Utility Paths Combination in HEN for Energy Saving and CO₂ Emission Reduction

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Abstract: Energy demand and flue gas emissions, namely carbon dioxide (CO₂) associated with the industrial revolution have exhibited a continuous rise. Several approaches were introduced recently to mitigate energy consumption and CO₂ emissions by either grass root design or retrofit of existing heat exchanger networks (HEN) in chemical process plants. In this work, a combinatorial approach of path combination is used to generate several options for heat recovery enhancement in HEN. The options are applied to successively shift heat load from HEN utilities using combined utility paths at different heat recovery approach temperature (HRAT) considering exchangers pressure drop. Industrial case study for HEN of the preheat train in crude oil distillation unit from the literature is used to demonstrate the approach. The obtained results have been studied economically using the cost targeting of Pinch Technology. As a result, both external energy usage and CO₂ emissions have been reduced from a heater device in HEN by 20% and 17%, respectively, with a payback of less than one year.

Keywords: HEN retrofit; path analysis; paths combination; energy saving; CO₂ emission

1. Introduction

Energy demand has prompted different approaches recently due to limited energy resources as well as technical and environmental constraints. As fossil fuel sources are depleting, energy optimization and upgrades of plants have become crucial to narrow the gap between energy supply and demand. In the literature, there are various strategies to achieve energy optimization in industrial processes. Research and development units in the industry are focusing on maximizing individual units’ throughputs following local and global economics. However, due to operational and forecasting constraints, they are faced with challenging trade-offs. As a result, retrofit of existing plants offers a viable alternative to overcome operational requirements.

Retrofit plans in heat exchanger networks (HEN) include reducing the use of utilities, upgrading heat transfer units, installing additional heat transfer area, re-piping streams and re-assigning new heat recovery matches. HEN is a heat recovery system that enables heat exchange between hot and cold streams in chemical process plants, which is essential for energy conservation within a plant. The grass-roots design of HEN as studied by Linnhoff et al. has been significantly improved through the use of Pinch Technology [1–3]. Tjoe and Linnhoff were the first to propose a systematic methodology for heat exchanger network retrofit using pinch analysis [4], based on the elimination of any cross-pinch match by disconnecting units that transfer heat across the pinch. Gadalla et al. have presented a methodology to maximize the use of existing equipment in HEN and distillation column based on rigorous simulation and optimization framework using pinch analysis [5]. Biyanto et al.
have recently conducted a HEN retrofit for maximum energy recovery without topological changes using a genetic algorithm (GA) to screen different optimization scenarios for selecting optimum heat transfer coefficient [6]. A step-wise approach for optimal HEN retrofit to reduce calculation times and annualized cost associated with HEN complexity has recently introduced by Ayotti-Sauve et al. [7]. Kang and Liu have conducted a comprehensive review and analysis for the synthesis of flexible HEN, including both grass-roots and retrofit design [8].

Different methodologies have been developed based on the concept of utility path analysis in HEN such as those developed by Varbanov and Makwana [9], where they first presented the rule of path construction for HEN retrofit. Van Reisen et al. have proposed a method of path analysis for decomposition and prescreening of HEN [10]. Their technique selects and evaluates only potential subnetwork parts of the existing HEN. In subsequent work, Van Reisen et al. have presented an extension to the path analysis procedure, by considering structural interconnections while solving the retrofit problem [11]. They divided the network into many sub-networks by a combination of structural units using path analysis. These units, called zones, must be as self-contained as possible, similar to the approach used in grass-root problems. Paths help to classify the zones that are better suitable to include structural modifications. The refined path zones are based on functions of plant sections as well as operational constraints such as temperature range of process streams. For enhancing the process-to-process heat recovery in HEN, Osman et al. have introduced a combinatorial approach of paths combination [12]. Their strategy depends on shifting heat loads through utility paths at the constraint of heat recovery approach temperature (HRAT) and exchanger pressure drop. In subsequent work, Osman et al. applied the same methodology to screen more extensive options of heat recovery enhancement in HEN with an option of varying HEN streams temperature [13].

Awad and Abdelgadir have conducted two different studies for energy saving in HEN of crude oil pre-heat train unit using the paths combination approach. However, they did not consider the effect of pressure drop while estimating the heat transfer coefficient in HEN devices [14,15]. They also ignored the emission of CO$_2$, although the main heater of the network is using heavy fuel.

HEN Retrofit study considering the constraints of the pressure drop in HEN was first recognized by Polley et al. [16]. Comprehensive research considering the pressure drop in HEN retrofit was conducted by Panjehshahi [17], Marcone et al. [18] and Gadalla [19].

Regarding HEN area distribution, along with economic assessment, Lai et al. have introduced a recent study where they presented a new customized approach for HEN retrofit [20]. They used a combination of individual stream temperature versus enthalpy to map hot and cold streams to minimize the overall heat exchanger area. They also used graphical cost screening tool and strategies to steer and customize HEN retrofit design toward a desired investment payback period.

Regarding environmental pollution outstretched from process plants, significant efforts and strategies have been made by Steyn [21] and John [22] to provide CO$_2$ emissions reduction solutions. These strategies include improving the energy efficiency in process plants and fuel switching as well as renewable energy technologies such as carbon capture and storage (CCS). Gadalla et al. have developed a simple approach for optimizing the process conditions of industrial units to reduce its CO$_2$ emissions and energy demands [5].

Kang and Liu have conducted a recent work by developing a systematic strategy for HEN retrofit to minimize total annual cost and CO$_2$ emission. Based on a multi-objective optimization model [23].

Most of the previous work conducted for energy saving in process plants were associated with costly topological changes in HEN. Such changes were either addition of new heat exchangers, re-piping or resequencing the existing devices. However, topological changes always require additional space (platform) in the plant, which might be unavailable or/and restricted for safety consideration. Topological changes also associated with civil work and have not been considered in previous studies.

Accordingly, in this work, the authors carried out energy optimization for an existing HEN (crude oil preheat train unit) using the combinatorial approach of path combination. Apart from the previous works of the authors that based on a fixed value of HRAT while ignoring the effect on CO$_2$ emission,
the current work is conducted at different HRAT values considering the cost targeting approach, exchangers’ pressure drop, and the impact of energy saving in HEN on CO₂ emissions.

2. Methods

The method applied for energy saving in HEN in the current study is a combinatorial approach of utility paths combination and cost targeting of pinch technology.

Utility path is an imaginary connection between a heater and a cooler through a definite match(es) in HEN [12]. A certain amount of heat duty can be shifted using the plus-minus principle along the utility path. For instance, if a certain amount of heat duty is to be subtracted from hot and cold utilities using the utility path, it must be added and deducted alternatively to and from the matches on that path.

The approach allows for successive heat load shifting from HEN utilities at the minimum HRAT values to ensure maximum possible heat recovery. Furthermore, the impact of reducing energy consumption on the reduction of flue gas emissions is calculated as a CO₂, emitted from the furnace heater in HEN.

