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A conceptual efficient design of energy recovery systems using a new energy-area key parameter

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ABSTRACT

Energy integration in petrochemical and refining industries is an effective concept to minimize dependence on heating and cooling utilities through networks of exchanger equipment. Pinch Analysis is very popular and successful technique to optimize heat recovery between heat sources and sinks. Yet, design of networks of exchangers is challenging and requires careful attention to energy consumption and exchanger areas. This work presents a graphical methodology to design exchanger networks taking into account both heat loads and transfer areas of exchanger units in one single information. A new parameter is introduced for design that is the ratio between the heat load and the exchanger area, and is determined in kW/m^2. It is defined as an energy-area parameter expressing how much heat the exchanger would transfer per every meter square of area. Such parameter will be valuable key in design to screen matches of exchangers providing that both the heat and area are considered. The higher the value of the parameter, the better the performance of the exchanger, i.e. maximum heat transfer rate for minimum exchanger area. The design methodology embedding the energy-area parameter guarantees HEN designs with energy targets and minimum areas. A case is studied for the production of 100,000 t/y of dimethyl ether. An optimum network is generated by applying the new parameter with less exchanger areas and hot utility of 25% and 30%, respectively compared with an automated design by Aspen Energy Analyzer®. Also, substantial savings of about 47% in the total cost of the network are earned.

1. Introduction

Despite the recent drop in oil prices, energy consumption still is of no doubt a major concern for economics and environment especially for chemicals industries with large energy demands (Klemes et al., 2020; El-Halwagi, 2012; Smith, 2005). These challenges fostered researchers to focus their research and efforts on improving energy efficiencies of such industries. Reducing the energy consumption in process industries normally falls into 3 directions. One direction is to consider the energy recovery systems alone. Another direction is to look at the background processes, such as reaction, distillation, absorption, etc. The third direction which is of more significance is to deal with the two units sequentially or simultaneously. Another classification of researchers' groups is divided into grassroots design (synthesis) and revamping of energy recovery systems or HENs. In HEN (heat exchanger network) synthesis, the main aim is to achieve the optimum design network taking into consideration the installation cost for heat exchangers and the utilities cost as well. However, the situation is more complicated in case of HEN retrofit as the main target is to reduce the overall cost through modification of preexisting networks. Moreover, the HEN retrofit is less flexible than HEN synthesis due to additional constraints of structure although it has an advantage of saving cost through using existing heat exchangers in newly adopted designs. Researchers' efforts can be classified distinctively according to these directions. The common concept amongst all research methodologies is the energy integration which was found a key element towards the sustainability of chemical process industries. Energy recovery systems are the key systems for tackling such a challenge as they are the sequences of equipment which can integrate heat among process streams. On the other hand, a few researchers targeted the energy integration together with mass integration in their approaches and applications (e.g. Liu et al., 2013; El-Halwagi and Manousiouthakis, 1990). In a great number of methods and solutions, Pinch Analysis has been employed extensively for both

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grassroots and retrofit scenarios. Klemeš et al. (2018) provides a comprehensive review for such research works.

It is well established that heat integration is considered as an effective route of increasing the energy efficiency. For many years, researchers focused to investigate the retrofit and the optimized design of HENs. Literature provides rich data in approaches and methodologies adopting retrofit applications and studies. Many researchers paid attention to the existing preheat trains only, while a few others looked at the background processes in addition. For example, Wang et al. (2020) proposed some shifted grid diagrams to retrofit HENs based on thermodynamics. Klemes et al. (2020) considered heat transfer enhancement techniques together with optimization in retrofit objectives. In the work of Lai et al. (2020), temperatures of streams were plotted against enthalpy to screen changes for retrofit focusing on process changes. On the other hand, some preheat trains of existing refiners were the target of retrofit case studies by applying standard Pinch Technology or a commercial software (e.g. Akpa and Okoroma, 2012). Other studies implemented retrofit and include process reassessment (Jiang et al., 2018), relocation of utilities coupled with optimization (Zamora et al., 2020), placing heat pumps in HENs (Yang et al., 2020), analyzing diagrams of heat flows (Mosadeghkhah and Beheshti, 2020), modifying heat integration schemes and processes (Cheng et al., 2014; Chew et al., 2015), fouling in heat exchangers (Coletti and Macchietto, 2011; Jackowskia et al., 2017; Loyola-Fuentes et al., 2017, 2019), network pinch (Asante and Zhu, 1997; Bakhtiari and Bedard, 2013). Research work addressing background processes/HENs in retrofit include some of the work by Ochoa-Estopier et al. (2018, 2014, 2013). These researchers developed models for distillation systems using artificial neural networks and area-based models to account for HENs details. Their work exploited the interaction between process and network, accounting for operational changes and large network structures. Enriquez-Gutierrez et al. (2015) provided correlations for distillation hydraulics to replace internals with better trays for capacity enhancement. More specific studies included in retrofit the operational changes for maximizing energy efficiency of existing crude refining units, such as the work by Gadalla et al. (2016) and Zhang et al. (2013).

In process engineering, HEN grassroots design/synthesis is a critical research area that reduces the equipment cost and decreases the energy consumption. HEN design as a promising method was adopted successfully in several process industries as an efficient and reliable heat integration technology. Simply, the HEN design aim is to investigate the best network among all possible combinations of heat exchangers in order to exchange heat between cold and hot streams resulting in a significant reduction of the amount of energy used from utilities. Early researchers started the pioneering efforts to obtain the best configuration for HEN design such as the works by Linnhoff and Hindmarsh (1983), Papoulias and Grossmann (1983), and Pho and Lapidus (1973). The first approach for HEN synthesis is the mathematical programming based method (MP) which is mainly focused on optimizing the overall cost of the network through consideration of investment costs and energy consumption. Adopting this approach may use a simplification approach using linear/mixed integer linear programming, e.g. Zhang et al. (2020b), Santos et al. (2020), Short et al. (2016), Faria et al. (2015). Unfortunately, even if this approach is capable to reach a minimal-cost solution but the limitation of its applicability is due to the nature of HEN design problem with large networks which is definitely associated with higher computational complexity compared to simple networks (Zhang et al., 2020a). Hence, the second approach is the metaheuristic optimization approach which can simply deal with sophisticated HEN design models in order to reach a near-optimum solution in a suitable time frame (Santos et al., 2020; Aguitoni et al., 2019; Pavao et al., 2018; Liu et al., 2018; Escobar et al., 2014). An early work on this type considered Tabu search stochastic optimization to address the synthesis problem. However, the main drawback of this approach is related to the lack of information that can firmly recognize the gap in the obtained solution compared with optimal solution, thus no guarantee for achieving the global optimum. Finally, the third main approach is Pinch insights-based. Linnhoff and Hindmarsh (1983) and Linnhoff and Flower (1978a,b) were the first to coin the Pinch method for design. It is generally considered as a flexible heuristic approach. This approach simply handles the problem through separating it into two sub problems below and above the pinch point. The drawback of this approach is that the optimum network configuration could be discarded due to the limitations of the possible configurations that could be obtained. So, it is not capable to optimize investment costs and energy uses simultaneously as its main target is to facilitate the maximum energy recovered (MER). Unlike most design methods that assume steady state operations in design, Hafizan et al. (2019) and Escobar et al. (2014) accounted for temperature disturbance and operating conditions changes while synthesizing HENs. Similarly, Isafiade et al. (2015) and Ahmad et al. (2012) looked at the design problem along with real environmental conditions with multiperiod and changes in operating conditions in a hydrotreating operation, respectively. Adopting graphical basis for design, Gadalla (2015a) introduced a new graphical method by applying Pinch Analysis for the analysis of networks for initially revamping purposes. This methodology was then extended in its applications to grassroots design of HENs by dividing the design problem into 2 parts, i.e. below/above the pinch (Gadalla, 2015b). Later in 2016, the graphical representation was applied to debottleneck Network Pinch problems (Gadalla et al., 2016). This latest work considered the background process in retrofit benefits, not only the existing exchanger equipment. The limitations of these 2 methods can be seen in accounting only for the maximum energy recovery, and not considering the minimum heat transfer areas of exchangers. Recent solutions to HEN synthesis are found in stream splitting as done by Kayange et al. (2020) adopting a non-structural model. A similar work has been conducted by Ziyatdinov et al. (2020), where a sequential technique is employed considering splitting of process streams. Several other researchers dealt with large-scale networks such as the work developed by Rathjens and Fieg (2020) which combined some optimization techniques with genetic algorithm and stage-wise structure. New researchers such as Liu et al. (2020) integrated the controllability of HENs within the synthesis of HENS, while Orosz and Friedler (2020) provided in their synthesis research a set of optimal solutions, enabling engineers to select the most appropriate design for further implementations. Other researchers such as Ghorbani et al. (2018, 2020b,a) combined both exergy and pinch analyses to design optimum complex integrated structures. They focused in their work on cryogenic natural gas plants and employing organic Rankine cycles to increase the thermal and exergy efficiency. Further, Hamedi et al. (2020) suggested that compressor/turbine work needs to be integrated within the HEN in synthesis and provided the solution relying on simulation without the need of correlation nor the simplification.

