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Total Site Analysis (TSA) and Exergy Analysis for Shaft Work and Associated Steam and Electricity Savings in Low Temperature Processes in Industrial Clusters

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Low temperature process cooling is an energy demanding part in many chemical production processes. Cooling systems operating at very low temperatures consume a large amount of high quality energy such as electricity or high pressure steam, used to drive refrigeration compressor units. Hence decreasing refrigeration load can make a major improvement on the process energy balance. In industrial process clusters with several processes operating at low temperatures, it is important to investigate opportunities for exchange of low-temperature energy between processes. This paper presents an investigation for a chemical cluster located in Stenungsund on the West Coast of Sweden. One chemical plant within the cluster operates two compression refrigeration systems at its steam cracker plant. One system is a propylene-based system with three temperature levels between 9 °C and -40 °C, driven by high pressure steam turbine drivers with a capacity of ca. 22 MW. The other is an ethylene refrigeration system with three temperature levels between -62 °C and -100 °C, electrically driven with a capacity of ca. 4.5 MW.

A previous Total Site Analysis (TSA) study of the cluster focused on integration opportunities within the cluster above ambient temperature, thereby decreasing the overall hot utility and cooling water and air demand. Utility savings below ambient temperature were not investigated in detail. This paper demonstrates how Heat Integration (HI) tools such as TSA and exergy analysis can be applied to target for shaft work and hot utility savings for processes and utility systems operating below ambient temperature. In total a savings potential corresponding to 15 % of the total shaft work consumption of the refrigeration systems was identified. In addition ca. 6.3 MW of utility steam which is currently used for sub-ambient process heating can be saved in addition to shaft work savings.

1. Introduction

1.1 The chemical cluster

The chemical cluster investigated in this paper is located in Stenungsund on the West Coast of Sweden, and is Sweden's largest agglomeration of its kind. The heart of the cluster is a steam cracker plant run by Borealis, which delivers both feedstock and fuel gas to the cluster. In the year 2010, 598 kt of ethylene and 197 kt of propylene were produced in the cracker plant corresponding to a total fuel and electricity consumption of 4239 GWh_{fuel} and 347 GWh_{el} (Borealis AB, 2011). The process consumes large amounts of low temperature cooling at temperature levels down to -100 °C. Cooling is supplied by propylene and ethylene compression refrigeration systems. Depending on the production capacity, the electrical capacity of the ethylene refrigeration system typically varies between 4 MW and

4.5 MW, ca. 10 % of the total electricity consumption of the cracker plant. In the propylene refrigeration system the compressor power is normally between 18 MW and 24 MW. Some of the surrounding companies also operate low temperature processes, e.g. an Air Separation Unit (ASU) and an ethylene import terminal. The companies already interact strongly with each other in terms of material exchange. Collaboration in terms of energy is very limited. Delivering non-utilised cooling capacity e.g. from evaporation of feedstocks from low temperature storage across the cluster is one way to decrease the clusters overall electricity and heat consumption. The amount of fresh water consumed by the cluster is restricted and not allowed to increase with future site expansions, which is an extra incentive to increase energy efficiency by decreasing the cooling and subsequently its' heating demand.

1.2 Refrigeration systems

Most of the cooling at the cracker plant is performed by two interconnected vapour-compression refrigeration systems, see Figure 1. The propylene system compressor is driven by a four stage steam turbine (steam expansion from 85 to 8.8 barg) and delivers cooling at three levels (9 °C, -21 °C, -40 °C). Shaft work savings in this system can be used for increased electricity production in an existing team turbine utilising the same steam levels.

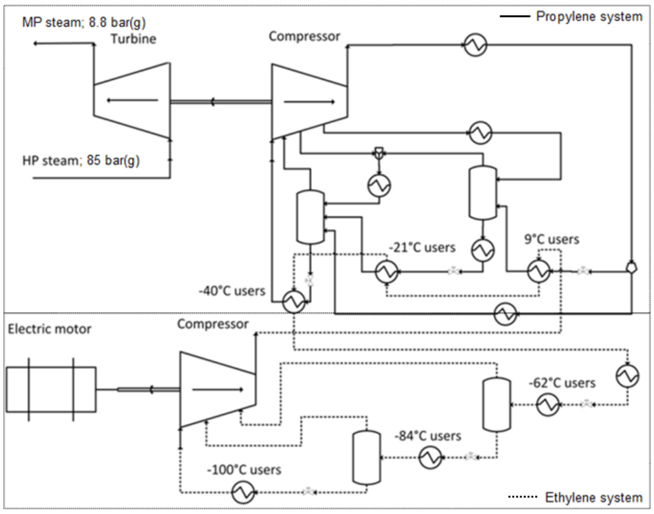

Figure 1 PFD of the propylene and ethylene refrigeration systems at the cracker plant.