2.1. Path Combination Approach

The approach is typically a combinatorial procedure for screening broader alternatives by combining the available utility paths in HEN systematically to enhance the process-to-process heat recovery with the addition of new heat transfer area [24]. The available utility paths in HEN are combined according to the combination law by Equation (1) [25].

\[ C(n, r) = \frac{n!}{(n-r)!r!} \]  

where, \( C \), \( n \), and \( r \): combination, number of paths in the HEN and size of combination, respectively; \( (r \leq n) \).

For \( n \) number of paths in HEN, different sets of combined paths can be generated including available single paths. For example, if 3 paths (A, B, and C) are available in an existing HEN, the possible combinations are a set of unilateral paths (A, B and C) each alone, sets of bilateral combined paths (AB, AC, and BC) and a set of trilateral combined paths (ABC). More detail of path combinations is available in a study introduced by Osman [24].

2.1.1. Heat-Shifting Process

Heat load shifting through utility paths in HEN is constrained by the minimum heat transfer driving force between hot and cold streams of HEN, which is called heat recovery approach temperature (HRAT). To select the most optimum HRAT, a range of several values between 2 °C to 24 °C is considered for this study.

A computer software called Hint, which was presented by Martin and Mato [26], has been used to run the heat-shifting process based on a simple energy balance concept. The Hint software package cannot shift the heat load for combined paths in a simultaneous way. However, it allows selection of each utility path and runs the heat load shifting until temperature driving force reaches the set HRAT value. Heat duties for exchangers, hot and cold utilities for HEN under study, are tabulated in Appendix tables for all the three heat-shifting options at different HRAT values.

2.1.2. Cost Targeting

For the selection of optimum HRAT, the range of HRAT values stated above is analyzed economically based on the cost targeting method of Pinch Technology [2,3].
The cost targeting depends on operating, annualized capital, and total costs. The operating cost for a new situation after heat-shifting is estimated by Equations (2)–(4).

\[
\text{Operating cost} = \sum HU_{\text{new.cost}} + \sum CU_{\text{new.cost}}
\]

\[
HU_{\text{new.cost}} = Q_{\text{new.H}} \cdot HU_{\text{price}}
\]

\[
CU_{\text{new.cost}} = Q_{\text{new.C}} \cdot CU_{\text{price}}
\]

where \( HU_{\text{new.cost}} \) and \( CU_{\text{new.cost}} \) represent the costs for hot and cold utilities after heat-shifting ($/yr). \( HU_{\text{price}} \) and \( CU_{\text{price}} \) are hot and cold utility prices, respectively ($/kW.yr). \( Q_{\text{new.H}} \) and \( Q_{\text{new.C}} \) are the new (after heat-shifting) hot and cold utility heat duty (kW), respectively.

For the annualized capital cost, the required additional heat transfer area due to heat-shifting process needs to be determined. Therefore, a new heat transfer area for each affected exchanger in HEN can be first predicted according to the following Equation (5)

\[
\frac{A_{\text{before}}}{A_{\text{after}}} = \frac{Q_{\text{before}}}{Q_{\text{after}}}
\]

where \( A_{\text{before}}, Q_{\text{before}}, A_{\text{after}}, Q_{\text{after}} \) are exchanger heat transfer area (m\(^2\)) and heat load (kW) before and after heat-shifting process, respectively.

The initial result from heat transfer area is used in the pressure drop correlations for shell and tube heat exchanger developed by Nie and Zhu [27]. Existing pressure drop for each exchanger is maintained to avoid extra pumping cost for HEN streams. Pressure drop is used to obtain the heat transfer coefficients \( h_T \) and \( h_S \) for tube and shell side, respectively, using Equations (6) and (7).

\[
\Delta P_T = K_{PT1} A h_T^{3.5} + K_{PT2} h_T^{2.5}
\]

\[
\Delta P_S = K_{S1} h_S^{2.86} + K_{S2} A h_S^{4.42} + K_{S3} A h_S^{4.69}
\]

where \( A \) is the predicted heat transfer area of the exchanger (m\(^2\)). \( \Delta P_T \) and \( \Delta P_S \) are pressure drop for tube and shell sides of the exchangers (kPa), respectively. \( K_{PT1} \) and \( K_S \) are dimensional constants for tube and shell sides of the exchanger, respectively. These constants are functions of fluids’ physical properties and exchanger’s geometrical configuration. More details about these constants are available in the Appendix A.

Due to the complexity of the above two correlations where both \( h_T \) and \( h_S \) are raised to a fractional power, they are solved using Mathcad software. The values of \( h_T \) and \( h_S \) for the affected exchangers in HEN are tabulated in Appendix A, Table A10 for all the heat-shifting options.

Based on the obtained heat transfer coefficient, the actual heat transfer area for each exchanger is calculated by the area targeting Equation (8).

\[
A = \left( \frac{1}{h_T} + \frac{1}{h_S} \right) \times \frac{Q}{\text{LMTD} \times F_T}
\]

where \( Q \) is the heat duty (kW) for each exchanger, and it is found from the energy balance Equation (9).

\[
Q = \dot{m} C_p \Delta T
\]

where \( \dot{m} \) is the stream mass flow rate (kg/s), \( C_p \) is the stream heat capacity (kW/kg·°C), and \( \Delta T \) is the inlet and outlet temperature difference (°C). The correction factor \( (F_T) \) is usually ranged between (0.0
and 1.0). However, in the present case, it is assumed to be 1.0. The logarithmic mean temperature difference \( \text{LMTD} \) is calculated as follows:

\[
\text{LMTD} = \frac{\Delta T_1 - \Delta T_2}{\ln \left( \frac{\Delta T_1}{\Delta T_2} \right)}
\]  \( (10) \)

\[
\Delta T_1 = T_{H,\text{in}} - T_{C,\text{out}}
\]  \( (11) \)

\[
\Delta T_2 = T_{H,\text{out}} - T_{C,\text{in}}
\]  \( (12) \)

where \( \Delta T_1, \Delta T_2 \) are exchanger hot side and cold side temperature difference, respectively. \( T_{H,\text{in}}, T_{H,\text{out}}, T_{C,\text{in}}, T_{C,\text{out}} \) are exchanger’s hot inlet, hot outlet, cold inlet and cold outlet temperature (°C), respectively.