In summary, the design of heat exchanger network can be performed through several methods. A great number of methods are Pinch Analysis-based, while the others rely on building network superstructures and the problem is solved by mathematical programming. The Pinch design method leads to networks achieving the energy targets for both heating and cooling. However, minimum areas of exchanger equipment are not guaranteed. On another hand, the mathematical programming-based methods guarantee minimum total annualized cost, irrespective of whether the solution fulfills the energy targets or no. Each of these methods exhibits pros and cons. The Pinch design method is simple and produces practical designs in many cases. The other method is optimum and yet in a great number of examples the solution seems very complex with too many stream splits and equipment. This current research presents a new design method for HENs featuring 3 aspects in the design: (1) it is simple and graphical based, (2) it guarantees minimum energy demands (targets) and (3) the method searchers for minimum heat transfer areas and provides simple networks structure.

2. Methodology

The new graphical methodology developed in this work evolves from the work presented by Gadalla (2015a,b) and guided by the Pinch Analysis principles for HEN design. A new parameter is defined as the energy-to-area ratio for the exchanger (Q/A), measured in kW/m^2. The Q/A parameter for an exchanger implies how much heat can the exchanger transfer per unit area of the equipment. This means for a constant heat transfer rate, a higher value of the energy-area parameter results in a smaller exchanger equipment, i.e. small exchanger area. On the other hand, an exchanger with a given area would transfer more heat for a higher value of Q/A. The higher the value of Q/A parameter, the better the performance of the exchanger.

2.1. An energy-area conceptual parameter: a new insight and motivation

For integrating heat between two streams (hot/cold), an exchanger equipment of area A (m2) is placed to transfer heat duty of Q (kW). The ratio Q/A is helpful in determining the capacity of the exchanger area to transfer heat load. This new parameter is embedded in the design of HENs to screen exchanger matches for better performances. A higher value of this parameter implies that an exchanger can transfer more heat for the same exchanger area. This also indicates the exchanger requires less area to transfer the same heat load. Both conditions are beneficial for design leading to lower capital cost in addition to energy cost. The following equations describe the heat balance across an exchanger equipment placed between two streams.

$$Q = m_H \cdot C_{pH} \cdot (T_{H1} - T_{H2}) \tag{1}$$

$$Q = m_C \cdot C_{pC} \cdot (T_{C1} - T_{C2}) \tag{2}$$

$$Q = U \cdot A \cdot \Delta T_{LMTD} \tag{3}$$

$$\Delta T_{LMTD} = \frac{(T_{H1} - T_{C2}) - (T_{H2} - T_{C1})}{Ln \frac{T_{H1}-T_{C2}}{T_{H2}-T_{C1}}} \tag{4}$$

where, Q is the heat flow (kW), m_H, m_C are the hot and cold stream flow rates (kg/s), C_{pH}, C_{pC} are specific heats of hot stream and cold stream (kJ/kg °C), T_{H1}, T_{H2}, T_{C1}, T_{C2} are stream temperatures for hot and cold streams respectively (°C) (1: inlet, 2: outlet), U is overall heat transfer coefficient (kW/m^2 °C), ΔT_{LMTD} is logarithmic mean temperature difference (°C).

Eq. (3) is rearranged as follows:

$$\frac{Q}{A} = U \cdot \Delta T_{LMTD} \tag{5}$$

As given above, the Q/A parameter is directly relative to the overall U and ΔT_{LMTD}. An exchanger with high values of U and ΔT_{LMTD} will result in a high Q/A value. Thus, the Q/A parameter for an exchanger can indicate the performance of this exchanger, i.e. how good the performance of the exchanger is. It can therefore be used in designing the heat exchanger networks (HENs) as a selection tool to screen exchanger matches according to their best performances. So, the designer should select the exchanger match with higher Q/A value when several matches are possible for heat exchange. This may include 3 different situations, as detailed below:

(1) Fixed heat flow; this condition indicates that heat exchangers transfer the same amount of heat load Q. In this case, the exchanger with higher value of Q/A would require lower value of heat transfer area for the same heat load transfer.
(2) Fixed heat transfer area A; this condition indicates that the exchangers have the same heat transfer areas. In this case, the exchanger with higher value of Q/A would transfer more heat load than the others for the same heat transfer area.
(3) Variable Q and variable A; In this case, the exchanger with larger number of Q/A would transfer more heat per unit area of heat transfer.

