CHEMICAL ENGINEERING TRANSACTIONS
VOL. 94, 2022

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Yee Van Fan, Jiří J. Klemeš, Sandro Nižetić

**ISBN** 978-88-95608-93-8; **ISSN** 2283-9216

DOI: 10.3303/CET2294204

# Graphical Revamping of a Crude Distillation Unit under Two Variable Operational Scenarios – Naphtha Stabilizer and Reformer Operated

Amany G. Abo-mousa[a], Dina A. Kamel[b], Hany A. Elazab*[,b,c], Mamdouh A. Gadalla[b,d], Mai K. Fouad[e]

[a]Higher Institute of Enginering and Technology, Chemical Engineering Department, Menofia, Egypt
[b]The British University in Egypt, Chemical Engineering Department, 11837, Egypt
[c]Jacobs School of Engineering, University of California San Diego, La Jolla, CA 92093-0403, USA.
[d]Port Said University, Chemical Engineering Department, 42526, Egypt
[e]Cairo University, Chemical Engineering Department, 12613, Egypt
Hany.elazab@bue.edu.eg

Energy costs represent significant parts of the total operating costs of crude refining industries. Energy integration is a typical solution to reduce heating and cooling utilities in crude refining plants through maximizing the target temperature of crude oil streams before entering the furnace. Over the past few decades, a significant progress has been made in energy integration methods including Pinch technology and mathematical programming approaches. Example of these is a graphical technique which plots $T_{hot}$ versus $T_{cold}$ for energy analysis and revamping studies. The current research employs the $T_{hot}$ - $T_{cold}$ diagrams in an algorithm to retrofit an existing crude atmospheric distillation unit (CDU) located in north of Egypt (Suez region). This real CDU unit is operated under two different operational modes: (i) without naphtha stabilizer; the process reformer is in operation to reform all naphtha streams without stabilization, and (ii) with naphtha stabilizer; LPG is separated from naphtha stream. The performance of the current HEN is analysed using the graphical axes of $T_{hot}$ - $T_{cold}$ diagrams. The graphical method is used to identify exchangers across the Pinch and recognize the potential modifications to improve the energy performance and reduce fuel consumption. Implementing the graphical identified modifications on the existing plant resulted in: (1) stabilizer scenario; energy savings are achieved by 21.1% with additional capital investment of 0.81 MM$ and annual energy savings of 0.82 M$, (2) reformer scenario; the energy savings are 0.42 MM$ with capital investment of 0.33 M$.

## 1. Introduction

Nowadays, the oil refining industry is facing a large number of challenges. Among such challenges are the high increase in crude prices, continuous oscillation in product demand and strict environmental regulations on industrial processes. Thus, refiners are forced to select more energy efficient methodologies and consequently they are exerting concerted efforts to improve energy efficiency for both existing and new units, which in-turn would help increase their profit and reduce their energy consumption cost (Nanovsky, 2019).

The energy problems of crude distillation units in refinery plants were reviewed by Gadalla et al. (2003) as the main energy-intensive unit and concentrated on the optimization of existing operating conditions to minimize energy requirements.

Smith (2005) introduced the energy consumption fundamentals in the distillation industry, revamping of distillation units, distillation sequencing and optimization of its superstructure. He presented all principles of the Pinch Analysis in details. Pinch Analysis is the leading method in Process Integration and is regarded as an essential solution to the problem of energy efficiency in chemical plants. It is an approach for targeting and prioritizing the integration of various process energy systems, including refinery systems (Gai et al., 2020). Together with chemical exergy analysis, Pinch Technology enable industrial processes to be designed with maximum energy recovery networks (Safder et al., 2020).

Paper Received: 09 March 2022; Revised: 15 April 2022; Accepted: 15 April 2022
Please cite this article as: Abo-mousa A.G., Kamel D.A., Elazab H.A., Gadalla M.A., Fouad M.K., 2022, Graphical Revamping of a Crude Distillation Unit under Two Variable Operational Scenarios – Naphtha Stabilizer and Reformer Operated, Chemical Engineering Transactions, 94, 1225-1230 DOI:10.3303/CET2294204