For estimating the annualized capital cost, capital investment should be calculated first using Equations (13)–(16):

\[
\text{Capital Investment} = \Delta N \left( a + b \left( \frac{\Delta A}{\Delta N} \right)^c \right)
\]  \( (13) \)

\[
\Delta N = \frac{\Delta A}{a_{\text{av shell}}}
\]  \( (14) \)

\[
a_{\text{av shell}} = \frac{A_{\text{ex HEN}}}{N_{\text{shell}}}
\]  \( (15) \)

\[
\Delta A = A_{\text{new HEN}} - A_{\text{ex HEN}}
\]  \( (16) \)

where \( A_{\text{ex HEN}}, A_{\text{new HEN}} \) and \( \Delta A \) denote existing, new and additional exchanger heat transfer area (m²), respectively, whereas \( \Delta N, a_{\text{av shell}}, \) and \( N_{\text{shell}} \) indicate the number of required extra shells, the average size of exchangers shell and number of exchanger shells, respectively. The values of cost coefficients \( a, b, \) and \( c \) are 33422, 814, and 0.81, respectively, for carbon steel exchanger. The data for heat duties and exchangers’ heat transfer area are tabulated in the Appendix tables for all heat-shifting options.

Annualized capital and total annual costs are calculated using Equations (17) and (18), respectively. It is assumed that the capital has been borrowed over a fixed period at a fixed interest rate.

\[
\text{Annual capital cost} = \text{capital investment} \times \frac{i(1+i)^n}{(1+i)^n - 1}
\]  \( (17) \)

\[
\text{Total annual cost} = \text{annual capital cost} + \text{operating cost}
\]  \( (18) \)

where \( i \) and \( n \) represent the fractional interest rate per year, and several years and are assumed to be 0.15/year and 2 years, respectively. The total annual cost changes according to the values of HRAT. The optimum HRAT is obtained at the point of the minimum total annual cost.

2.1.3. Economic Assessment

Economic analysis is conducted based on the amount of savings ($/yr), capital investment ($), and payback period (yr). As per Al-Riyami et al. [28], saving, investment, and payback period are calculated based on the following assumptions:

- Investment is considered only for the required additional area.
- No piping or other costs are considered.
- The cost of hot and cold utility is fixed.

Saving can be calculated from the Equations (19)–(21) below:

\[
\text{Saving}_{\text{cost}} = \sum HU_{\text{ex cost}} - \sum HU_{\text{new cost}} + \sum CU_{\text{ex cost}} - CU_{\text{new cost}}
\]  \( (19) \)

\[
HU_{\text{ex cost}} = Q_{\text{ex H}} \times HU_{\text{price}}
\]  \( (20) \)
where, $HU_{ex.cost}$ and $CU_{ex.cost}$ are existing (before heat-shifting) hot and cold utility cost ($/yr), respectively. $Q_{ex.H}$ and $Q_{ex.C}$ are existing (before heat-shifting) hot and cold utility heat duty (kW), respectively. $HU_{new.cost}$ and $CU_{new.cost}$ are presented in Equations (3) and (4) above.

The capital investment cost ($) for HEN, where an additional area is required, are calculated in Equations (13)–(16) above. The payback period is calculated using Equation (24) below:

\[
Payback = \frac{\text{Investment}}{\text{Saving}}
\]  

2.1.4. Energy Saving in HEN and CO\(_2\) Emission

CO\(_2\) emissions can be regarded as an additional parameter in search of optimum solution(s). Burning fuel in the presence of excess air results in combustion that produces carbon dioxide and water vapor according to the stoichiometric Equation (23):

\[
C_xH_y + \left(\frac{x}{4} + \frac{y}{2}\right)O_2 \rightarrow xCO_2 + \frac{y}{2}H_2O
\]  

where $x$ and $y$ denote the number of carbon C and hydrogen H atoms present in fuel compositions, respectively. To estimate the mass flow rate ($M$) of emissions ($\text{Mass of CO}_2$) in kg/hr, Equation (24) is adopted from Gadalla et al. [5].

\[
M_{CO_2} = \left(\frac{Q_{\text{Fuel}}}{NHV}\right)C\% \cdot \alpha
\]  

where $Q_{\text{Fuel}}$ is fuel heat quantity, calculated by Equation (25), $Q_{\text{proc}}$ is the process heat duty of heater in HEN, ($\eta_{\text{Furn}}$ is furnace efficiency, $NHV$ is fuel net heat value, and $C\%$ is the percentage of carbon content in fuel; case study values), and $\alpha$ is the molar mass ratio for CO\(_2\) to C which is 3.67.

The overall methodology can be summarized in the flow diagram shown in Figure 1.

3. HEN Case Study

The case study adopted in this work is a HEN for a pre-heat train of a crude oil distillation unit taken from Panjishahi and Tahouni [29], Awad [14] and Abdelgadir [15]. The schematic representation of HEN with stream data (temperature, exchanger heat load, the duty of hot and cold utility, and specific heat mass flow) is shown in Figure 2. The available utility paths in such HEN are identified separately as in Figure 3.

The paths combination approach has been used by Abdelgadir [15] to generate several options of heat-shifting in HEN of a pre-heat train unit while ignoring the exchangers’ pressure drop. However, only three options were found feasible in terms of optimum HRAT value. These best options are adopted in this study for further analysis considering exchangers’ pressure drop and the effect of energy saving on CO\(_2\) emission. The selected options are listed in Table 1.

| Option No. | Combined Paths      |
|------------|---------------------|
| 1          | A and B             |
| 2          | B and D             |
| 3          | A, B, C, D and E    |
Figure 1. Overall methodology flow diagram.
Figure 2. Grid diagram of existing heat exchanger networks (HEN) of crude oil pre-heat train with stream data.

Figure 3. Available individual utility paths in HEN.

According to a previous study by Panjeshahi and Tahouni [29], hot and cold utility prices for the preheat train are tabulated in Table 2:

|            | Cost Data for Crude Oil Preheat Train |
|------------|-------------------------------------|
| Hot Utility (Furnace) | 107 ($/kW.yr)             |
| Cold Utility      | 10.7 ($/kW.yr)            |

All the data (including equations) required to estimate the heat transfer coefficients for shell and tube sides of the exchangers are available in the Appendix. Geometrical configurations and fluid properties of exchangers are used to calculate the exchanger pressure drop. Heat duty is used to calculate the exchanger heat transfer area. Then both exchanger pressure drop and heat transfer area are used to calculate the heat transfer coefficients [24].
Furnace fuel used as HEN hot utility reacting with excess air (O2) produces flue gases including CO2. It is assumed that the fuel in the furnace is fuel oil with a carbon content of 87.26% and net heat value NHV of 39,830 kJ/kg is fed at 25 °C with air at the same temperature [30].

4. Results and Discussion

The optimum HRAT value for HEN that corresponds to the lowest total cost can be obtained from the cost targeting profile of Pinch Technology. It is worth mentioning that the total cost is a summation of operation and annualized capital costs. Therefore, heat-shifting options may reveal similar lower total cost but with different HRAT values where the higher is preferred as a heat transfer driving force. Figure 4 illustrates the cost targeting profile for the three options of heat-shifting in the HEN example used in this study. Compared to options 1 and 2, it is clear that option 3 shows the best profile of total capital cost to be lowest at 8.38 × 10^6 $/yr corresponds to optimum HRAT of 10 °C. Although the optimum HRAT value shown in the profile of option 1 is 10 °C (similar to that of option 3), but the total cost is higher. In contrast, option 2 illustrates the same trend that is showing a low total cost of 8.5 × 10^6 $/yr at lower optimum HRAT value of 6 °C, which can be insufficient heat transfer driving force.

