CHEMICAL ENGINEERING TRANSACTIONS

VOL. 56, 2017

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

Guest Editors: Jiří Jaromír Klemeš, Peng Yen Liew, Wai Shin Ho, Jeng Shiun Lim

ISBN 978-88-95608-47-1; **ISSN** 2283-9216

DOI: 10.3303/CET1756204

Development of a Model for Benchmarking of Energy Consumption and CO_2 Emission in Cold-End of Olefin Plant

Nassim Tahouni, M. Hassan Panjeshahi*

School of Chemical Engineering, College of Engineering, University of Tehran, Tehran, Iran
mhpanj@ut.ac.ir

Benchmarking of different process industries, such as petrochemical processes, with respect to energy consumption and CO_2 emission, is a fundamental measure while implementing a comprehensive energy plan at the national level. Olefin Plant is one of the process industries that is highly energy intensive and needs to be addressed when looking at petrochemical complexes. In this research, olefin cold-end, which requires heat removal from the process via refrigeration at very low temperatures, has been studied. In sub-ambient processes, shaft work requirement is a dominant factor that causes very high energy cost. A conceptual mathematical model has been developed to facilitate energy benchmarking in olefin cold-end processes. A conceptual model using Pinch analysis is developed to predict energy consumption in refrigeration cycles. To develop the model, the cold-end from five Iranian olefin plants were studied and the effect of different factors such as technology, capacity, feedstock and product types were investigated. The gap between the current level of energy consumption and best practice technology using Pinch analysis was determined. The comparison showed an average potential of 17.7 % reduction in shaft work requirement. Having developed the aforementioned model, there is no need to undertake a full retrofit study for olefin cold-end processes anymore because the model can easily be applied to similar processes and the scope for improvement can be identified. Both time and money associated with extra engineering work can be saved. Application of this model to all olefin's cold-end processes in Iran showed that there would be 65,838 kW/h potential for energy consumption reduction, which is equivalent to about 382,519 t of CO_2 emissions.

1. Introduction

Olefin plant is one of the most energy-intensive industries in the petrochemical complexes. Ren et al. (2006) reviewed energy efficiency in conventional steam cracking and innovative olefin technologies and reported up to 20 % savings in the pyrolysis section of naphtha cracking and up to 15 % savings in the compression and separation parts in total. A low-temperature separation system such as the cold-end of olefin plant usually consists of three main systems: separation systems (usually distillation column), heat exchange system (multi-stream plate fin heat exchanger or other exchangers) and refrigeration system. The design of the low-temperature separation system is complicated because an interaction exists among the design of distillation columns, heat exchanger networks and refrigeration cycles (Tahouni et al., 2010).
Despite of low thermodynamic efficiency and high operational costs, distillation is still very popular for separation systems. Distillation columns demand high-quality energy via reboiler and then reject lower-quality energy via condenser (Kiss et al., 2012). Numerous studies have been reported on improving the efficiency of distillation columns. There are many factors such as different reflux ratios, working pressure (Castillo and Dhole, 1995), side condensing/reboiling, feed preheating/cooling (Van Der Ham and Kjelstrup, 2011) and heat pumps that affect the column efficiency. Dhole and Linnhoff (1993) developed a methodology based on a combination of thermodynamics and practical aspects of column modifications to provide inputs to engineers on the pre-design targets. Pejpichestakul and Siemanond (2013) performed Column Grand Composite Curve on three columns for ethanol production using ethylene hydration and reduced the energy consumption up to 28 %.
Mafi et al. (2009) indicated that the exergetic efficiency of the low-temperature cascade refrigeration system in a typical olefin plant is 30.88 %, showing a high potential for improvements. They provided an exergy analysis for multi-stage cascade low-temperature refrigeration systems used in olefin plants and discussed the reasons

Please cite this article as: Tahouni N., Panjeshahi M.H., 2017, Development of a model for benchmarking of energy consumption and co2 emission in cold-end of olefin plant, Chemical Engineering Transactions, 56, 1219-1224 DOI:10.3303/CET1756204

for deviation from reversible processes. Tirandazi et al. (2011) reported that the exergetic efficiencies of the heat exchanger and expansion sections get the lowest rank among the other compartments of the multi-stage refrigeration cycle used for ethane recovery plant. Fábrega et al. (2010) performed exergy analysis to determine the location and amount of exergy degradation in refrigeration cycles for ethylene and propylene production process and decreased exergy losses by 13 %.