Besides, El-Halwagi (2012) utilized distillation units in many applications for energy integration and optimization and added an introduction to the conceptual design of bio-refining distillation as an alternative prospective.
Generally cooling and heating utilities consume a huge amount of energy in many chemical and petrochemical industries. In separation processes and crude oil cracking fired heaters burn a huge amount of natural gas or fuel oil to supply energy required for crude oil fractionation (Ravi Kumar et al., 2021). In addition, steam used in stripping or heating, is produced by the combustion of fuel products or natural gas. On the other hand, cooling is provided for the removal of heat of reactions in a number of industrial applications.
Energy integration or heat recovery for processes is the minimization of energy consumption by recovering heat from hot streams or units which require cooling and heating cold streams or units that need heating. Hot process streams and units are known as heat sources while cold process streams and units are known as heat sinks (Klemeš et al., 2020). Such integration is usually applied in heat exchanger networks and in the preheating train of processes. The overall energy consumption for a process is the energy amount provided by the external utilities. The more external requirements are needed by the process, the more is the process cost (Linnhoff et al., 1982).
Operational optimization of distillation units is applied more than revamping. While implementing operational optimization is easy in both the distillation units and the HENs as the equipment structure doesn’t change, it is more popular to revamp the HEN than the distillation tower (Clavijo Mesa et al., 2021). Structural changes of the distillation unit are more complex because they require higher capital investment and more installation time than structural changes of the HEN, which usually require the relocation of existing heat exchangers or addition of ones and the installation of stream splitters (Wang et al., 2021).
The application of revamping of projects and operational optimization is motivated by increasing of productivity, the changes in feedstock conditions and the increase of energy cost. Nowadays, in any industrial design, one of the main targets is to maximize the heat recovery in the process and to minimize the energy requirement (utility consumption). To reach this target Pinch Analysis is used (Li et al., 2019).
Gadalla and co-workers (Gadalla, 2015a) and much more recently (Alhajri et al., 2021); developed a new graphical representation for the revamping of heat exchanger networks. Temperatures of hot energy sources were analyzed for an existing preheat train versus streams of cold energy sources. Y-axis represents the temperatures of all hot streams in the developed graphical representation, while the X-axis represents the corresponding temperatures of the cold streams. Each heat exchanger was plotted graphically and locations of the network inefficiencies were identified. However, the work did not take into consideration the driving force and the area of all heat exchangers in the analysis.
This paper proposes the $T_{hot}$ - $T_{cold}$ Graphical Analysis method for HEN revamping. Using the graphical methodology, the Pinch Analysis Principles can be easily applied for more energy improvements. Heat optimization is applied to an existing heat exchanger network with two operational modes:

- The first operational mode is the distillation with naphtha stabilizer to separate LPG from naphtha stream.
- The second operational mode without naphtha stabilizer is reforming all naphtha streams without stabilization to decrease the energy consumption.

## 2. Methodology

A Graphical revamping methodology “$T_{hot}$ - $T_{cold}$ diagrams” using Pinch analysis principles was applied to the existing HEN to maximize the temperature of the crude oil stream before entering the furnace and consequently, reduce the furnace duty and overall energy consumption. Then a complete economic study is performed to evaluate the payback period.
A recently developed graph was constructed to represent the existing HENs (Gadalla, 2015b). For a fixed network, every existing exchanger was represented by a straight line, the slope of which is proportional to the heat capacities ratio of its hot and cold streams. On the other hand, the length of every exchanger line was attached to the heat load transferred across that exchanger.
That graphical representation could easily recognize heat exchangers Across the Pinch, the Pinch of the network, Pinching matches and suitable replacement for energy saving. Besides, such a graph could identify promising adjustments to improve the energy performance and lower the consumption of fuel and cooling water (Gadalla, 2015b).

## 3. Case study and results

In the present work, the methodologies presented by Gadalla (2015b) were applied to a case study of an atmospheric distillation unit for energy analysis. Actual industrial data were kindly supplied by SOPC (Suez Oil Petroleum Company, Suez, Egypt). The existing unit is operated under two different operational modes; (i) without naphtha stabilizer when the process reformer is in operation to reform all naphtha streams without stabilization and (ii) with naphtha stabilizer when LPG is separated from naphtha stream. The unit processes over 5,000 t/d of crude oil.

### 3.1 First operational scenario

Relevant data for process streams is presented in Table 1. The minimum temperature driving force is approximately 25 °C for all exchanger unit. The hot utility (fuel & HP steam), and cold utility (Air & Water) targets are 20.71 MW, and 22.86 MW. The Hot and Cold Pinch Temperatures are 257 ºC and 232 ºC and the potential fuel savings is 13.5%.