![Figure 4. Total cost targeting profile for the three options.](image)

It worth mentioning that option 3 is having the most degrees of freedom where it contained all the HEN paths from A to E. However, the targeting process yields higher total cost for option 3 than option 2 at the lowest HRAT value. That is because option 3 is affecting all HEN exchangers where the additional area is required for them all, and hence increasing the capital and total cost. The Appendix A Tables A11–A13 show a detailed area distribution in HEN using the three options.

The external energy requirements for options 1, 2 and 3 are determined from the energy consumption profiles. Figure 5 shows the energy consumption profile, which has been reduced due to the heat-shifting process at the penalty of additional heat transfer area for options 1, 2 and 3. The pattern of option 3 (a combination of utility paths: A, B, C, D and E in HEN example) indicates the lowest energy consumption and reasonable heat transfer area requirements. Using option 3 at the
optimum HRAT of 10 °C, energy consumption has dropped from 1.34 × 10^5 kW for the present case to 1.07 × 10^5 kW, where 2.7 × 10^4 kW of external energy usage is saved. The additional area requirement is distributed through all the affected exchangers in HEN, which is 5390 m^2 where it increased from 6960 m^2 to be 12,350 m^2 at optimum HRAT value of 10 °C. The area requirement for option 1 is the lowest compared with option 2 and 3; however, energy consumption is trending very high. Option 2 is trending close to option 3 and even better in terms of area requirement, but the optimum HRAT value is low.

![Figure 5](image-url)

**Figure 5.** Energy consumption profile with heat transfer area for the three options.

A complete area-energy trade-off can make the right decision to choose the best energy saving option. Therefore, these options are studied economically where the profiles of investment ($), savings ($/year), and payback periods (yr) are analyzed concerning HRAT to select the most excellent option.

Figure 6 illustrates the economic profile of option 1. The economic profile shows a gradual decrease in investment, savings, and payback with increasing HRAT. When HRAT increased from 2 °C to the optimum HRAT of 10 °C, the investment cost has dropped by 50%. On the other hand, savings have slightly decreased from 1000K $/yr to around 800K $/yr at optimum HRAT. The payback has tremendously decreased from 1.4 yr to approximately 0.86 yr at optimum HRAT of 10 °C.

Figure 7 illustrates the economic profile of option 2. While the ratio of saving to investment started at almost 1 (superimposed saving and investment at HRAT of 2 °C), it became higher with higher HRAT values. Although, this option is showing a short payback period of 0.84 yr, the optimum HRAT of 6 °C makes it insufficient for the heat transfer process between hot and cold streams. This option can be operable by applying some constructional changes in HEN to relax the HRAT value at the expense of higher investment and payback. The constructional changes may include the addition of new HEN devices, exchanger resequencing, and re-piping.
payback has tremendously decreased from 1.4 yr to approximately 0.86 yr at optimum HRAT of 10 °C.

Figure 6. Investment, savings, and payback for option 1.

Figure 7 illustrates the economic profile of option 2. While the ratio of saving to investment started at almost 1 (superimposed saving and investment at HRAT of 2 °C), it became higher with higher HRAT values. Although, this option is showing a short payback period of 0.84 yr, the optimum HRAT of 6 °C makes it insufficient for the heat transfer process between hot and cold streams. This option can be operable by applying some constructional changes in HEN to relax the HRAT value at the expense of higher investment and payback. The constructional changes may include the addition of new HEN devices, exchanger resequencing, and re-piping.

Figure 8 illustrates the economic profile of option 3. The saving and investment profiles of option 3 are similar to that of option 1. The investment cost profile in this option is lower while the saving profile is higher. As a result, the payback period is fastest with 0.82 yr at the optimum HRAT value. For the HEN case study, option 3 is considered as the best energy saving solution compared to option 1 and 2.

Also, the effect of reducing energy consumption in HEN on CO2 emissions is analyzed. The profiles of CO2 emission along the range of HRAT values for options 1, 2, and 3 are shown in Figure 9. At optimum HRAT, option 3 shows the most CO2 emission reduction of 17% compared with 15% and 8% for options 2 and 1, respectively. Therefore, option 3 is considered the best environmental option where the annual CO2 emission from the HEN furnace heater has dropped from 25,190 kg/hr to 20,909 kg/hr at the optimum HRAT of 10 °C.

The profiles of CO2 emission mass flow rate (kg/hr) concerning investment cost for options 1, 2, and 3 are shown in Figure 10. Although option 3 shows a higher investment cost around $1.3 M, it gives the lowest annual CO2 emissions of 20,900 kg/hr at optimum HRAT of 10 °C.
Also, the effect of reducing energy consumption in HEN on CO\textsubscript{2} emissions is analyzed. The profiles of CO\textsubscript{2} emission along the range of HRAT values for options 1, 2, and 3 are shown in Figure 9. At optimum HRAT, option 3 shows the most CO\textsubscript{2} emission reduction of 17\% compared with 15\% and 8\% for options 2 and 1, respectively. Therefore, option 3 is considered the best environmental option where the annual CO\textsubscript{2} emission from the HEN furnace heater has dropped from 25,190 kg/hr to 20,909 kg/hr at the optimum HRAT of 10 °C.
The profiles of CO$_2$ emission mass flow rate (kg/hr) concerning investment cost for options 1, 2, and 3 are shown in Figure 10. Although option 3 shows a higher investment cost around $1.3 M, it gives the lowest annual CO$_2$ emissions of 20,900 kg/hr at optimum HRAT of 10 °C.

![Figure 10. Emission of CO$_2$ concerning investment for the three options.](image_url)

5. Conclusions

Heat recovery enhancement is conducted using an approach based on mathematical laws of combination to generate several options of solutions. The present utility paths in the heat exchanger network have combined to successively shift heat load from heaters and coolers to the network exchangers. The heat-shifting process is performed for different values of heat recovery approach temperature while considering the pressure drop in HEN devices. From cost targeting analysis, the best option is selected based on the optimum heat recovery approach temperature. Then, an economic analysis has been performed for the options based on energy saving, investment, and payback period at the optimum heat recovery approach temperature. Finally, CO$_2$ emission has been evaluated concerning the heat recovery approach temperature and investment. Compared to a previous work done by Osman et al. [24], who introduced paths combination for HEN retrofit at a fixed, the current study considered a wide range of temperature driving force using the cost targeting of Pinch Technology. Moreover, the present study analyses the impact of energy saving on the emission of CO$_2$ compared to those using paths combination while ignoring the environmental impact such as Awad [14] and Abdelgadir [15].