Many researchers have applied the benchmarking approach to screen the energy efficiency of different industrial plants. Energy benchmark is a powerful tool that compares or evaluates the energy performance of an industrial plant or process unit against a reference or a plant or process standard (Ke et al., 2013). Experience suggests that the ability to benchmark and evaluate energy efficiency is an essential step for successful implementation of an energy performance improvement system. Saygin et al. (2011) estimated the energy savings potentials in 17 industry sectors by comparing their efficiency with Best Practice Technology (BPT) currently under operation.

In this paper, a novel conceptual-mathematical model is developed to facilitate energy benchmarking in olefin cold-end processes. This research focused on the olefin cold-end process, which requires heat removal from the process via refrigeration cycles supplying low-temperature cooling. As in sub-ambient processes, shaft work requirement is a dominant factor that causes a very high energy cost. A conceptual model using pinch analysis is developed to predict energy consumption in refrigeration cycles. The cold-end from five Iranian olefin plants were studied and effect of different factors such as technology, capacity, feed stock and product types were investigated. The gap between the current level of energy consumption and best technology using pinch analysis was determined. Owing to the aforementioned model, there is no need to undertake a full retrofit study for olefin cold-end processes anymore because the model can easily be applied to similar processes and the scope for improvement can be identified.

2. Methodology for Benchmarking

There are four factors which affect the energy consumption in olefin plant, which are technology licensor, capacity, feed and product. Technology licensor determines the separation consequences and configuration resulting in different energy consumption criteria. Capacity affects the energy consumption criteria reversely and also as the capacity increases the investments for retrofit project become more economical. The type of feed determines the severity of cracking process and changes the type of furnace and hot section of olefin plant more than the cold section. The scope of petrochemical plants is to synthesise, crack or purify the feedstocks to produce desirable products. The type of products determines the energy demand in processes. Among distillation towers in olefin plants, only ethylene and propylene separation columns are working below the ambient temperature and these two columns have significantly affect the energy consumption criteria. After determining these effective factors, several plants are selected to investigate the factors' significance.

Data for the scope of this model which include de-ethanizer, de-methanizer, C2-splitter processes and associated ethylene and propylene refrigeration cycles are collected. Commercial simulation software is used to simulate the plants and present all information for the current situation. Energy balance is performed on the plants and energy consumption breakdown is presented to illustrate the effect of column consequences and refrigeration cycle configuration.

Specific energy consumptions (SEC) in the refrigeration cycles are the indicators in this paper. The indicators are determined in unified basis for all plants for feasible comparison with other plants and best technology. Two criteria are defined using the following Eqs(1) and (2).

$$\mathrm{SEC1} = \frac{\text{Refrigeration Cycle work}}{\text{Total flow to cold section}} \quad (1)$$

$$\mathrm{SEC2} = \frac{\text{Refrigeration Cycle work}}{\text{Ethylene production capacity}} \quad (2)$$

Due to the extremely cold temperatures in the processing units of olefin cold-end, which affects the specific economic factors due to costly refrigeration processes, the minimum approach temperature is very small in this section in comparison with the hot section. The significant potential for energy savings in the cold-end of olefin plant is related to refrigeration systems. The new methodology proposed to benchmark energy consumption through cold-end olefin plant using Pinch analysis is presented in Figure 1.

Since one of the best technology criteria for grass root design of the heat exchanger networks is minimum temperature approach (ΔTmin), the composite curves (CC) and grand composite curve (GCC) are drawn with ΔTmin of 2 °C. Exergy grand composite curve (EGCC) is produced by converting the temperature axis in the grand composite curve to the Carnot factor and it is a very helpful tool for estimating the work of refrigeration cycles. The area between the EGCC or GCC and the refrigeration levels is related to the refrigeration cycle work. By choosing proper refrigeration levels (those having minimum distance by core process), exergy loss can be reduced. In this part, for the new GCC, the duty and level of refrigeration are selected to meet the ΔTmin in each refrigeration level and minimise the enclosed area. The refrigeration cycle is simulated according to the new loads and refrigeration levels and the shaft work of compressors are also computed assuming constant compressor efficiency. Aforementioned indicators for the benchmarking are determined again after performing Pinch analysis. The gap between the benchmark for BT current situations shows the potential for energy saving.