*Table 1: Stream data for the First operational mode.*

| Stream | Tin (ºC) | Tout (ºC) | Mass flowrate (kg/h) | Cp (kcal/kg. ºC) | Q (Mkcal/h) |
|---|---|---|---|---|---|
| C1 "crude oil 'main stream'" | 25 | 349 | 255,492 | 0.942 | 53.95 |
| C2 "boiler feed water" | 55 | 90 | 13,900 | 1.0277 | 0.5 |
| H1 " gas oil" | 257 | 55 | 58,515 | 0.5541 | 6.55 |
| H2 "fuel oil" | 318 | 80 | 127,318 | 0.626 | 18.97 |
| H3 "kerosene" | 157 | 38 | 22,426 | 0.5995 | 1.6 |
| H4 "top pump around" | 190 | 88 | 84,790 | 0.6845 | 5.92 |
| H5 "bottom pump around" | 272 | 173 | 106,274 | 0.7423 | 7.81 |
| H7 "effluent water" | 122 | 40 | 13,900 | 1.1581 | 1.32 |
| H8 "fractionator OVHD ' tower outlet'" | 122 | 60 | 102,000 | 1.9292 | 12.2 |
| H9 "fractionator OVHD 'A-5 outlet'" | 60 | 40 | 93,848 | 0.9377 | 1.76 |
| H10 "mixed feed 'naphtha &LPG'" | 47 | 40 | 47,109 | 0.5155 | 0.17 |

#### 3.1.1 Graphical representation

The graphical method for the analysis of the energy performance of the First operational mode of the existing HEN at its $\Delta T_{min}$ of 25 ˚C is represented in Figure 1. The identification of every Cross-Pinch Exchanger, using the graphical representation in Figure 1, showed that the two exchangers E-8 and E-10 are placed in the left upper region, where heat integration takes place across the Pinch.

#### 3.1.2 Revamping of the existing network

The following modifications were performed with the aim of improving energy performance and reducing the consumption of heating and cooling utilities:

•Modification [1]: All matches with loads Cross-Pinch were disconnected and then their heat duties on the cold and hot streamside were split according to the Pinch temperatures.

•Modification [2]: For more realistic application of the modified HEN, a maximum of 60 % additional heat transfer area was added to existing exchangers.

(1) For the implementation of modification [1] Above the Pinch for E-8, a new heat exchanger “NEW1” was installed Above the Pinch. At the intersection point (40˚C,173.1˚C), the new location of air cooler [C-3] was plotted between the hot and cold ends.

(2) Above the Pinch, an exchanger line was drawn from the Pinch Points (232 ˚C,257 ˚C) to intersect with the supply temperature of hot stream H2 (318 ˚C), and represents the new location of E-10.

(3) For the implementation of modification [1] Below the Pinch, for E-10, a new heat exchanger “NEW2” was installed on the main cold stream C1 to recover 2.935 MW from the hot stream H2. The remaining cooling requirement of hot stream H2 was provided by air cooler [C-1] “1.656 MW” compared to that of the existing “3.635 MW” with savings of 7.6 % and the graphical representation of the modified HEN is presented in Figure 2.

As a result of the above modifications, the crude inlet temperature to the fired heater 2H-1 increased from 253 ˚C to 266 ˚C with savings in heating utilities of 13.5 % and its heat load decreased to 20.7 MW, compared with 23.94 MW for the existing network. In addition, the temperature before the fired heater 2H -1 increased by 13˚C over the base case. On the other hand, the consumption of cooling utilities decreased by a 2.95 MW equivalence. This corresponds to a saving of 13.5 % in the fuel requirement (or hot utility) and 11.5 % for cooling utilities (air coolers) with the existing performance.