The real contribution of this study is:

- Merging path combination approach with cost targeting of Pinch Technology to obtain high optimized solutions for energy saving in an existing heat exchanger network and reducing the emission of CO$_2$.
- The obtained energy saving solutions are considered as low-hanging fruit results where only minor retrofit is considered without topology changes to the network.
The approach adopted for this study is following the concept of Pinch Technology, and it is applied only for simple heat exchanger network such as preheat train unit. Systems that are more complicated can be investigated using the same approach under both Pinch Technology and mathematical programming to generate a hybrid-automated plan.

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### Nomenclature

| Symbol | Definition |
|--------|------------|
| A      | Exchanger heat transfer area (m²). |
| A_C    | Exchanger shell side cross-sectional area (m²). |
| A_E1, A_E2, A_E3, A_E4, A_E5, A_E6 | Heat transfer area for HEN exchangers after heat-shifting (m²). |
| A_newHEN | Overall heat transfer area of HEN after heat-shifting (m²). |
| B_C    | Baffle cut (to direct the stream fluid across the tubes). |
| c      | Constant in the tube side pressure drop correlation. |
| C_P    | Specific heat capacity (kJ/kg.°C). |
| D_s    | Shell diameter (m). |
| d_o    | Outside tube diameter (m). |
| d_l    | Inside tube diameter (m). |
| E_1, E_2, E_3, E_4, E_5, E_6 | Heat exchanger devices in HEN. |
| F_I, F_o | Exchanger tube and shell sides flow rate, respectively (m³/s). |
| F_hn, F_hw, F_hb, F_hL, F_pb, F_PL | Correction factors in the shell side pressure drop correlation. |
| h_T, h_S | Tube and shell side heat transfer coefficients, respectively (kW/m².°C). |
| k      | Thermal conductivity (W/m.°C). |
| k_PT1, k_PT2, k_S1, k_S2, k_S3, k_ST, k_S5, k_PS1, k_PS2, k_PS3, k_PS4 | Dimensional constants in the exchanger tube and shell sides pressure drop correlation. They depend on the geometrical configuration and fluid physical properties. |
| N_T, N_TP | Exchanger’s number of tubes and number of tube passes, respectively. |
| P_C    | Pitch configuration factor. |
| P_T    | Exchanger’s tube pitch (center to center distance between adjacent tubes). |
| P_r    | Prandtl number. |
| Q_E1, Q_E2, Q_E3 | Exchangers’ heat duties (kW) for HEN of the preheat train after heat-shifting. |
| Q_E4, Q_E5, Q_E6 | Cold utilities heat duties (kW) for HEN of the preheat train after heat-shifting. |
| Q_C1, Q_C2, Q_C3, Q_C4, Q_C5 | Hot utility heat duty (kW) for HEN of the preheat train after heat-shifting. |
| Q_H    | | |
| ∆P_T  | Tube side pressure drop (kPa). |
| ∆P_S  | Shell side pressure drop (kPa). |
| Greeks | Density (kg/m³). |
| ρ      | Viscosity (cP). |
| μ      | Velocity (m/s). |
Appendix A

All the data in Tables A1–A4 are adopted from Panjishahi and Tahouni [27]. Table A1, shows flow rates and fluid physical properties for crude pre-heat train HEN streams.

**Table A1.** Flow rates and physical properties for crude oil pre-heat train.

| Stream No. | Flow Rate (kg/s) | $\rho$ (kg/m$^3$) | $C_p$ (J/kg.$^\circ$C) | $\mu$ (cP) | $k$ (W/m.$^\circ$C) |
|------------|-------------------|-------------------|------------------------|-----------|---------------------|
| 1          | 23                | 700               | 2600                   | 0.3       | 0.12                |
| 2          | 44                | 700               | 2600                   | 0.4       | 0.12                |
| 3          | 13                | 750               | 2600                   | 0.5       | 0.12                |
| 4          | 56                | 750               | 2600                   | 0.5       | 0.12                |
| 5          | 253               | 630               | 2600                   | 0.2       | 0.12                |
| 6          | 148               | 750               | 2600                   | 0.4       | 0.12                |
| 7          | 200               | 800               | 2600                   | 1.0       | 0.12                |

**Table A2.** Heat exchangers’ specifications for heat exchanger networks (HEN) of crude oil pre-heat train.

| Geometrical Species | E1 | E2 | E3 | E4 | E5 | E6 |
|---------------------|----|----|----|----|----|----|
| $P_C$               | 1  | 1  | 1  | 1  | 1  | 1  |
| Shell ID (mm)       | 1143 | 1219 | 1143 | 940 | 1524 | 940 |
| Baffle Spacing      | 509.1 | 605.1 | 419.3 | 197.3 | 1246.4 | 255.3 |
| Tube Count          | 1590 | 1810 | 1590 | 1075 | 2827 | 1075 |
| Tube Passes         | 2  | 2  | 2  | 2  | 2  | 2  |
| Tube ID (mm)        | 15.4 | 15.4 | 15.4 | 15.4 | 15.4 | 15.4 |
| Tube OD (mm)        | 19.1 | 19.1 | 19.1 | 19.1 | 19.1 | 19.1 |
| Tube Pitch (mm)     | 25.4 | 25.4 | 25.4 | 25.4 | 25.4 | 25.4 |
| $B_C$               | 0.20 | 0.20 | 0.25 | 0.20 | 0.20 | 0.25 |
| $F_{hn}$            | 1  | 1  | 1  | 1  | 1  | 1  |
| $F_{hw}$            | 1  | 1  | 1  | 1  | 1  | 1  |
| $F_{hb}$            | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| $F_{hl}$            | 0.8 | 1  | 0.8 | 0.8 | 0.8 | 0.8 |
| $F_{Pb}$            | 1  | 1  | 1  | 1  | 1  | 1  |
| $F_{PL}$            | 0.5 | 0.5 | 1  | 1  | 1  | 0.5 |
| $h_{TF}$            | 0.719 | 0.649 | 0.758 | 0.862 | 0.752 | 0.763 |
| $h_{SF}$            | 0.719 | 0.649 | 0.758 | 0.862 | 0.752 | 0.763 |

**Table A3.** Exchanger’s pressure drop, heat duty, and exchangers’ area for existing HEN.

| Data | Heat Exchangers | $E_1$ | $E_2$ | $E_3$ | $E_4$ | $E_5$ | $E_6$ |
|------|-----------------|-------|-------|-------|-------|-------|-------|
| $\Delta P_T$ (kpa) | 53.164 | 10.776 | 31.272 | 32.749 | 11.549 | 32.749 |
| $\Delta P_S$ (kpa) | 26.364 | 24.357 | 13.954 | 4.303 | 27.859 | 7.783 |
| Q (kW) | 22.000 | 38.480 | 15.000 | 7500 | 23.000 | 6000 |
| A (m²) | 1360 | 2760 | 800 | 280 | 1480 | 280 |
Appendix A.1. Heat Recovery Duties

The heat recovery (heat duties for exchangers) after heat-shifting process for option 1, 2 and 3 are tabulated Tables A4–A6.