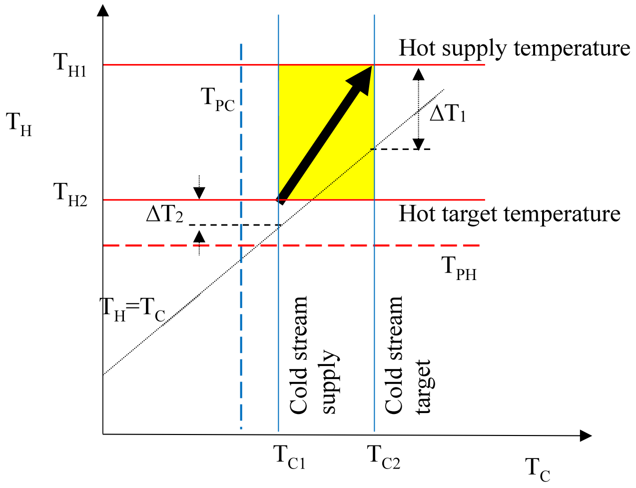


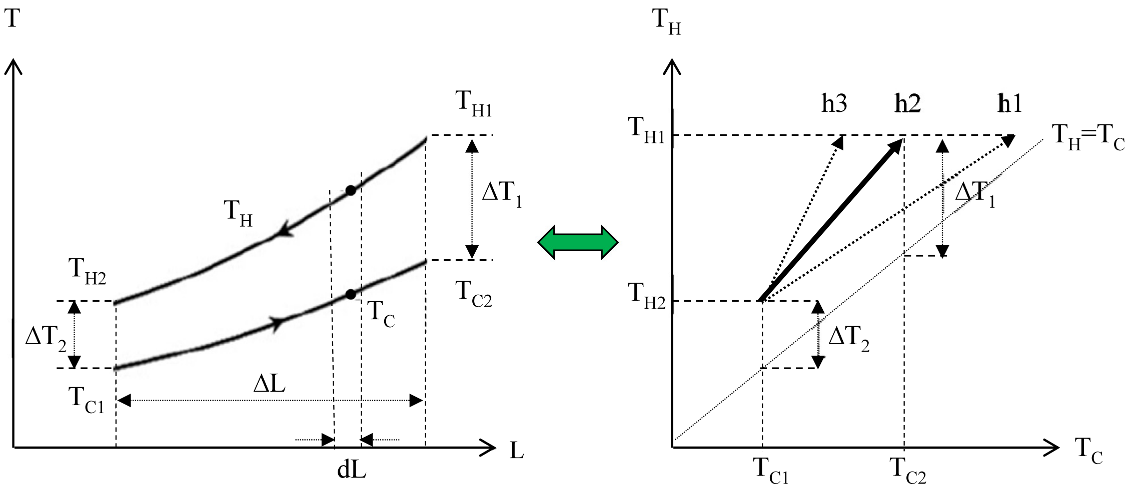
Fig. 1. A graphical representation of heat exchanger on T_H-T_C axes (T_{PH} and T_{PC} are hot and cold pinch temperatures).

2.2. T_H-T_C graphical diagram and Q/A parameter

The work developed previously (Gadalla, 2015a) considers the plot of hot stream temperatures (T_H) versus cold stream temperatures (T_C) on 2T-axes. A typical heat exchanger is plotted in this diagram as a straight line assuming constant heat capacities using the inlet and outlet stream temperatures (Fig. 1). This line connects the temperatures of the terminal streams, i.e. inlet hot and outlet cold/outlet hot and inlet cold. The hot stream is shown on the ordinate by 2 horizontal lines (from supply to target temperatures); similarly, the cold stream is displayed on the abscissa vertically from supply to target temperatures. The shaded area between these cold/hot streams represents the location of heat exchanger. The diagonal shown in the figure shows the thermodynamic limitation conditions $T_H = T_C$. The temperature driving force on both hot and cold sides can be read as shown in the figure by ΔT_1 and ΔT_2. This means, $\Delta T_1 = T_{H1} - T_{C2}$ and $\Delta T_2 = T_{H2} - T_{C1.}$

2.3. Graphical analysis of Q/A parameter

The below figure (Fig. 2) shows the temperature profile across an exchanger unit in parallel with its graphical representation as



(a) Exchanger temperature profile (b) Exchanger line

Fig. 2. Temperatures profile and graphical representation for heat exchangers (counter current flow).

proposed by Gadalla (2015a). The temperature of both streams passing in the equipment are plotted against the exchanger length. The hot stream transfers heat to cold stream. The stream temperatures change along the length of the equipment as demonstrated by the figure. Applying a differential energy balance on the exchanger, neglecting the heat losses, results in the following equation (Kern, 1983):

$$dQ = U \cdot dA \cdot \Delta T = U \cdot dA \cdot (T_H - T_C) \tag{6}$$

where, dQ is the heat transfer across an increment of exchanger area dA, with the driving force of $\Delta T = T_H - T_C$. The heat transfer rate is determined as the limit as dQ varies from 0 to Q, where dA becomes the exchanger area A. The temperature driving force can be calculated as ΔT_{LMTD} (see Eq. (4)) or by the arithmetic mean temperature difference $\Delta T_{AMTD.}$

$$\Delta T_{AMTD} = \frac{1}{2}\left((T_{H1} + T_{H2}) - (T_{C1} + T_{C2})\right) \tag{7}$$

Eq. (7) can be rearranged by the analysis shown in Fig. 2(a) as given below.

$$\Delta T_{AMTD} = \frac{1}{2}\left(\Delta T_1 + \Delta T_2\right) \tag{8}$$

The exchanger line h2 shown in Fig. 2(b) represents the temperature profile between the two streams (hot and cold). The figure also shows 2 other exchangers (h1, h3) which are considered as alternatives to exchanger h2. The two alternatives transfer the same heat flow from hot to cold streams with different outlet temperatures. Thus, the flow rates will vary to maintain energy balance across the exchangers. This is indicated by the different slopes of the exchanger lines. Among the 3 exchanger units, the larger the slope, the larger the temperature driving force. This implies the exchanger line with larger slope will result in a higher Q/A value, i.e. better exchanger performance. In Fig. 2(b), the exchanger unit h3 with the highest slope is expected to result in the smallest heat transfer area as it exhibits the highest Q/A value among the 3 exchangers (h1, h2 and h3). This can be explained by referring to Eqs. (6)–(8) and Fig. 2(b) as ΔT_1 increases with the slope and hence the temperature driving force increases, leading to higher Q/A values.

As pointed out in Eq. (5), the calculation of the Q/A parameter is highly dependent on the value of the overall heat transfer coefficient (U). For grassroots design, the overall heat transfer coefficient U is assumed initially as suggested by Kern (1983). For the case studies considered in this work, the value of U is taken from Kern (1983) to be 317 W/m^2· °C. In an ideal application of the Q/A parameter, after energy balance an exchanger type is proposed in addition to fluid allocations. Then, the individual film and shell heat transfer coefficients for every exchanger match are calculated. Then, the clean overall coefficient U is determined. And hence the dirt factor is calculated to check whether the proposed exchanger equipment would tolerate the expected fouling or not. However, this current work does not continue with detailed heat exchanger design. To do so, this would require embedding the simultaneous calculations of exchanger design together within the design procedure for exchanger matches. On the other hand, for revamping situations where the exchangers are already existing, the actual coefficient U would be determined providing that the routing of the fluids is given, and the design is known. In this case, the procedure would follow to calculate the dirt factor knowing both the clean and actual coefficients, and compares the value with the allowable fouling factor to ensure safe operation. In both grassroots and revamping situations, the procedure can allow the individual overall coefficients for every exchanger match.

In design situations, the material of construction of the exchanger shell/tube can have impact on the values of Q/A parameter. This impact including the fluid routing in the exchanger and the individual heat transfer coefficients can be taken into account in a detailed procedure with the details of exchanger equipment.