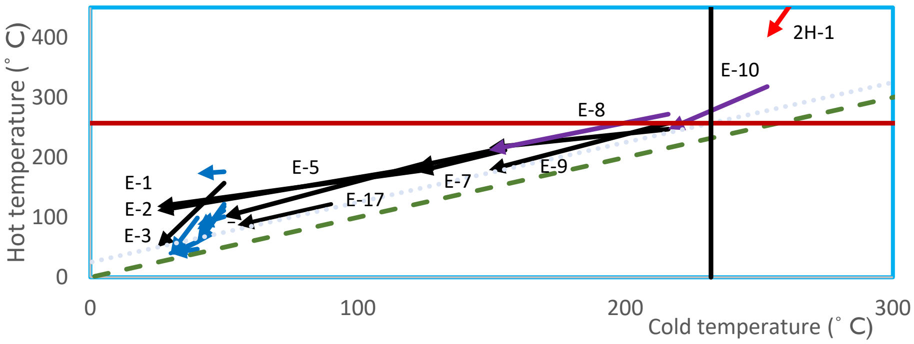


*Figure1: First operational mode HEN graphical representation.*

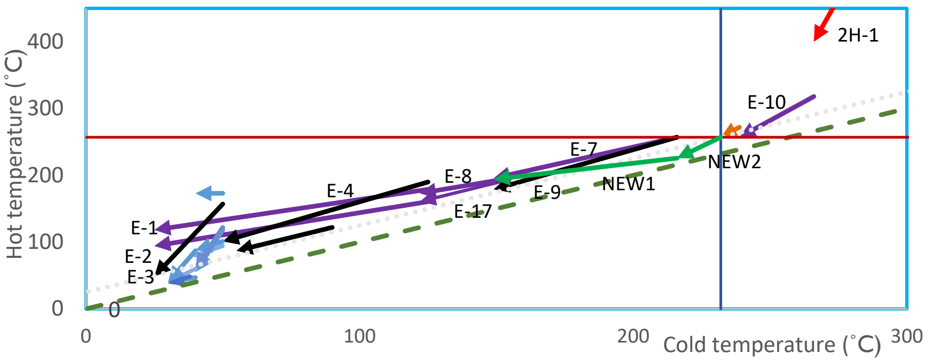


*Figure 2: The graphical representation of the modified HEN.*

### 3.2 Second operational mode

#### 3.2.1 Energy analysis of the existing network

Data for additional process streams is presented in Table 2 including supply and target temperatures, heat duty, flow rates and specific heat capacities. It is noted that the minimum temperature driving force is approximately 25 °C for all exchanger units (i.e. $\Delta T_{min}$ = 25 °C). The crude oil enters the fired heater at a temperature of 253 ˚C and exits at a temperature of 349˚C to enter the atmospheric tower. On the other hand, the naphtha leaving the stabilizer, enters and exits the reboiler at a temperature of 170 ˚C and 180 ˚C. The HEN energy consumption targets for this operational mode, at its minimum temperature of $\Delta T_{min}$= 25 ˚C, are hot utility (fuel & HP steam) equals 22.2 MW, cold utility (Air & Water) equals 24.35 MW and Hot and Cold Pinch temperatures are 195 ºC and 170 ºC. The performance of the existing network is not up to the required standard. Hot utilities consumption is (28.24 MW) 21% higher than the targeted consumption, which indicates that fuel oil and natural gas are excessively consumed.

*Table 2: Additional stream data for the Second operational mode*

| Stream | Tin (ºC) | Tout (ºC) | Mass flowrate (kg/h) | Cp (kcal/kg. ºC) | Q (Mkcal/h) |
|---|---|---|---|---|---|
| C1 "crude oil 'main stream'" | 25 | 349 | 255,492 | 0.94 | 53.95 |
| C2 "boiler feed water" | 55 | 90 | 13,900 | 1.0277 | 0.5 |
| H6 "stabilized naphtha" | 180 | 40 | 41,573 | 0.6185 | 3.6 |
| H11 "stabilizer OVHD" | 67 | 40 | 27,545 | 3.496 | 2.6 |

On the other hand, cold utilities consumption is (30.3941 MW) higher by 19.8 % than the targeted consumption which indicates excessive consumption of air and water used in cooling.

All exchanger units are represented by straight lines and the following features are noticed:

(1) The following heat exchangers perform in accordance to the Pinch Analysis rules:

i. Exchangers E-1 to E-4, E-13, and E-17 are integrating heat Below the Pinch.

ii. Exchanger E-10 is integrating energy Above the Pinch.

iii. The heaters including fired heater and reboiler heat cold process streams Above the Pinch.
iv. All water and air coolers are cooling the process hot streams Below the Pinch.

(2) Heat exchangers from E-5 to E-9 do not perform in accordance with the Pinch Analysis rules and are integrating energy Across the Pinch as shown in Figure 3.