The ethylene refrigeration system is driven by an electrical motor. Cooling is delivered to the process at three levels (-62 °C, -84 °C, -100 °C). The two systems are interconnected where part of the propylene systems' cooling capacity is used to cool the ethylene system.

1.3 Related work

This work is based on a previous project called "Total Site Analysis (TSA) Stenungsund", in which opportunities for site wide heat integration throughout the chemical cluster in Stenungsund were investigated. The study mainly focused on heat integration opportunities above ambient temperature (Hackl and Andersson, 2010; Hackl et al., 2011). Hirata (2011) describes how process integration methods can be used for investigating low temperature heat integration measures in an ethylene production process. Hirata and Kakiuchi (2011) studied the integration of excess heat driven adsorption heat pumps to replace cooling capacity in the refrigeration system of an ethylene production process. Fábrega et al. (2010) performed an exergetic analysis of the refrigeration system in a steam cracker plant. In the study the equipment with the highest rates of exergy destroyed were identified and measures reducing exergy destruction by ca. 13 % were suggested. Linnhoff and Dhole (1992) developed a methodology which extends Pinch Analysis (PA) for the design of low temperature processes. It combines PA with exergy concepts. The main goal of the method is to give an increased understanding on how to design a refrigeration system and the heat exchanger network. Fritzson and Berntsson (2006) applied the method to target for energy efficiency measures in an industrial case study. Dhole and Linnhoff (1993) extended the method further for site wide targeting of fuel savings, co-generation potential, emissions and cooling savings. In the literature this method is mainly applied to processes above ambient temperature. Site-wide recovery of cooling capacity across different plants and companies and resulting shaft work savings is not dealt with in detail.

1.4 Aim

In this study process integration tools, such as TSP and exergy analysis are used to target for cooling capacity and resulting shaft work savings. An industrial case study is presented in which different options for decreasing the heat and power consumption of the chemical cluster by increased heat integration across the total site and other improvements to the cooling systems are investigated.

2. Methodology

Pinch Analysis (PA) is a widely used approach for process heat integration. It was developed by Bodo Linnhoff at the University of Leeds in the end of the 70-ties (Linnhoff and Flower, 1978) and has been developed further at among others the University of Manchester Institute of Science and Technology (UMIST). An updated version of the user guide on PA was published by Kemp (2007). For site-wide heat integration so-called Total Site Analysis (TSA), an extension to PA is used. A thorough description of the methodology is given by Klemes et al. (2010). Studies have shown that energy savings of up to 20 % to 40 % can be achieved by PA (Heck et al., 2009). PA mainly focuses on targeting for heat integration potential and related fuel savings. Primary energy savings achieved by heat integration measures saving cooling capacity in refrigeration systems (as investigated in this study) cannot be directly evaluated using regular PA. Linnhoff and Dhole (1992) developed a methodology which enables targeting for shaft work savings in low temperature processes by combining exergy and PA concepts. The main difference to conventional PA is that the y-axis of the Composite Curves (CC) and Grand Composite Curve (GCC) show a Carnot efficiency corrected temperature instead of temperature. Carnot efficiency is defined by $\eta_c=1-T_a/T$ (T_a=ambient temperature). An example of such a curve is shown in Figure 2.

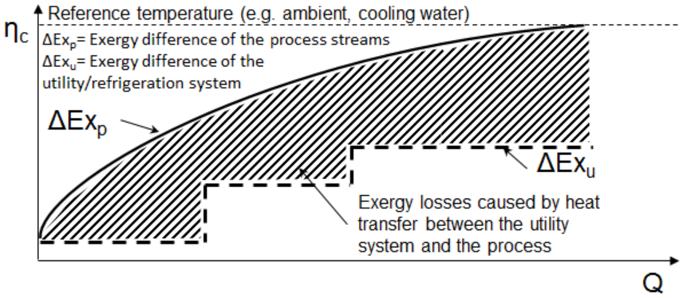

Figure 2: A schematic example of a exergy CC showing the composite curve of the process, composite curve of the utility system, the resulting exergy difference of the process streams and the utility system and the exergy losses caused by heat transfer between the utility system and the process (Linnhoff and Dhole, 1992).