2.4. HEN design using Q/A parameter

The design procedure followed in this work is based on both the graphical representation on T_H-T_C diagrams (Gadalla, 2015a) and the new Q/A parameter. As guided by Pinch Analysis principles (Smith, 2005), the design of HENs is divided into 2 subproblems, one above the pinch and another below. Each division is designed alone, irrespective of the other to not violate the Pinch Analysis principles. Following the Pinch principles will guarantee that the final designs achieve the energy targets for a given minimum temperature approach difference (ΔT_{min}), i.e. minimum utilities.

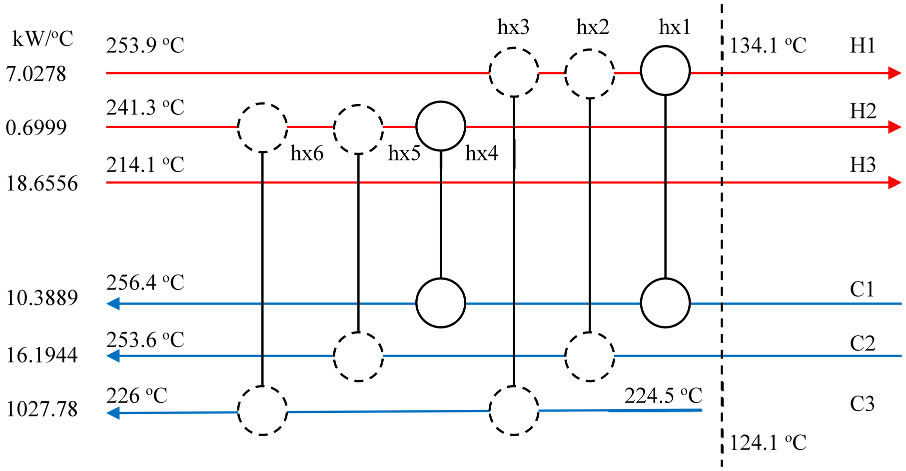


Fig. 3. An illustrative example of HEN.

2.5. HEN design' optimization

The Q/A parameter can be used together with the graphical design to optimize the HEN design. An objective function is set to be the summation of the Q/A parameters for all exchangers. The optimization together with the graphical design are performed using the solver tool built in MS Excel® to maximize the objective function (Σ(Q/A)). The solver tool of MS Excel® uses GRG (general reduced gradient) as a solving method for the optimization. The GRG solving tool is appropriate to NLP problems which is the case for HEN designs. The manipulated variables can be the streams' split fractions, exchanger matches, and intermediate stream temperatures. The optimization constraints are set within the optimization routine, including those defined by the problem and any other external ones. Energy balance is also embedded in the optimization to calculate the intermediate temperatures when process streams are split.

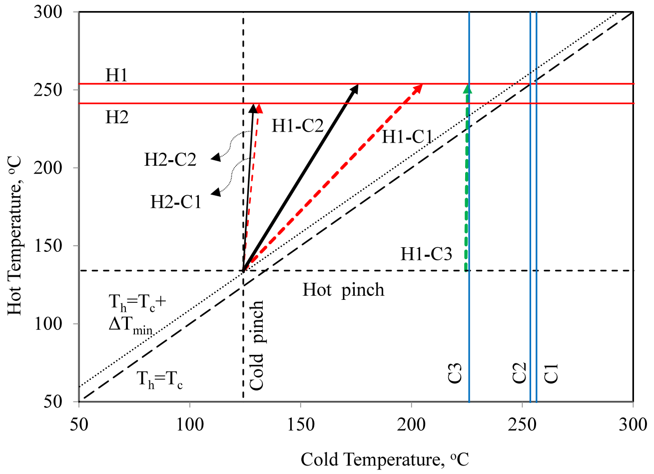


Fig. 4. A T_H-T_C diagram for illustrative example.

2.6. Illustrative example – biodiesel production process

As an illustration for the Q/A parameter application, consider the case of HEN shown in Fig. 3. The case is for a production plant to produce biodiesel using supercritical transesterification of waste cooking oil with high acid value (Aboelazayem et al., 2018). As shown in Fig. 3, the HEN involves 3 hot streams and 3 cold streams, supplying relevant data and pinch temperatures. The example has minimum hot utility of 2602 kW at ΔT_{min} of 10 °C. Note that only the part above the pinch is considered for application to highlight the applicability of the proposed method. This implies that the part below the pinch is the same for the results. In order to make the design of the HEN above the pinch, exchanger matches are proposed. For example, the hot stream H1 may transfer heat to streams C1, C2, and C3. A conventional HEN design procedure would take any possible match between H1 and cold streams as long as the match obeys the Pinch Analysis principles. Then the design continues from this match to the next step of design till completing the HEN design. However, the new design methodology of this current work would suggest that the match between H1 and C2 (hx2) is better among all matches. The reason is that the Q/A parameter for this match is the highest (10.48) compared to the other matches (7.76). A graphical representation of the 3 matches is given in Fig. 4. As shown, the exchanger match H1-C3 is excluded because of infeasibility since it is located below the diagonal $T_H = T_C$ (thermodynamic limitation). It is also visually observed from Fig. 4 that the slope of the exchanger line hx2 (match H1-C2) is larger than that for the exchanger hx1 (match H1-C1). This observation agrees with the discussion presented above in Section 2.3. The detailed calculation results of the areas for the 3 matches are demonstrated in Table 1. It is clear from the results that the best exchanger match exhibits the highest Q/A parameter and smallest exchanger area, proving the proposed selection. It must be noted that all exchanger matches transfer the same heat flow of 841.9 kW which is the heat flow content of the hot stream above the pinch. This concludes that the best match transfers the same flow rate of heat for a lower heat transfer area. This leads to a minimum capital cost of the exchanger. The design can then continue from this exchanger match towards the complete network design. The same procedure can be done based on the matches among the stream H2 and the streams C1, C2, C3 (see Table 2). It is obvious again from the table results that the exchanger match with the highest Q/A value (H2-C2) is the best match with the smallest exchanger area between H2 and cold streams. The same visual observation of the larger slope is still valid as the best match shows a higher slope value.

It must be noted that in the above calculations, the overall heat transfer coefficient U has been set as constant value (317 W/m^2.°C). However, the ideal solution should include the details of U values for every exchanger match between process streams. A detailed calculation is given in Tables A.1 and A.2 (Appendix) in which values of U for every exchanger match are considered in

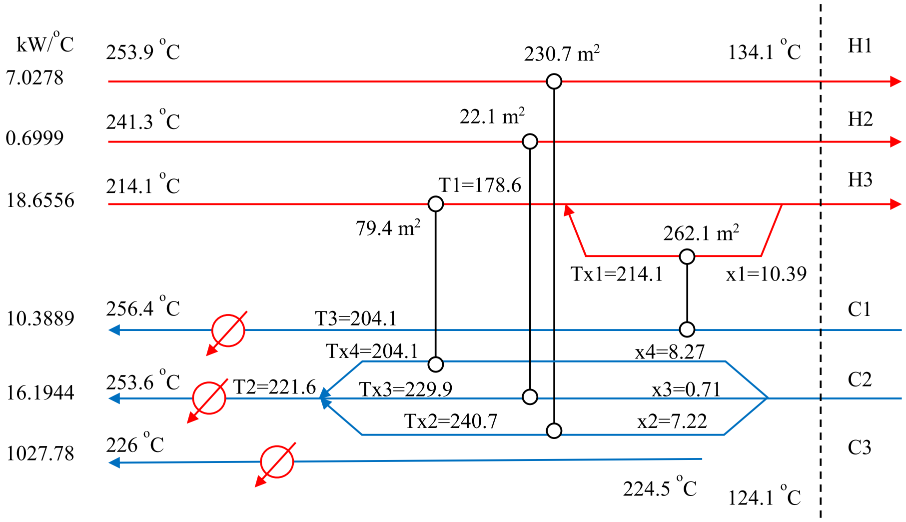


Fig. 5. Optimization variables for HEN design.