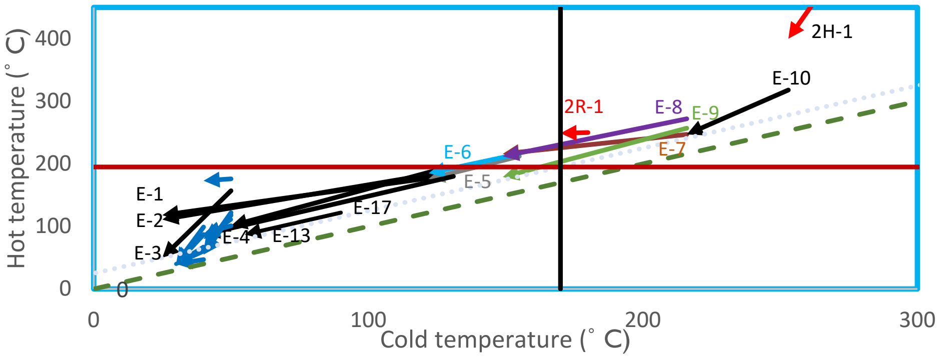


Figure 3: Graphical representation of the Second operational mode existing network.

### 3.2.2 Revamping of the existing network

The HEN modifications were implemented using Aspen Energy Analyzer, according to the following steps with exchangers. Step 1: Relocation of E-4 at the intersection point (161 ˚C,190 ˚C) with the supply temperature of the crude oil after the preflash drum of 149 ˚C. This was followed by the installation of a new heat exchanger (NEW2) to recover 1.525 MW from the hot stream (H2) which leaves (NEW2) at a temperature of 177.2 ˚C. As a result of the above modifications, heat exchangers E-7, E-8 and E-9 are shifted Above the Pinch at the cold streamside and E-6 Below the Pinch at both sides as shown in Figure 4.

Step 2: Above the Pinch, on the hot streamside, an exchanger line is drawn from the Pinch Points (170 ˚C,195 ˚C) to intersect with the supply temperature of the hot stream (H1) (257 ˚C). This exchanger line represents the new location of E-9. With the same procedure, heat exchanger E-7 is relocated. The heat load on heat exchanger E-8 is decreased from 5.021 MW to 2.098 MW. All such modifications Above the Pinch lead to an increase in the heat load on heat exchanger E-10 from 6.787 MW to 10.35 MW. As a result, the heat required by the fired heater decreases from 23.9 MW to 22.1 MW with a saving in the heating utility demand by 6.37 %.

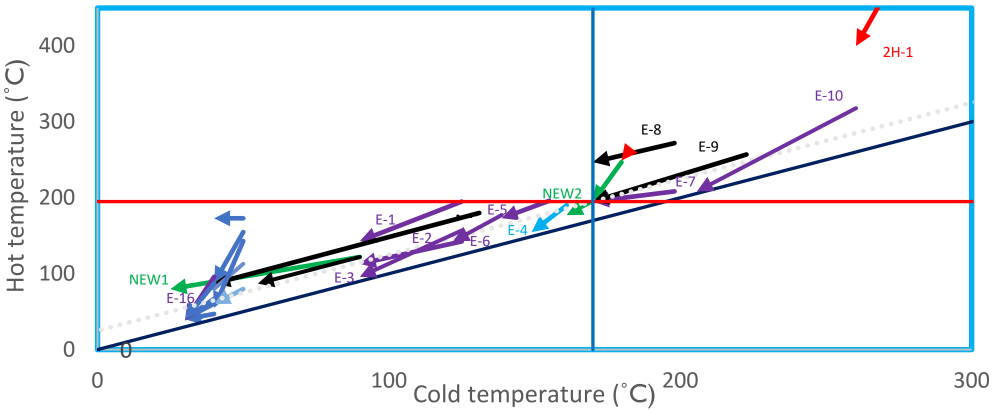


*Figure 4: The graphical representation of the modified HEN.*

The following savings are achieved by the implementation of the suggested modifications in the HEN:
The crude oil temperature increased by 7.3 ˚C to reach 260.3 ˚C while the heat load of the fired heater 2H-1 decreased from 23.94 MW in the actual HEN to 22.13 MW. In addition, crude oil temperature, before entering reboiler '2R-1', increased by 9.8 ˚C to reach 179.8 ˚C and its total load decreased from 4.3 MW for the actual HEN to 0.07 MW and a total 21 % energy savings in heating could be achieved. The corresponding consumption of cooling water reached 8.49 MW (loads of E-11, E-12, E-14, E-15, E-16, and E-18), compared with 7.81 MW with an increase of 8.7 %. On the other hand, the electricity consumption by air coolers is equivalent to 15.85 MW (load of A-1, A-2, A-3, A-4, and A-5), compared with 22.58 MW with savings of 29.8 %. So Heat optimization by graphical solution of the two modes operation of the case study was applied and the results of the overall saving are shown in the Table 3.