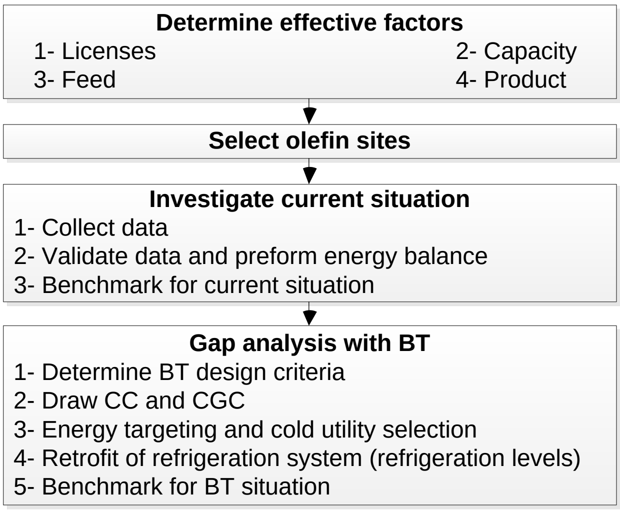


Figure 1: New methodology proposed to benchmark energy consumption using Pinch analysis

3. Case Study

Five plants are selected for study in this paper to compare the impact of technology licensor, capacity, feedstock and product type factors. Process flow diagrams for the selected plants are collected and reviewed. Table 1 shows the ethylene conversion and recovery section for the five selected plants. Ethylene conversion for Cases 4 and 5 is higher than the other plants due to their feedstock.

Cracked gas outlet stream pressure reached to about 35 bar in five compression stages and then cooled to a sub-ambient temperature prior to entering the cold-end of olefin plant. This high-pressure stream is then cooled gradually to very low temperatures via pressure valves and columns through the separation process. The sequences of the columns change the working pressure and temperature (Figure 2).

Each plant has three columns to separate C3+, absorb C2+ and split C2 cut, but the sequences of these three columns are varied for each technology licensor. Linde technology is using two absorber columns in addition to three common columns in other units.

Table 1: Ethylene conversion and recovery in 5 selected olefin plants

Plant	Case 1	Case 2	Case 3	Case 4	Case 5
Technology Licensor	Lummus	Linde	Linde	Technip	Technip
Ethylene conversion (%)	45.16	37.71	57.89	78.90	76.92
Mass flow to cold section (kg/h)	150,989	166,587	362,046	272,221	139,941
Ethylene mass fraction in flow to cold section (%)	45.97	39.64	40.89	51.55	51.19
Liquid ethylene product (kg/h)	0	17,536	37,272	37,879	3,900
Gas ethylene product (kg/h)	68,465	49,551	108,080	88,384	59,869
Ethylene recovery (%)	98.6	98.4	98.2	90.0	89.0

4. Results

Cold-end of olefin plants and their associated refrigeration cycles are simulated with commercial simulation software and the results are verified with PFD's data. Table 2 compares energy consumption and SEC criteria for each case study in the current situation. Two linear equations are developed in Figure 3 showing the relationships between refrigeration cycle work and ethylene production capacity/mass flow to cold section. The results of Case 1 are omitted to develop these equations because this plant uses the Lummus old technology and approximately consumes energy twice other units. This surplus energy consumption is due to the sequence of separation columns and heat exchanger networks design. Based on the R^2 value in Figure 3, Eq(3) is used to model the energy consumption in refrigeration cycles versus ethylene production capacity.

$$\text{Refrigeration cycle work (kW)} = 0.3337\left(\frac{\text{kW.h}}{\text{kg}}\right) \times \text{Ethylene production capacity}\left(\frac{\text{kg}}{\text{h}}\right) + 111.67\ \text{(kW)} \qquad (3)$$