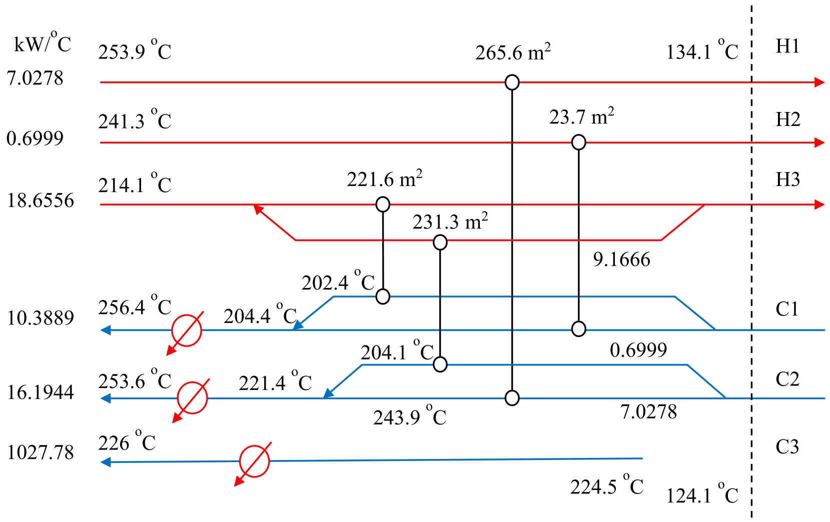


Fig. 6. Standard pinch for HEN design.

Table 1
Exchanger matches between H1 and C1, C2 and C3.

Exchanger match	Q/A parameter	Heat load (kW)	Exchanger area (m^2)
H1-C1	7.76	841.9	108.6
H1-C2	10.48	841.9	80.4
H1-C3	Infeasible	Infeasible	Infeasible

U = 317 W/m² °C (Kern, 1983).

Table 2
Exchanger matches between H2 and C1, C2 and C3.

Exchanger match	Q/A parameter	Heat load (kW)	Exchanger area (m^2)
H2-C1	13.22	75.029	5.68
H2-C2	13.43	75.029	5.59
H2-C3	Infeasible	Infeasible	Infeasible

U = 317 W/m² °C (Kern, 1983).

the design method. The U values taken from Kern (1983) reflect the nature of process streams and revealed that H1 and C1 are biodiesel streams, H2 is waste cooking oil, C2 is a mixture of waste cooking oil and methanol (Aboelazayem et al., 2018).

Fig. 5 shows the optimization variables for a superstructure built for the example mentioned in Fig. 3. The optimization problem is solved by maximizing the objective function (ΣQ/A). The results of the optimum manipulated variables are shown in Fig. 5, leading to a maximum Σ(Q/A) of 18.53 with total heat transfer area of 594.3 m^2. It is worth mentioning that the stream H3 in Fig. 5 has to be split in order to fulfill the CP (heat capacity flow) rule of Pinch design method. This rule states that a hot stream needs to be split to be integrated with cold stream if the CP of this hot stream is greater than that of the cold stream. This will ensure that the driving force across exchanger matches will be feasible/practical (i.e. more or equal ΔTmin). This implies the CP of hot stream must be less or at most equal to the CP of the cold stream. For this reason, the stream H3 is split in order to be able to exchange heat with cold stream C1 since its CP=18.66 which is more than that for C1. On the other hand, one possible design is shown in Fig. 6 as a potential design which a designer might reach using conventional Pinch method. The Σ(Q/A) of the design is calculated and reported to be 12.94 and the corresponding total heat transfer area is 742.2 m^2. It is clear that the optimum design obtained in Fig. 5 shows better results and a reduction of 20% in the total exchanger areas compared with the standard Pinch design. This means the design exhibiting maximum Σ(Q/A)

Table 3
HEN optimum designs comparison.

Design	Designs by Aspen Energy Analyzer®		New work design (maximum Σ(Q/A))
	Minimum energy	Minimum total cost	
Exchanger area (m^2)	796.2	325.0	594.3
Total heating requirement (kW)	2,602.0[a]	3,145.2	2,602.0[a]
Capital cost ($)[b]	822,470.2	215,380.6	276,149.3
Energy cost ($/yr)[b]	634,888.0	767,425.9	634,888.0
Total annualized cost ($/yr)	717,135.0	788,964.0	662,502.9
Number of exchangers	6	4	4
Number of stream splits	6	7	5

[a] Hot energy target.
[b] Utility costs and exchanger capital costs are taken from the work by Lai et al. (2019).

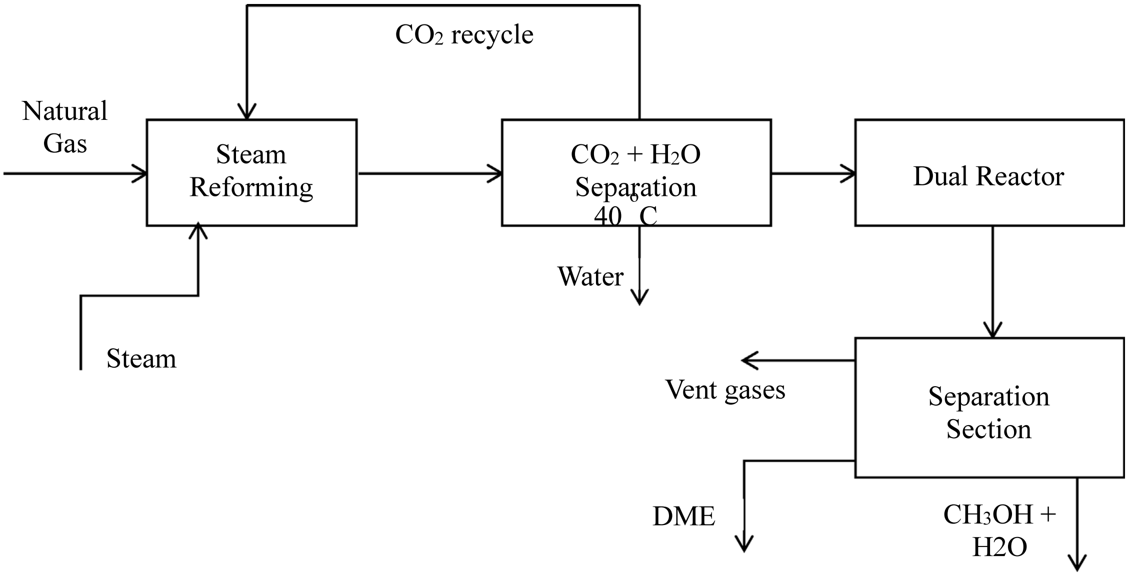


Fig. 7. A schematic diagram for DME production (direct method).

is optimum from the point of view of total cost of energy and capital, providing that it achieves the energy targets as the other design does.