*Table 3: Results for the two operational modes.*

| Item | First operational mode | | Second operational mode. | |
|---|---|---|---|---|
| | Base case | Graphical solution | Base case | Graphical solution |
| Crude oil feed temperature before fired heater (°C) | 253 | 266 | 253 | 260.3 |
| Hot Energy saving (%) | | 13.5% | | 21.1% |
| Cold Energy saving (%) | | 12.3% | | 19.6% |
| New HE cost ($) | | 98,316.66 | | 382,686.4092 |
| Additional area cost ($) | | 175,196.02 | | 217,145.72 |
| Total capital cost used ($) | | 337,989 | | 810,520 |
| Operating cost saving ($) | | 424,718 | | 825,930 |
| Payback period (y) | | 0.8 | | 0.98 |

## 4. Conclusion

In the present work, the heat exchanger network (HEN) of an existing crude atmospheric distillation unit (CDU) located in north of Egypt (Suez region), was chosen as a case study. Graphical revamping is implemented with the aim of the enhancement of its performance. Results showed that energy consumption is reduced from 23.94 MW to 20.71 MW with saving 13.5% for first operational mode and for the second, energy consumption is reduced from 28.28 MW to 22.2 MW with saving 21.1%. The highest profit was achieved by the graphical solution with payback periods of 0.8 and 0.98 y for first and second modes.

## References


Alhajri I. H., Gadalla M. A., Abdelaziz O. Y., Ashour F. H. 2021, Retrofit of heat exchanger networks by graphical Pinch Analysis - A case study of a crude oil refinery in Kuwait, Case Studies in Thermal Eng, 26,101130.

Clavijo Mesa M. V., Patino-Rodriguez C. E., Guevara Carazas F. J., Gunawan I., Droguett E. L., 2021, Asset management strategies using reliability, availability, and maintainability (RAM) analysis, Journal of the Brazilian Society of Mechanical Sciences and Engineering, 43(11).

El-Halwagi M. M., 2012, Sustainable Design Through Process Integration: Fundamentals and Applications to Industrial Pollution Prevention, Resource Conservation, and Profitability Enhancement, Elsevier Inc.

Gadalla M. A., 2015a, A novel graphical technique for Pinch Analysis applications: Energy Targets and grassroots design, Energy Conversion and Management, 96, 499–510.

Gadalla M. A. ,2015b, A new graphical method for Pinch Analysis and energy integration, Chemical Engineering Transactions, 43, 1291–1296.

Gadalla M., Jobson M.,Smith R., 2003, Optimization of existing heat-integrated refinery distillation systems, Chemical Engineering Research and Design, 81(1), 147–152.

Gai L., Varbanov P. S., Klemeš J. J., Sun L., 2020, Hierarchical targeting of hydrogen network system and heat integration in a refinery, Chemical Engineering Transactions, 81, 217–222.

Klemeš J. J., Wang Q. W., Varbanov P. S., Zeng M., Chin H. H., Lal N. S., Li N. Q., Wang B., Wang X. C., Walmsley T. G., 2020, Heat transfer enhancement, intensification and optimisation in heat exchanger network retrofit and operation, Renewable and Sustainable Energy Reviews, 120, 1-31.

Li B. H., Chota Castillo Y. E., Chang C. T., 2019, An improved design method for retrofitting industrial heat exchanger networks based on Pinch Analysis, Chemical Eng Research and Design, 148, 260–270.

Linnhoff B., Townsend D.,Boland D., Hewitt G.,Thomas B., Guy A., Marsland R., 1982, 1st ed., User guide on process integration for the efficient use of energy, Rugby, UK, Institution of Chemical Engineers.

Nanovsky S., 2019, The impact of oil prices on trade, Review of International Economics, 27(1), 431–447.

Ravi Kumar K., Krishna Chaitanya N. V. V., Sendhil Kumar, N., 2021, Solar thermal energy technologies and its applications for process heating and power generation – A review, Journal of Cleaner Production, 282, 125296.

Safder U., Ifaei P.,Yoo C. K.,2020, A novel approach for optimal energy recovery using pressure retarded osmosis technology: Chemical exergy pinch analysis – Case study in a sugar mill plant, Energy Conversion and Management, 213, 112810

Smith R., 2005, Chemical Process: Design and Integration, John Wiley & Sons Ltd., 1st ed., Chichester, UK.

Wang B., Klemeš J. J., Li N., Zeng M., Varbanov P. S., Liang Y., 2021, Heat exchanger network retrofit with heat exchanger and material type selection: A review and a novel method, Renewable and Sustainable Energy Reviews, 138, 1-26.