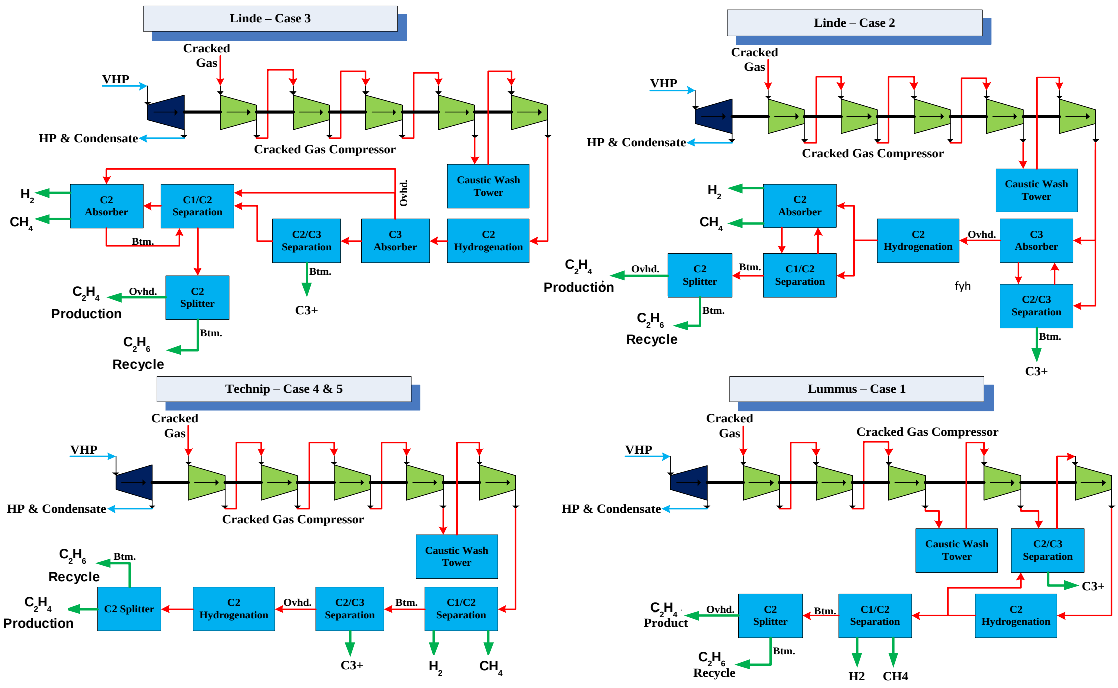


Figure 2: Sequences of distillation columns in five selected plants

Table 2: Results for current situation

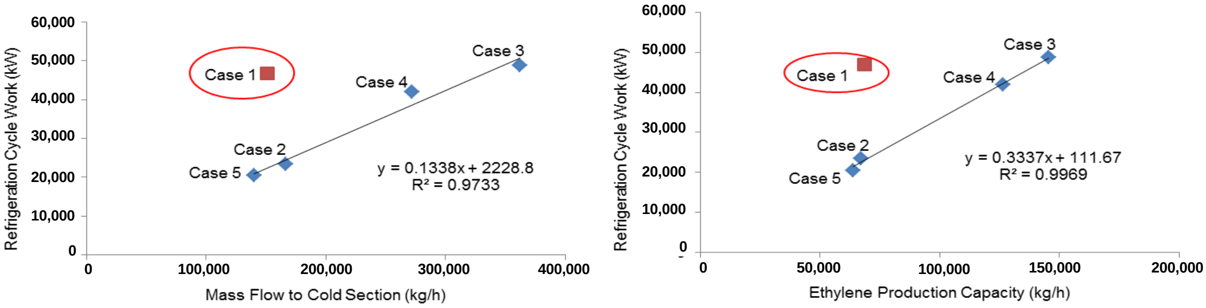
Plant	Case 1	Case 2	Case 3	Case 4	Case 5
C_3H_6 Refrigeration Cycle Energy Consumption (kW)	34,100	10,682	23,129	30,538	16,093
C_2H_4 Refrigeration Cycle Energy Consumption (kW)	12,763	12,776	25,705	11,380	4,458
Energy Consumption in Refrigeration (kW)	46,863	23,459	48,834	41,917	20,551
Cooling Water Duty	101,508	44,416	85,416	68,686	31,730
SEC1 (kW/kg)	0.310	0.141	0.135	0.154	0.147
SEC2 (kW/kg)	0.684	0.350	0.336	0.332	0.322

Another plant (case 6) which has the highest production capacity in Iran is used to verify the developed Eq(3). Case 6 consumes 56,800 kW shaft work through ethylene and propylene refrigeration cycles and produces 16,982 kg/h ethylene. Table 3 compares the design data with the results obtained using Eq(3).