The area between the respective curve and the reference temperature line in the exergy CC represents the theoretical amount of exergy necessary to supply in order to achieve the desired target temperature. The area between the upper full line and the reference temperature line represents the exergy difference of the process streams, ΔEx_p. This is the minimum exergy input necessary to cool the process streams to their target temperature. A utility system able to reach this minimum exergy input needs an infinite amount of utility levels and an infinitely small ΔT_{min}. The area between the lower dashed line and the reference temperature line represents the exergy input to a real utility system designed for cooling the given process. The area between the process (full) line and the utility system (dashed) line can be considered as exergy losses caused by the utility systems' design (cooling temperature levels, ΔT, etc.). The presented curves can be used to target for reduction of the exergy losses by identifying changes to the design of the utility system resulting in a decrease of exergy losses. The areas shown in the Carnot efficiency based curves only represent exergy differences. In order to estimate the real shaft work requirement the exergetic efficiency of the system investigated has to be considered, which can be expressed by the following equation (1):

$$\eta_{ex} = {}^{\Delta Ex_u}\!/_{W} \tag{1}$$

where ΔEx_u is the theoretical shaft work obtained from exergy Pinch curves of the real refrigeration system and W, the actual shaft work for the investigated process obtained by measurements or process simulation of the refrigeration system if such measurements are not available. Once determined for the investigated system η_{ex} can be used to estimate shaft work demand consequences of changes to the process, heat exchanger network and refrigeration systems. (Smith, 2005) proposes a typical value of 0.6 for η_{ex}, while Linnhoff and Dhole (1992) propose 0.59. The method has been shown to be very accurate. Linnhoff and Dhole (1992) applied it to a refrigeration system in an ethylene production plant and showed a difference of only 1.9 % compared to process simulation results on the same unit. In this study an exergetic efficiency of 0.66 was found by using real shaft work data obtained for the targeted cooling systems. The method can also be applied to target for shaft work savings at total sites, by applying the exergy concept to Total Site Profiles (TSP) as demonstrated by Dhole and Linnhoff (1993). They used exergy TSP to target for fuel, co-generation, emissions and cooling. In this paper the methodology is extended to low temperature processes.

3. Results and discussion

3.1 Increased recovery of low temperature utility

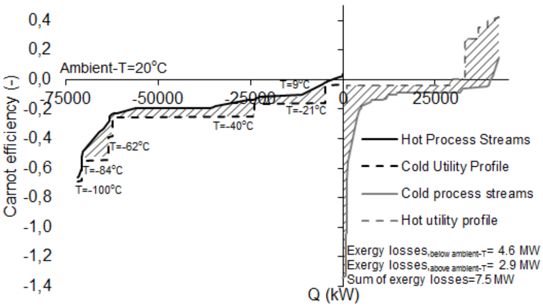

Figure 3: Exergy TSP showing process streams at the steam cracker plant cooled by refrigerants and the cold utility profile (left), the total sites cold streams below ambient-T and the respective hot utility profile (right).

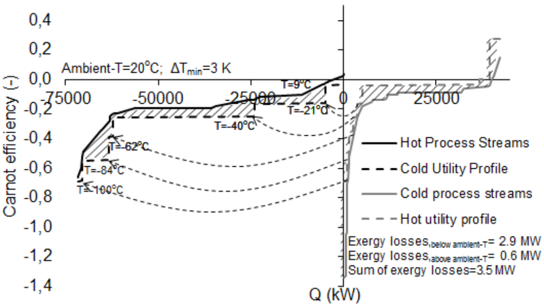

Figure 4: Exergy SSSP showing process streams at the steam cracker plant cooled by refrigerants and the cold utility profile (left), the total sites cold streams below ambient-T and a suggested improved hot utility profile (right).

Process stream data and utility data from a previous TSA study was used to construct the exergy efficiency TSP for process streams below ambient temperature. Figure 3 shows the resulting curves. The left side of Figure 3 shows hot process streams (full line) and the cold utility profile (dashed line). The right side shows cold process streams (full line) and the current hot utility (dashed line) used for process heating. The area between the curves (striped) represents the exergy losses caused by heat transfer between the utility system and the process streams. It can be seen in the right side of Figure 3 that there is a large gap between the hot utility profile and the cold process streams. This means that the exergy losses due to heat transfer are high and that there is a potential for the recovery of cooling capacity. A utility system utilizing optimal cooling loads (retaining the cluster’s existing cold utility levels) was designed. This is shown at the right side of Figure 4. Thereby the area between the curves is decreased so that the sum of exergy losses is decreased from currently 7.5 MW to 3.5 MW. These numbers include both exergy losses caused by heat transfer above and below ambient temperature.