Table 3 compares the results obtained from the optimization employing the Σ(Q/A) parameter with two design alternatives solved by the Aspen Energy Analyzer®. It must be noted that the Aspen Energy Analyzer® applies the method of mathematical programming and optimization algorithm, by building a superstructure for the possible solutions (scenarios). The superstructure considers all possibilities for exchanger matches with stream splitting and bypassing. Two objective functions can be specified, one for minimizing energy consumption and another for minimizing the total annualized costs. The optimization of the software finds the best compromise between utility requirements, heat exchange area and unit shell number. The user of the software can set the number of scenarios or solutions needed to synthesize. This option is of importance in the case of revamping where the designer is limited with number of solutions. The first alternative design is a HEN achieving the minimum energy consumption, while the second design is achieved by minimizing the sum of exchanger areas and energy costs. As shown in the table, the design of the new work, i.e. maximum Σ(Q/A), shows less heat exchanger areas with the lowest total annualized costs. Specifically, the new work provides a HEN design with reduction in total transfer area and total annualized cost of 25 and 7.6% respectively. In addition, the new design exhibits a simpler network with less stream splits and number of exchanger units (see Appendix). The design of maximum Σ(Q/A) shows 5 splits of process streams in comparison with 6 and 7 splits for the designs of minimum energy and minimum total cost respectively (see Figs. A.1 and A.2). It may also be observed that the design of minimum total costs obtained by Aspen Energy Analyzer consumes hot energy in excess of 21% compared with the energy target.

3. Case study – dimethyl ether DME production plant

The new method presented above is applied to design a HEN for manufacturing plant of dimethyl ether (DME) with annual capacity of 100,000 tones with 99.5% purity (weight basis). In this production plant, DME is directly synthesized from synthesis gas in a single packed bed dual reactor avoiding methanol as an intermediate product. Fig. 7 shows a schematic block diagram for the production process. In the dual reactor, carbon monoxide reacts with H2 according to the overall reaction resulting in DME. In steam reforming, reactions are endothermic and thus require large amount of heat. Unlike the DME synthesis process, reactions are exothermic, where cooling is necessary. The reactor products include DME, water, unreacted CO/CO_2, H_2, and methanol side product. The detailed process flow diagram is obtained by process simulation and was designed through a graduation project at the University of Port Said in 2018 (Egypt). The extracted data for streams from the simulation results are shown in Table 4.

$$3CO + 3H_2 = CH_3OCH_3 + CO_2 \qquad \Delta H_{298} = -58.8 \text{ kcal/mol} \quad (9)$$

4. Results and discussion

The energy targets obtained for the DME production plant, assuming ΔT_{min} = 10 °C, are summarized as: 12.38 MW for

Table 4
DME production plant stream data.

Stream no.	Inlet temperature (°C)	Outlet temperature (°C)	Mass flow × specific heat (kW/°C)	Enthalpy change (kW)
1	37.78	900	19.70	16,990
2	254.8	900	42.56	27,460
3	900	40	52.86	45,460
4	169.6	35	35.11	4,726
5	62.18	200	224.64	30,960
6	169.8	90	199.87	15,950
7	185.3	187.5	1262.27	2,777
8	187.5	33.3	115.89	17,870
9	38.2	260	32.58	7,227
10	260	10	45.28	11,320
11	1.41	60	8.41	493
12	70.79	58.6	403.53	4,919
13	105.9	106	52870.00	5,287
14	1.41	−50	47.38	2,436
15	−50.14	−79	23.76	686
16	84.84	85.48	1704.69	1,091
17	−79	15	17.34	1,630
18	20.51	19.24	465.28	591
19	58.6	20	2.73	105
20	106	45	5.57	340

minimum heating requirement, 22.87 MW for minimum cooling requirement, 169.8 °C for hot pinch temperature, 159.8 °C for cooling pinch temperature. These data are generated using Aspen Energy Analyzer®. Fig. 8 illustrates the composite curve for the production process of DME.

4.1. Heat integrated process (using automated design)

A HEN is designed for the production plant of DME synthesis using a commercial software (Aspen Energy Analyzer®). The software generates 20 design alternatives with different levels of heat integration and total network costs (capital and utilities). The generated design with minimum total cost is selected and the associated HEN is shown in Fig. A.3. For this design, the hot utility consumption is reported to be 17.60 MW; the cold utility requirement is of 28.09 MW; the total heat transfer area required is 13,844 m^2 for 52 exchanger equipment. The selected design suggests that the HEN includes 4 heaters with fired heating duties and 1 heater with HP steam. The heating duties of the 4 fired heating exchangers are 596, 5296, 5293, 1213 kW, while for the HP steam heater the duty is 5202 kW.

4.2. Heat integrated process (using Q/A parameter)

The new design procedure proposed is followed to obtain better design for the heat integrated process considering the Q/A parameter for design. As presented previously, this parameter is maximized when exchanger matches are selected. The design is achieved in 2 parts, one part for above the pinch and another part for below the pinch. Fig. 9 illustrates the network configuration obtained using the Q/A parameter in design. The part of the network above the pinch (169.8 °C) includes 10 exchangers, while the below-pinch network involves 19 exchanger units. The design obtained by applying the Q/A parameter leads to total exchanger area of 10,275 m^2 and 29 exchangers. The design obtained by the current work proposes after heat integration that only 2 fired heaters are necessary with heating duties of 5008 and 7371 kW to provide heating demand of DME production plant.

4.3. Economic analysis for designs

Both the automated design and the Q/A-parameter's design are analyzed with respect to the cost implications. For every design, the purchase exchanger cost is estimated according to the cost correlations provided by Lai et al. (2019). On the other hand, the utility costs of HP steam and fired heating are also determined (Lai et al., 2019). Table 5 provides a comparative analysis of the economics of the 2 designs presented above. It is very obvious that the design generated by the new work is more advantageous with respect to the automated design. Less number of exchanger units and lower utility costs lead to around 47% reduction in the total annualized cost of the Q/A-parameter's design. Also, the total heat transfer areas are estimated at 25% smaller than those of the automated design. Comparing the 2 networks in Figs. 9 and A.3, it is realized that the current work's design shows less stream splits in relation to the automated design, i.e. 4 versus 16 stream splits. In addition, the new work design achieves the energy targets while the automated design does not. This shows the benefits of considering the new parameter of Q/A in designing the heat exchanger networks for heat integration.