Table A4. Exchangers heat duties for HEN at different heat recovery approach temperature (HRAT) values using option 1.

| HRAT (°C) | Q₁ (kW) | Q₂ (kW) | Q₃ (kW) | Q₄ (kW) | Q₅ (kW) | Q₆ (kW) | Total Heat Recovery (kW) |
|-----------|---------|---------|---------|---------|---------|---------|-------------------------|
| 2         | 25,435  | 38,480  | 20,330  | 7500    | 23,000  | 6000    | 120,745                 |
| 4         | 25,201  | 38,480  | 20,112  | 7500    | 23,000  | 6000    | 120,293                 |
| 6         | 24,980  | 38,480  | 19,883  | 7500    | 23,000  | 6000    | 119,843                 |
| 8         | 24,753  | 38,480  | 19,654  | 7500    | 23,000  | 6000    | 119,387                 |
| 10        | 24,526  | 38,480  | 19,425  | 7500    | 23,000  | 6000    | 118,931                 |
| 12        | 24,299  | 38,480  | 19,197  | 7500    | 23,000  | 6000    | 118,476                 |
| 14        | 24,072  | 38,480  | 18,968  | 7500    | 23,000  | 6000    | 118,020                 |
| 16        | 23,845  | 38,480  | 18,739  | 7500    | 23,000  | 6000    | 117,564                 |
| 18        | 23,618  | 38,480  | 18,510  | 7500    | 23,000  | 6000    | 117,108                 |
| 20        | 23,390  | 38,480  | 18,281  | 7500    | 23,000  | 6000    | 116,651                 |
| 22        | 23,163  | 38,480  | 18,053  | 7500    | 23,000  | 6000    | 116,196                 |
| 24        | 22,936  | 38,480  | 17,834  | 7500    | 23,000  | 6000    | 115,750                 |

Table A5. Exchangers heat duties for HEN at different HRAT values using option 2.

| HRAT (°C) | Q₁ (kW) | Q₂ (kW) | Q₃ (kW) | Q₄ (kW) | Q₅ (kW) | Q₆ (kW) | Total Heat Recovery (kW) |
|-----------|---------|---------|---------|---------|---------|---------|-------------------------|
| 2         | 22,000  | 38,480  | 18,185  | 7500    | 32,800  | 6000    | 124,965                 |
| 4         | 22,000  | 38,480  | 18,000  | 7500    | 32,601  | 6000    | 124,581                 |
| 6         | 22,000  | 38,480  | 17,850  | 7500    | 32,243  | 6000    | 124,073                 |
| 8         | 22,000  | 38,480  | 17,770  | 7500    | 31,567  | 6000    | 123,317                 |
| 10        | 22,000  | 38,480  | 17,700  | 7500    | 30,845  | 6000    | 122,525                 |
| 12        | 22,000  | 38,480  | 17,600  | 7500    | 30,259  | 6000    | 121,839                 |
| 14        | 22,000  | 38,480  | 17,500  | 7500    | 29,674  | 6000    | 121,154                 |
| 16        | 22,000  | 38,480  | 17,425  | 7500    | 28,975  | 6000    | 120,380                 |
| 18        | 22,000  | 38,480  | 17,364  | 7500    | 28,212  | 6000    | 119,556                 |
| 20        | 22,000  | 38,480  | 17,287  | 7500    | 27,522  | 6000    | 118,789                 |
| 22        | 22,000  | 38,480  | 17,200  | 7500    | 26,878  | 6000    | 118,058                 |
| 24        | 22,000  | 38,480  | 17,129  | 7500    | 26,160  | 6000    | 117,269                 |

Table A6. Exchangers heat duties for HEN at different HRAT values using option 3.

| HRAT (°C) | Q₁ (kW) | Q₂ (kW) | Q₃ (kW) | Q₄ (kW) | Q₅ (kW) | Q₆ (kW) | Total Heat Recovery (kW) |
|-----------|---------|---------|---------|---------|---------|---------|-------------------------|
| 2         | 22,461  | 38,480  | 17,342  | 8300    | 32,870  | 8950    | 128,403                 |
| 4         | 22,312  | 38,480  | 17,194  | 8140    | 32,770  | 8830    | 127,746                 |
| 6         | 22,120  | 38,480  | 16,940  | 8100    | 32,740  | 8820    | 127,200                 |
| 8         | 22,015  | 38,480  | 16,740  | 7900    | 32,560  | 8735    | 126,430                 |
| 10        | 22,013  | 38,480  | 16,172  | 7860    | 32,340  | 8530    | 125,395                 |
Table A6. Cont.

| HRAT (°C) | Q_{E1} (kW) | Q_{E2} (kW) | Q_{E3} (kW) | Q_{E4} (kW) | Q_{E5} (kW) | Q_{E6} (kW) | Total Heat Recovery (kW) |
|-----------|-------------|-------------|-------------|-------------|-------------|-------------|--------------------------|
| 12        | 22,011      | 38,480      | 16,079      | 7820        | 31,870      | 8100        | 124,360                  |
| 14        | 22,010      | 38,480      | 16,049      | 7790        | 30,913      | 8080        | 123,322                  |
| 16        | 22,009      | 38,480      | 16,000      | 7730        | 30,076      | 7990        | 122,285                  |
| 18        | 22,007      | 38,480      | 15,932      | 7692        | 29,260      | 7879        | 121,250                  |
| 20        | 22,005      | 38,480      | 15,909      | 7640        | 28,340      | 7841        | 120,215                  |
| 22        | 22,004      | 38,480      | 15,882      | 7610        | 27,480      | 7722        | 119,178                  |
| 24        | 22,002      | 38,480      | 15,878      | 7560        | 26,560      | 7663        | 118,143                  |

Appendix A.2. Energy Consumption

Energy consumption (heat duties of hot and cold utility devices) after the heat-shifting for HEN using options 1, 2, and 3 at different HRAT values are tabulated in Tables A7–A9.

