figure 6: Compressors in the OGCC

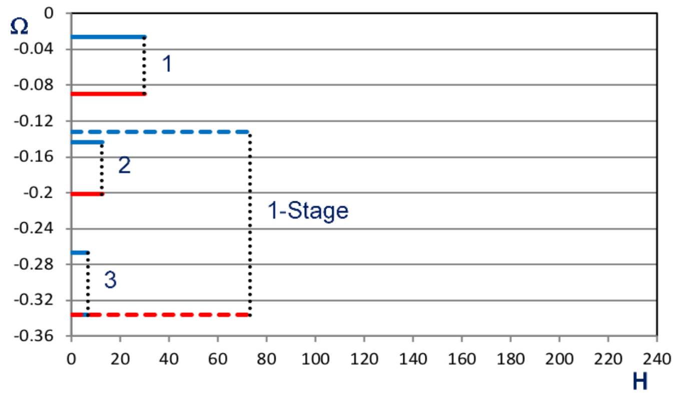

Figure 7: Throttle valves in the OGCC

Table 3: Single stage refrigeration cycle

Level		Compressor	Throttle	Evaporator	Condenser
1	Source Ω	1	- 0.3363	- 0.3363	Source Ω **:**
	Sink Ω	0.8805	- 0.1321	OGCC	Sensible: 0.2888
	ΔH (MW)	133.89	73.116	190	Latent: 0.0325
	Exergy Loss (MW)	16.000	14.930	37.331	
					Sink Ω : OGCC
Energy balance over the cycle: $Q_{evap} + W_{comp} = Q_{cond}$					
Total ΔH in Condenser (MW): 323.89					ΔH (MW) :
Total ΔH in Evaporator (MW): 190.00					Sensible: 110.04
Total W in Compressor (MW): 133.89					Latent: 19.96
.					
					Exergy Loss :
					Sensible: 29.000
					Latent: 0.340
					Total: 29.340

Table 4: Triple stage refrigeration cycle

Level		Compressor	Throttle	Evaporator	Condenser
1	Source Ω	1	- 0.0896	- 0.0896	Source Ω **:**
	Sink Ω	0.8838	- 0.0261	OGCC	Sensible : 0.2205
	ΔH (MW)	46.44	29.878	60	Latent : 0.0325
	Exergy Loss (MW)	5.396	1.897	2.354	
					Sink Ω : OGCC
2	Source Ω	1	- 0.2016	- 0.2016	
	Sink Ω	0.8534	- 0.1438	OGCC	ΔH (MW):
	ΔH (MW)	22.49	12.453	50	Sensible: 66.94
	Exergy Loss (MW)	3.297	0.720	3.771	Latent : 63.06
3	Source Ω	1	- 0.3363	- 0.3363	Exergy Loss:
	Sink Ω	0.8159	- 0.2666	OGCC	Sensible: 12.711
	ΔH (MW)	12.64	6.706	80	Latent: 1.028
	Exergy Loss (MW)	2.327	0.467	9.665	Total: 13.739

Table 5: Comparison of exergy losses

Exergy Loss	1-Stage (MW)	3-Stage (MW)	Diff. (MW)	Diff. (%)
Compressor	16.000	11.021	4.979	31.1
Throttle	14.930	3.084	11.846	79.3
Evaporator	37.331	15.791	21.540	57.7
Condenser	29.340	13.739	15.601	53.2
Total	97.601	43.635	53.966	55.3

Table 6: Comparison of shaft power consumption

Shaft Work	1-Stage (MW)	3-Stage (MW)	Diff. (MW)	Diff. (%)
Total	133.89	81.57	52.32	39.1

4. Conclusions

Several industrial processes operate below ambient temperatures, where the refrigeration system is highly energy intensive due to required power in compressors. To minimize the power, one can apply a method of combining Pinch and Exergy concepts. New tools are introduced in this paper to calculate the exergy losses through refrigeration cycles. These curves are linear and all enclosed areas have a rectangular shape. So, all thermal exergy losses can readily be calculated to achieve a higher efficiency for the refrigeration system. The OGCC diagram can be integrated with optimization methods and acts as a platform to display which refrigeration levels are more energy attractive. Using the OGCC, the overall reduction of exergy losses in compressors, throttling valves, evaporators and condenser (53.97 MW) is very close to the reduction of shaft work requirement achieved by simulation (52.32 MW). Considering 8000 h for the number of work hours in a year, the power reduction is 53.97×8000 = 431760 MWh, which is equal to reduction of 305,000 ton of CO_2 per year (EPI, 2018).

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