5. Conclusions

A new parameter has been introduced relating the heat duty over an exchanger to the exchanger area. The new parameter Q/A was embedded into a graphical design method developed recently to design HENs for screening matches characterized by maximum heat duties per minimum exchanger areas. An illustrative example of biodiesel production plant has been considered to apply the new design method to generate HEN designs with better performances. It has been shown that the exchanger with higher Q/A would transfer more heat for minimum area, and thus this exchanger performs more efficiently. The HEN design by the Q/A parameter resulted in valuable savings in exchanger areas and total utility costs when compared with conventional network designs. An optimum HEN has been designed for a case study of producing a dimethyl ether chemical with 100,000 t/yr. The optimum network showed significant improved results over the conventional automated designs, reaching at around 47% savings in total annualized costs and 20% reductions in exchanger areas. In addition, the designs provided by the new parameter (Q/A) show simpler networks with less number of exchanger equipment and a few stream splits. The novelty of the work is that the new Q/A parameter accounts for 2 important design factors in one single information. Besides, the design method is simple and

Table 5
HEN optimum designs comparison.

Design	Aspen Energy Analyzer®	New work design (maximum $\Sigma(Q/A)$)
Exchanger heat transfer area (m^2)	13,844	10,275
$\Sigma(Q/A)$	–	695
Total heating requirement (MW)	17.60	12.38[a]
Total cooling requirement (MW)	28.09	22.87[a]
Capital cost ($)[b]	2,877,567	2,090,899
Hot utility cost ($/yr)[b]	2,571,078	1,299,795
Total annualized cost ($/yr)	2,858,834	1,508,884
Number of exchangers	52	29

[a] Energy target.
[b] Utility costs and exchanger capital costs are taken from the work by Lai et al. (2019).

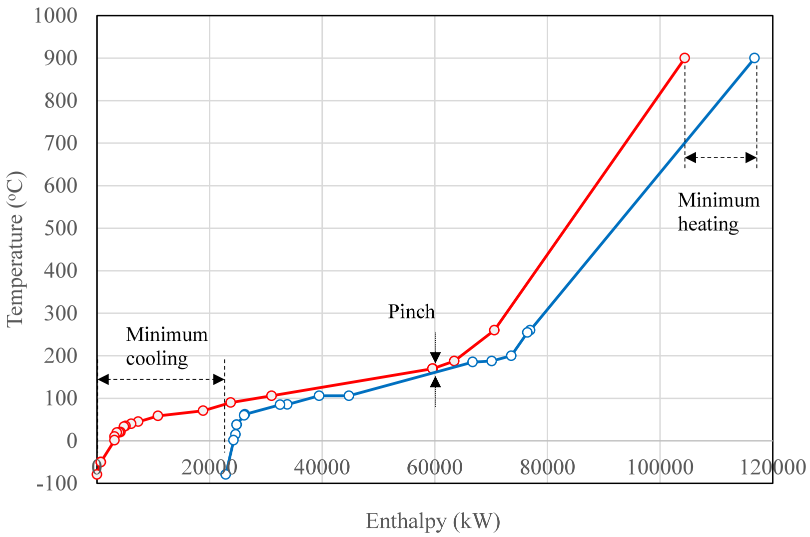


Fig. 8. Composite curve for DME production (direct method).

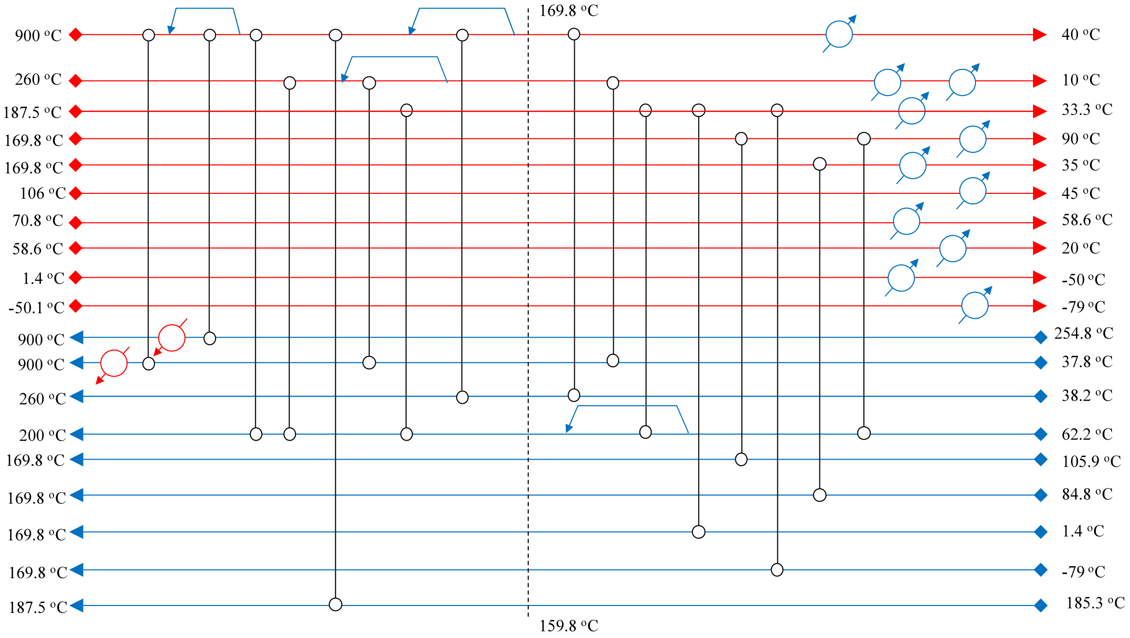


Fig. 9. New network design using Q/A parameter for DME production.

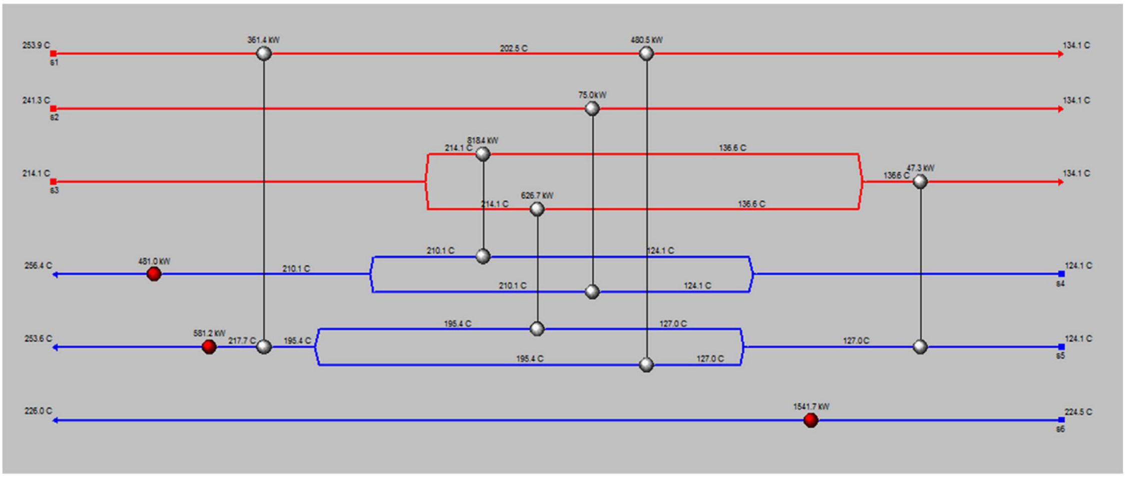


Fig. A.1. HEN design alternative 1 (minimum energy).