Table A7. Hot and cold utilities heat duties for HEN at different HRAT values using option 1.

| HRAT (°C) | Q_{H} (kW) | Q_{C1} (kW) | Q_{C2} (kW) | Q_{C3} (kW) | Q_{C4} (kW) | Q_{C5} (kW) | Total Utility Requirement (kW) |
|-----------|-------------|-------------|-------------|-------------|-------------|-------------|-----------------------------|
| 2         | 71,655      | 2970        | 5982        | 3316        | 22,613      | 9890        | 116,426                    |
| 4         | 72,107      | 2970        | 6200        | 3316        | 22,847      | 9890        | 117,330                    |
| 6         | 72,557      | 2970        | 6429        | 3316        | 23,058      | 9890        | 118,220                    |
| 8         | 73,013      | 2970        | 6658        | 3316        | 23,295      | 9890        | 119,142                    |
| 10        | 73,469      | 2970        | 6887        | 3316        | 23,522      | 9890        | 120,054                    |
| 12        | 73,924      | 2970        | 7115        | 3316        | 23,749      | 9890        | 121,004                    |
| 14        | 74,380      | 2970        | 7344        | 3316        | 23,976      | 9890        | 121,876                    |
| 16        | 74,835      | 2970        | 7573        | 3316        | 24,202      | 9890        | 122,786                    |
| 18        | 75,292      | 2970        | 7802        | 3316        | 24,430      | 9890        | 123,700                    |
| 20        | 75,749      | 2970        | 8031        | 3316        | 24,658      | 9890        | 124,614                    |
| 22        | 76,204      | 2970        | 8259        | 3316        | 24,885      | 9890        | 125,524                    |
| 24        | 76,660      | 2970        | 8488        | 3316        | 25,112      | 9890        | 126,436                    |

Table A8. Hot and cold utilities heat duties for HEN at different HRAT values using option 2.

| HRAT (°C) | Q_{H} (kW) | Q_{C1} (kW) | Q_{C2} (kW) | Q_{C3} (kW) | Q_{C4} (kW) | Q_{C5} (kW) | Total Utility Requirement (kW) |
|-----------|-------------|-------------|-------------|-------------|-------------|-------------|-----------------------------|
| 2         | 67,435      | 2970        | 8127        | 3316        | 26,048      | 90          | 107,986                    |
| 4         | 67,819      | 2970        | 8312        | 3316        | 26,048      | 289         | 108,754                    |
| 6         | 68,327      | 2970        | 8462        | 3316        | 26,048      | 647         | 109,770                    |
| 8         | 69,083      | 2970        | 8542        | 3316        | 26,048      | 1323        | 111,282                    |
| 10        | 69,875      | 2970        | 8612        | 3316        | 26,048      | 2045        | 112,866                    |
| 12        | 70,561      | 2970        | 8712        | 3316        | 26,048      | 2721        | 114,328                    |
| 14        | 71,246      | 2970        | 8812        | 3316        | 26,048      | 3216        | 115,608                    |
| 16        | 72,020      | 2970        | 8887        | 3316        | 26,048      | 3915        | 117,156                    |
| 18        | 72,844      | 2970        | 8948        | 3316        | 26,048      | 4678        | 118,804                    |
| 20        | 73,611      | 2970        | 9025        | 3316        | 26,048      | 5368        | 120,338                    |
| 22        | 74,342      | 2970        | 9112        | 3316        | 26,048      | 6012        | 121,800                    |
| 24        | 75,131      | 2970        | 9183        | 3316        | 26,048      | 6730        | 123,378                    |
Table A9. Hot and cold utilities heat duties for HEN at different HRAT values using option 3.

| HRAT (°C) | \( Q_H \) (kW) | \( Q_{C1} \) (kW) | \( Q_{C2} \) (kW) | \( Q_{C3} \) (kW) | \( Q_{C4} \) (kW) | \( Q_{C5} \) (kW) | Total Utility Requirement (kW) |
|-----------|----------------|-----------------|----------------|----------------|----------------|----------------|-----------------------------|
| 2         | 63,997         | 20              | 8970           | 2516           | 25,587         | 20             | 101,110                    |
| 4         | 64,654         | 120             | 9118           | 2676           | 25,736         | 120            | 102,424                    |
| 6         | 65,200         | 150             | 9372           | 2716           | 25,928         | 150            | 103,516                    |
| 8         | 65,970         | 235             | 9572           | 2916           | 26,033         | 330            | 105,056                    |
| 10        | 67,005         | 440             | 10140          | 2956           | 26,035         | 550            | 107,126                    |
| 12        | 68,040         | 870             | 10,233         | 2996           | 26,037         | 1020           | 109,196                    |
| 14        | 69,078         | 890             | 10,263         | 3026           | 26,038         | 1977           | 111,272                    |
| 16        | 70,115         | 980             | 10,312         | 3086           | 26,041         | 4550           | 117,489                    |
| 18        | 71,150         | 1091            | 10,380         | 3124           | 26,043         | 5410           | 119,560                    |
| 20        | 72,188         | 1129            | 10,403         | 3176           | 26,045         | 6330           | 121,630                    |
| 22        | 73,222         | 1248            | 10,430         | 3206           | 26,047         | 7457           | 123,757                    |
| 24        | 74,257         | 1307            | 10,434         | 3256           | 26,049         | 8630           | 125,880                    |

As per Nie and Zhu [28], Smith [31] and Osman et al. [24], the heat transfer coefficients for tube side and shell side can be obtained while considering the exchanger pressure drop. The dimensional constants in the pressure drop Equations (6) and (7) are calculated as follows:

\[
K_{PT1} = \frac{0.023 \rho^{0.8} \mu^{0.2} d_{ij}^{0.8}}{F_l d_o} \left( \frac{1}{K_{HT}} \right)^{3.5} \quad (A1)
\]

\[
F_l = \frac{\pi d_i^2}{4} \frac{N_T}{N_{TP}} \quad (A2)
\]

\[
K_{PT2} = 1.25 N_{TP} \rho \left( \frac{1}{K_{HT}} \right)^{2.5} \quad (A3)
\]

\[
N_T = \frac{\pi D_S^2}{4} \frac{P_C}{P_T} \quad (A4)
\]

\[
K_{HT} = c \left( \frac{k}{d_j} \right) P_T \left( \frac{d_i}{\mu} \right)^{0.8} \quad (A5)
\]

\[
Pr = \frac{C_p \mu}{k} \quad (A6)
\]

\[
K_{S1} = 2 \frac{K_{PS1} - K_{PS3}}{K_{S6}^{0.8}} \quad (A7)
\]

\[
K_{S2} = \frac{K_{PS2}}{K_{S6}^{0.42}} \quad (A8)
\]

\[
K_{S3} = \frac{K_{PS4}}{K_{S6}^{0.89}} \quad (A9)
\]

\[
K_{PS1} = \frac{1.298 F_{pb} (1 - B_C) D_S \rho^{0.83} \mu^{0.17}}{P_T d_o^{1.17}} \quad (A10)
\]

\[
K_{PS2} = \frac{0.5261 F_{pb} F_{PL} P_C (1 - 2 B_C) (P_T - d_o) \rho^{0.83} \mu^{0.17}}{F_{ed} d_o^{1.17}} \quad (A11)
\]

\[
K_{PS3} = \frac{2.596 F_{pb} F_{PL} (1 - 2 B_C) D_S \rho^{0.83} \mu^{0.17}}{P_T d_o^{1.17}} \quad (A12)
\]
\[ K_{PS4} = \frac{0.2026F_{PL}P_{C}P_{T}(P_{T} - d_{e})\rho}{F_{\rho d_{o}} \left( \frac{2}{D_{S} + 0.6B_{C}} \right)} \]  
\[ K_{hS} = \frac{0.24F_{hT}F_{hL}F_{hB}P_{T}0.64C_{P}^{0.333}k^{0.667}}{\mu^{0.307}d_{o}^{0.36}} \]  
\[ F_{o} = vA_{C} \]  
\[ A_{C} = \left( \frac{P_{T} - d_{e}}{P_{T}} \right)D_{S}L_{B} \]