Table 3: Results for current situation

Case 6*	Design data (kW)	Developed equation (kW)	Error (%)
Shaft work consumption in refrigeration cycle	56,800	56,782	-0.032

The BT benchmark based on pinch analysis is carried out to compare the energy performance of the current plants with plants designed with the best technology criteria. The temperature differences between process streams and refrigeration levels are selected at $\Delta T\text{min}$ = 2 °C to reduce the area between GCC and refrigeration levels indicating the exergy loss in heat exchanger network ($\sigma T_{0,HEN}$) (Panjeshahi et al. 2008). Figure 4 shows the GCC and placement of refrigeration levels for case 3.



a. Energy consumption versus mass flow to cold section b. Energy consumption versus ethylene production capacity

Figure 3: Benchmarking refrigeration cycle work in cold section for current situation

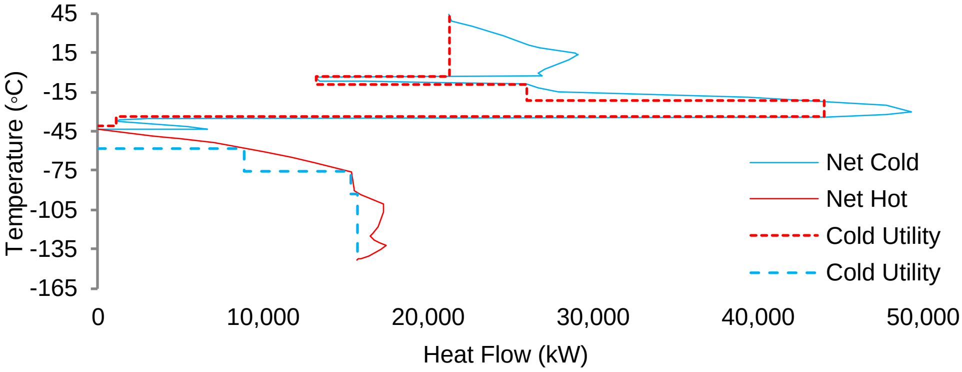


Figure 4: GCC for BT of cold-end case 3 with ∆Tmin = 2 °C

Table 4 compares the energy consumption and SEC criteria for each case study in BT situation. Two linear equations are developed (Figure 5) for BT situation to show the relationships between refrigeration cycle work and ethylene production capacity/mass flow to cold section. Case 1 criteria are reduced to more than others but are still about 1.7 times the other units, which highlights the importance of the sequence of separation. The design of the low temperature separation process is complicated because of the interaction amongst the heat exchanger network, separation process and refrigeration cycles. Eq(4) presents a conceptual-mathematical model which is developed to allow energy benchmarking for BT in olefin cold-end processes.

$$\text{BT} - \text{Refrigeration cycle work(kW)} = 0.1216\left(\frac{\text{kW.h}}{\text{kg}}\right) \times \text{Mass flow tocold section}\left(\frac{\text{kg}}{\text{h}}\right) - 414.71\ (\text{kW}) \qquad (4)$$

Table 4: Results for BT situation

Plant	Case 1	Case 2	Case 3	Case 4	Case 5
CH_6 Refrigeration Cycle Energy Consumption (kW)	22,459	7,857	17,381	24,017	12,092
C_2H_4 Refrigeration Cycle Energy Consumption (kW)	8,097	11,681	25,365	10,207	4,167
Energy Consumption in Refrigeration (kW)	30,556	19,538	42,746	34,224	16,259
Cooling Water Duty	74,916	40,076	79,512	58,762	22,673
SEC1 (kW/kg)	0.202	0.117	0.118	0.126	0.116
SEC2 (kW/kg)	0.446	0.291	0.294	0.271	0.255