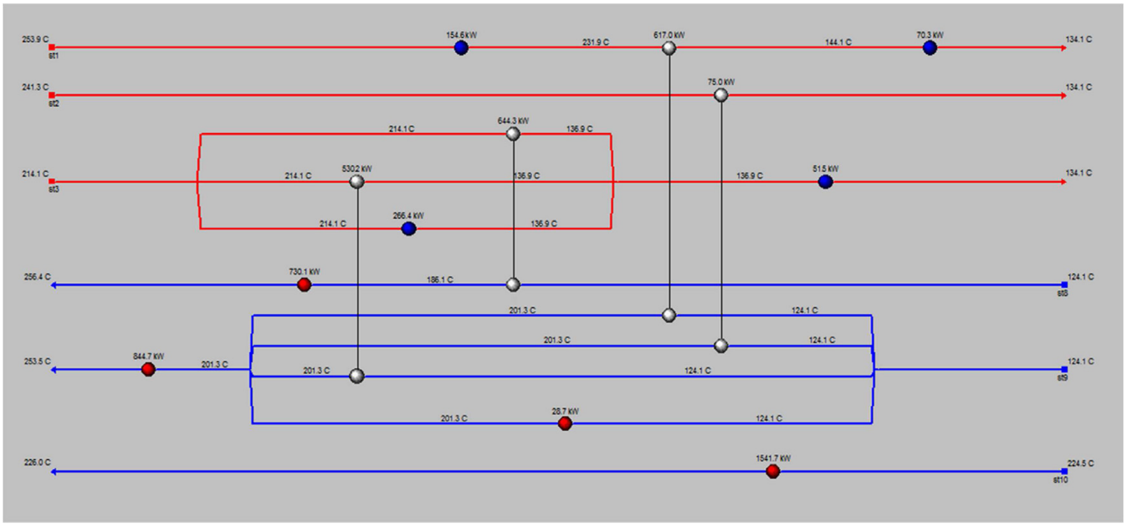


Fig. A.2. HEN design alternative 2 (minimum total cost).

guarantees less exchanger areas while achieving optimum energy targets. In addition, it generates less number of exchangers and stream splits compared literature solutions. The advantage of the proposed method is that it does not require software or simulation packages. However, one of its advantages is that the procedure becomes tedious for very complex networks with large number of process streams and the expected exchanger matches will be huge. This limitation can be addressed through automation. Another limitation of the proposed solution is that a single value for the overall coefficient U has been used. Although this can be overcome by specifying a different value for every exchanger match which is manageable in the design procedure. In conclusion, the new design methodology is helpful and can be utilized to design networks for maximum heat transfer and minimum exchanger areas.

Nomenclature

A: heat exchanger area (m^2)
CP: heat capacity flow (kJ/s °C)
C_{pC}: specific heat of cold stream (kJ/kg °C)
C_{pH}: specific heat of hot stream (kJ/kg °C)
dA: increment of exchanger area (m^2)
dQ: heat flow across increment of exchanger area (kW)
m_C: mass flow rate of cold stream (kg/s)
m_H: mass flow rate of hot stream (kg/s)
Q: heat duty or flow (kW)
T_C: temperature of process cold stream (°C)
T_H: temperature of process hot stream (°C)
T_{C1}: temperature of inlet cold stream to exchangers (°C)
T_{C2}: temperature of outlet cold stream from exchangers (°C)
T_{H1}: temperature of inlet hot stream to exchangers (°C)
T_{H2}: temperature of outlet hot stream from exchangers (°C)
T_{PC}: temperature of cold pinch point (°C)
T_{PH}: temperature of hot pinch point (°C)
ΔT: temperature driving force of exchanger (°C, K)
ΔT_{min}: minimum temperature approach difference (°C, K)
ΔT_{AMTD}: arithmetic mean temperature difference (°C, K)
ΔT_{LMTD}: logarithmic mean temperature difference (°C, K)
U: overall heat transfer coefficient (kW/m^2 °C)

Abbreviation

C: cold stream
DME: dimethyl ether
H: hot stream
HEN(s): heat exchanger network(s)
hx: exchanger unit

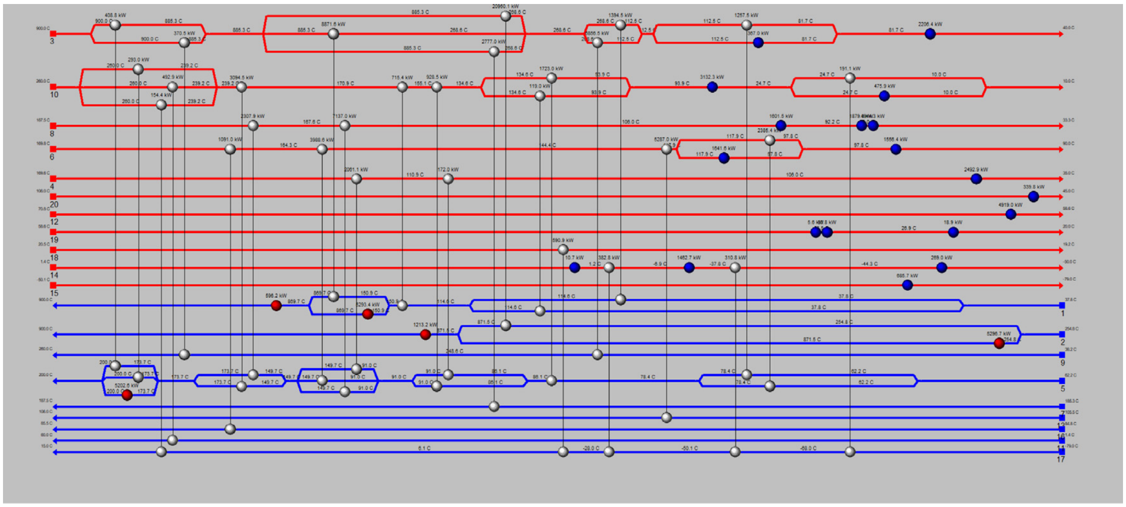


Fig. A.3. HEN design for DME production plant (commercial software).

Table A.1
Exchanger matches between H1 and C1, C2 and C3.

Exchanger match	U (W/m^2 °C)	Q/A parameter	Heat load (kW)	Exchanger area (m^2)
H1-C1	317	7.76	841.9	108.6
H1-C2	422	13.95	841.9	60.36
H1-C3		Infeasible	Infeasible	Infeasible

Data for U are extracted from Kern (1983).

Table A.2
Exchanger matches between H2 and C1, C2 and C3.

Exchanger match	U (W/m^2 °C)	Q/A parameter	Heat load (kW)	Exchanger area (m^2)
H2-C1	230	9.59	75.029	7.82
H2-C2	345	14.62	75.029	5.13
H2-C3		Infeasible	Infeasible	Infeasible

Data for U are extracted from Kern (1983).

CRediT authorship contribution statement

Ibrahim H. Alhajri: Data curation, Visualization, Writing - review & editing. **Mamdouh A. Gadalla:** Conceptualization, Methodology, Software, Formal analysis, Writing - original draft, Supervision. **Hany A. Elazab:** Software, Visualization, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

See Figs. A.1, A.3, Tables A.1 and A.2.

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