Consequently, the obtained heat transfer coefficient for tube and shell sides of all the affected exchangers at optimum HRAT for the heat-shifting options are tabulated in Table A10 below:

**Table A10.** Heat transfer coefficients for exchangers’ tube and shell sides (kW/m²·°C) of the affected exchangers in HEN for option 1, 2 and 3 at optimum HRAT.

| Heat-Shifting Options | Optimum HRAT (°C) | E1 (hr) | E1 (hS) | E2 (hr) | E2 (hS) | E3 (hr) | E3 (hS) | E4 (hr) | E4 (hS) | E5 (hr) | E5 (hS) | E6 (hr) | E6 (hS) |
|-----------------------|-------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| 1                     | 10                | 0.342   | 0.456   | 0.35    | 0.433   | 0.325   | 0.451   | -       | -       | -       | -       | -       | -       |
| 2                     | 6                 | -       | -       | -       | -       | 0.331   | 0.463   | 0.346   | 0.432   | 0.324   | 0.531   | 0.333   | 0.511   |
| 3                     | 10                | 0.35    | 0.467   | 0.35    | 0.433   | 0.337   | 0.473   | 0.348   | 0.436   | 0.324   | 0.531   | 0.335   | 0.514   |

Appendix A.3. Heat Transfer Area Distribution

For each exchanger in HEN of the preheat train after heat-shifting, the actual heat transfer area at different HRAT values, is tabulated in Tables A11–A13 for options 1, 2, and 3. Also, the overall heat transfer area for the existing HEN is presented in the same tables for the selected options.

**Table A11.** Heat transfer area for HEN exchangers after heat-shifting, using option 1.

| HRAT (°C) | A_{E1} (m²) | A_{E1} (m²) | A_{E1} (m²) | A_{E1} (m²) | A_{E1} (m²) | A_{E1} (m²) |
|-----------|-------------|-------------|-------------|-------------|-------------|-------------|
| 2         | 4349        | 3155        | 3288        | 280         | 280         | 280         |
| 4         | 3619        | 3138        | 2782        | 280         | 280         | 280         |
| 6         | 3210        | 3116        | 2470        | 280         | 280         | 280         |
| 8         | 2913        | 3099        | 2246        | 280         | 280         | 280         |
| 10        | 2677        | 3078        | 2071        | 280         | 280         | 280         |
| 12        | 2499        | 3062        | 1929        | 280         | 280         | 280         |
| 14        | 2345        | 3045        | 1810        | 280         | 280         | 280         |
| 16        | 2210        | 3025        | 1706        | 280         | 280         | 280         |
| 18        | 2092        | 3009        | 1615        | 280         | 280         | 280         |
| 20        | 1984        | 2989        | 1533        | 280         | 280         | 280         |
| 22        | 1894        | 2974        | 1460        | 280         | 280         | 280         |
| 24        | 1809        | 2958        | 1394        | 280         | 280         | 280         |
### Table A12. Heat transfer area for HEN exchangers after heat-shifting, using option 2.

| HRAT (°C) | $A_{E1}$ (m^2) | $A_{E1}$ (m^2) | $A_{E1}$ (m^2) | $A_{E1}$ (m^2) | $A_{E1}$ (m^2) | $A_{new,HEN}$ (m^2) |
|-----------|----------------|----------------|----------------|----------------|----------------|------------------|
| 2         | 2474           | 3965           | 3203           | 365            | 2903           | 280              | 13,190           |
| 4         | 2416           | 3917           | 2669           | 363            | 2866           | 280              | 12,511           |
| 6         | 2399           | 3850           | 2360           | 360            | 2798           | 280              | 11,987           |
| 8         | 2236           | 3755           | 2145           | 354            | 2677           | 280              | 11,447           |
| 10        | 2155           | 3664           | 1981           | 348            | 2553           | 280              | 10,981           |
| 12        | 2072           | 3588           | 1848           | 343            | 2453           | 280              | 10,584           |
| 14        | 2006           | 3516           | 1736           | 339            | 2361           | 280              | 10,238           |
| 16        | 1936           | 3436           | 1641           | 334            | 2253           | 280              | 9880             |
| 18        | 1869           | 3355           | 1558           | 328            | 2140           | 280              | 9530             |
| 20        | 1810           | 3282           | 1485           | 324            | 2041           | 280              | 9222             |
| 22        | 1759           | 3217           | 1419           | 319            | 1954           | 280              | 8948             |
| 24        | 1709           | 3151           | 1360           | 315            | 1935           | 280              | 8750             |

### Table A13. Heat transfer area for HEN exchangers after heat-shifting, using option 3.

| HRAT (°C) | $A_{E1}$ (m^2) | $A_{E1}$ (m^2) | $A_{E1}$ (m^2) | $A_{E1}$ (m^2) | $A_{E1}$ (m^2) | $A_{E1}$ (m^2) | $A_{new,HEN}$ (m^2) |
|-----------|----------------|----------------|----------------|----------------|----------------|----------------|------------------|
| 2         | 4174           | 4406           | 3151           | 760            | 3134           | 862            | 16,487           |
| 4         | 3467           | 4330           | 2623           | 604            | 3101           | 813            | 14,938           |
| 6         | 3149           | 4272           | 2262           | 579            | 3094           | 799            | 14,155           |
| 8         | 2769           | 4170           | 1998           | 490            | 3049           | 764            | 13,240           |
| 10        | 2556           | 4022           | 1626           | 469            | 2986           | 691            | 12,350           |
| 12        | 2386           | 3884           | 1514           | 444            | 2854           | 577            | 11,659           |
| 14        | 2243           | 3755           | 1435           | 423            | 2684           | 572            | 11,112           |
| 16        | 2122           | 3635           | 1362           | 399            | 2535           | 553            | 10,606           |
| 18        | 2017           | 3528           | 1292           | 382            | 2397           | 531            | 10,147           |
| 20        | 1924           | 3421           | 1239           | 364            | 2256           | 524            | 9728             |
| 22        | 1841           | 3322           | 1188           | 351            | 2125           | 502            | 9329             |
| 24        | 1767           | 3227           | 1150           | 336            | 1996           | 492            | 8968             |

The parameters and symbols used in the Appendix equations and tables are defined as in the nomenclature Table below.

**References**

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