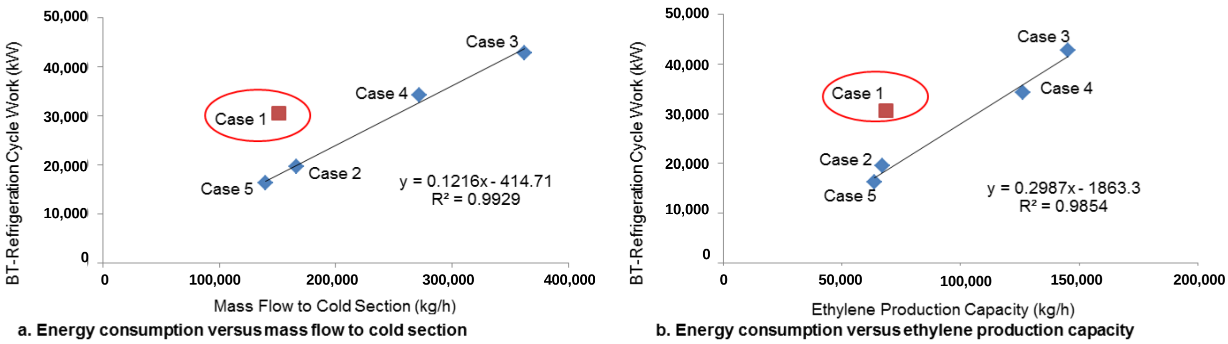


Figure 5: Benchmarking refrigeration cycle work in cold section for BT situation

5. Conclusions

In this paper, benchmarking of cold-end was implemented for different olefin plants, with respect to energy consumption and CO_2 emission. The scope of improvements can be identified through the development of a conceptual-mathematical model for energy performance in existing plants and similar plants with BT (designed based on Pinch technology concepts). Application of this model to all olefin cold-end processes in Iran showed that there would be a 17.7 % potential for reduction of shaft work in refrigeration cycles, which is equivalent to about 382,519 t of CO_2 emissions. The proposed model enables the engineers to target energy savings in retrofit projects ahead of numerous calculations. As the model can be applied to a group of similar processes and the scope of enhancement can be identified, both engineering time and money can be saved.

Reference

Castillo F.J.L. Dhole V.R., 1995, Pressure analysis of the ethylene cold-end process, Computers & Chemical Engineering 19, 89-94.

Dhole V.R. Linnhoff B., 1993, Distillation column targets, Computers & Chemical Engineering 17, 549-560.

Fábrega F.M., Rossi J.S., d'Angelo J.V.H., 2010, Exergetic analysis of the refrigeration system in ethylene and propylene production process, Energy 35, 1224-1231.

Ke J., Price L., McNeil M., Khanna N.Z., Zhou N., 2013, Analysis and practices of energy benchmarking for industry from the perspective of systems engineering, Energy 54, 3-44.

Kiss A.A., Flores Landaeta S.J., Infante Ferreira C.A., 2012, Towards energy efficient distillation technologies – Making the right choice, Energy 47, 531-542.

Mafi M., Naeynian S.M.M., Amidpour M., 2009, Exergy analysis of multistage cascade low temperature refrigeration systems used in olefin plants, International Journal of Refrigeration 32, 279-29.

Panjeshahi M.H., Ghasemian Langeroudi E., Tahouni N., 2008, Retrofit of ammonia plant for improving energy efficiency, Energy 33, 46-64.

Pejpichestakul W., Siemanond K., 2013, Process heat integration between distillation columns for ethylene hydration process, Chemical Engineering Transactions 35, 181-186.

Ren T., Patel M., Blok K., 2006, Olefins from conventional and heavy feedstocks: Energy use in steam cracking and alternative processes. Energy 4, 425-451.

Saygin D., Worrel E., Patel M.K., Gielen D.J., 2011, Benchmarking the energy use of energy-intensive industries in industrialized and in developing countries, Energy 36, 6661-6673.

Tahouni N., Smith R., Panjeshahi M.H., 2010, Comparison of stochastic methods with respect to performance and reliability of low-temperature gas separation processes, The Canadian Journal of Chemical Engineering 88, 256-267.

Tirandazi B., Mehrpooya M., Vatani A., Ali Moosavian S.M., 2011, Exergy analysis of C2+ recovery plants refrigeration cycles, Chemical Engineering Research and Design 89, 676-689.

Van Der Ham L. V., Kjelstrup S., 2011, Improving the heat integration of distillation columns in a cryogenic air separation unit, Industrial and Engineering Chemistry Research 50, 9324-9338.