The potential for increased recovery of cold utility and its' consequences on exergy losses are summarized in Table 1. It is shown that by changing the utility system in order to recover more cooling capacity from cold process streams, while keeping the current utility levels, it is possible to decrease the exergy losses in the cooling system by ca. 1.6 MW. Taking into account η_{ex} (= 0.66) this corresponds to a shaft work of ca. 2.5 MW. This is app. 10 % of the total shaft work consumption of the cooling systems. In the improved hot utility system for several heat exchangers suggested it is suggested to replace utility steam with a refrigerant to recover cooling capacity. This measures in addition to relieving the refrigeration systems also save ca. 3.3 MW of utility steam at pressure levels between 1.8 bar(g) and 28 bar(g).

Table 1: Summary of the processes cooling demand, the potential for cooling recovery from cold process streams and the resulting avoided exergy losses considering the current cold utility levels.

Cold utility level	Current cold utility demand [kW]	Potential additional recovery of cold utility from cold process streams [kW]	Avoided exergy losses [kW]
C2/-100°C	1060	1019	701
C2/-84°C	7320	404	220
C2/-°62C	930	930	358
C3/-40°C	38340	1306	333
C3/-21°C	19250	168	27
C3/9°C	4753		
Sum	71653	3827	1639

3.2 Further energy efficiency measures

In Section 3.1 it was described how shaft work consumption can be reduced by increasing the recovery of cooling capacity from cold process streams. Another way to decrease exergy losses and thereby increase the energy efficiency of the refrigeration systems is to improve the way cold utility is used in the process. Figure 5 shows the hot process streams and the cold utility profile of the clusters' below ambient temperature streams.

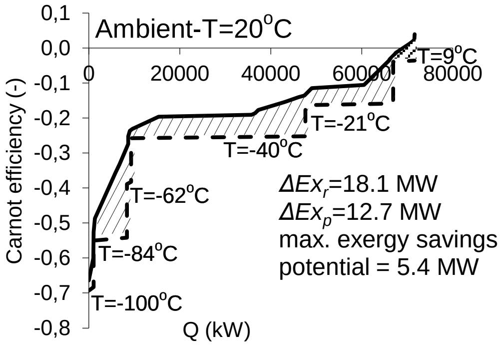

Figure 5: Exergy CC showing process streams at the steam cracker plant cooled by refrigerants (full line) and cold utility profile (dashed line).

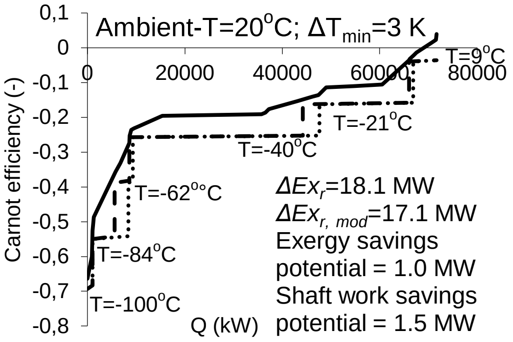

Figure 6: Exergy CC showing improved utility profile (dashed line) at the current cold utility levels; current utility profile (dotted line).

The area between the two curves corresponds to 5.4 MW, which represents the exergy being lost due to the way heat is transferred from the process streams to the cold utility system. Figure 6 illustrates the design of an improved cold utility system. The current cooling levels are kept, but instead cold utility is used at an as high temperature as possible. Thereby the area between the utility and process curve is decreased (ΔEx_r of current refrigeration system is 18.1 MW; $\Delta Ex_{r,\ mod}$ of the suggested refrigeration system is 17.1 MW), which corresponds to avoided exergy losses of ca. 1 MW, as shown in Figure 6.

Taking into account η_{ex} (=0.66) shaft work savings of ca. 1.5 MW can be achieved by the suggested changes to the utility system. This corresponds to ca. 5.4 % of the total shaft work consumed in the refrigeration systems. Additional savings can only be obtained by changing the cooling levels. This is considered to be a more unlikely measure as this involves changes to the compressors themselves and to a large number of heat exchangers which have to be redesigned for new utility temperature levels.

4. Conclusions

Heat integration tools, namely TSP and exergy analysis were used to target for energy savings potential in cooling operations within a chemical cluster. The tools were shown to be very useful in an industrial case study. Increased recovery of cooling capacity together with an improved use of refrigerant for process cooling resulted in potential shaft work savings of ca. 4 MW. This corresponds to app. 15 % of the total shaft work consumption of the cooling systems investigated. The refrigeration systems are electricity and steam driven which means that saving shaft work results in even larger savings of these utilities. In addition utility steam savings due to avoided process stream heating of ca. 6.3 MW can be achieved as a by-product of recovering cooling capacity from cold process streams.

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