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Research Article

Heat Integration in Synthetic Fuel Production Plants

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Abstract

This study addresses the integration of thermal energy to enhance the quality of energy management in methanol production systems. In this study, the minimum number of heat exchangers (HXs) required for optimum heat transfer was obtained by the pinch analysis method, taking into account temperature ranges and compression temperatures. This approach minimizes energy consumption and maximizes energy recovery, as it allows the waste heat generated within the system to be used in others that need heat. Thus, in order to maintain the system, there is a significant decrease in the amount of heat input and heat loss to the outside. In addition, this study evaluated the carbon emissions from coal at the end of heat integration (HI) and the ability of the system to reduce CO2 emissions. The results show that the heat exchanger network (HEN) optimized by the pinch analysis method significantly reduces the utility consumption and increases the energy recovery in methanol production. Thermal integration leads to a significant increase in emissions reductions, making the process more environmentally friendly. In conclusion, this research highlights the importance of thermal energy integration in methanol production and industrial processes, offering energy efficiency improvements and environmental benefits. As a result of the study, the emission reduction, which was 4513 tons/day with the same number of heat exchangers, increased to 4890 tons/day at the end of heat integration.

Key Words

Heat integration, heat exchanger network, methanol production, thermal load distribution, emissions reduction.

Sentetik Yakıt Üretim Tesislerinde Isı Entegrasyonu

Öz

Bu çalışma, metanol üretim sistemlerinde enerji yönetiminin kalitesini artırmak için termal enerjinin entegrasyonunu ele almaktadır. Bu çalışmada, optimum ısı transferi için gerekli olan minimum ısı değiştirici (HX) sayısı, sıcaklık aralıkları ve sıkıştırma sıcaklıkları dikkate alınarak, pinç analizi yöntemi ile elde edilmiştir. Bu yaklaşım, sistem içinde üretilen atık ısının ısıya ihtiyaç duyan diğer sistemlerde kullanılmasına olanak tanıdığı için enerji tüketimini en aza indirir ve enerji geri kazanımını en üst düzeye çıkarır. Böylece sistemin devamlılığını sağlamak için dışarıya ısı girişi ve ısı kaybı miktarında ciddi bir azalma olur. Ayrıca bu çalışma, ısı entegrasyonu (HI) sonunda kömürden kaynaklanan karbon emisyonlarını ve sistemin CO_2 emisyonlarını azaltma yeteneğini değerlendirmektedir. Sonuçlar, pinç analiz yöntemiyle optimize edilen ısı değiştiricisi ağının (HEN), şebeke tüketimini önemli ölçüde azalttığını ve metanol üretiminde enerji geri kazanımını arttırdığını göstermektedir. Isıl entegrasyon, emisyon azaltımlarında önemli bir artışa yol açarak süreci daha çevre dostu hale getirmiştir. Sonuç olarak bu araştırma, enerji verimliliği iyileştirmeleri ve çevresel faydalar sunan metanol üretimi ve endüstriyel süreçlerde termal enerji entegrasyonunun önemini vurgulamaktadır. Çalışma sonucunda aynı sayıda ısı değiştirici ile 4513 ton/gün olan emisyon azaltımı, ısı entegrasyonu sonunda 4890 ton/gün'e çıkmıştır.

Anahtar Kelimeler

Isı entegrasyonu, ısı değiştiricileri ağı, metanol üretimi, ısıl yük dağılımı, emisyon azaltımı

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1. Introduction

CO_2 capture and storage (CCS) technologies, especially the use of Methyl-Diethanolamine (MDEA) and Piperazine (PZ) adsorbents, when combined with organic Rankine cycles (ORC), playing promising roles in reducing CO_2 emissions and energy consumption Malekli et al., (2023). The chemical reactions and physical distillation that take place in these processes are processes that occur endothermically or exothermically to produce synthetic fuel. Based on this, in order to reduce the total energy need and costs in methanol production, it is possible to meet the energy needs of endothermic processes from exothermic processes by taking into account the temperature levels of the flows Roetzel et al., (2020). Matching the addition and removal of heat utilities in a process is known as heat integration. Heat integration first used in crude preheat trains for oil refinery. Crude oil is first processed in refineries using thermal energy from various product streams before being heated to its final temperature above the atmosphere. Refineries process large quantities of oil; therefore, there is a lot of heat energy in the product streams. The integration of process flow and energy is often implemented even if it provides a low financial return Turton et al., (2008). The ideal way to install a heat exchanger network (HEN) is to install a WHRS or adapt an existing network to perform basic functions at the minimum overall yearly cost; This is determined mainly by operating costs and initial investment cost Masso & Rudd, (1969).

There are mechanical and thermal limitations due to the 1st and 2nd laws of Thermodynamics that must always be taken into account in the design of a system. Therefore, heat is only transferred from the high-temperature stream to the low-temperature stream and vice versa. In addition, the heat transfer amount cannot be greater than the product of the temperature change and heat capacities of one of the flows. In this context, when the temperatures of cold and hot streams are close in HXs, a large heat transfer area is needed (Besevli et al., 2024). Thus, when the driving forces for mass or heat exchange are in lower levels such as temperature difference, the required transfer equipment becomes large, presenting a challenge in design. When looking at systems with multiple HXs exchanging mass or heat (so-called "exchange networks"), it is observed that there is a pinch point, which is a point at which the temperature difference between flows is at a minimum value. Therefore, to ensure the success of designing HENs, the pinch point should be detected, and the characteristics of this point should be used to design the entire network. Boldyryev, S, (2018), the study identified the potential for utilizing waste heat from cement production and determined a site-wide recovery potential using process integration techniques. The author used an energy consumption analysis of a cement factory to determine the minimal energy requirements for production and then suggested ways to increase energy efficiency using a process integration technique. According to the authors, the cement factory's energy use may be cut by 30%. The outcomes contribute to the cement plant's profitability and lessen the industry's negative environmental effects while also promoting sustainability Boldyryev, (2018). Pavia, R. et al, (2023) In this study, a heat integration method for separating monochlorobenzene was suggested. Design and simulation were done for both the traditional process structure and the suggested integrated one. Optimization was conducted with the aim of reducing the expenses related to cooling and heating while simultaneously identifying the optimal operating conditions for heat integration. A simulation of a utility plant was conducted, encompassing both cooling water and steam generation components, in order to attain more precise approximations of CO2 emissions, water and energy usage, as well as operating expenses. The sustainable performances of the processes were assessed through the utilization of the eco-efficiency comparison index method and a range of environmental and economic indicators, namely CO2 emissions, water consumption, and utility costs. This was done to evaluate the benefits of heat integration and compare the processes in question. The study found that the suggested approach lowered nearly 57% of environmental effects and utility expenses. The composite evaluation index revealed that the proposed heat-integrated industrial plant improved the eco-efficiencies of initial processes by up to 83%, indicating a viable and sustainable strategy Paiva et al., (2023). Zhai et al., (2023), was based on heat integration and heat pump techniques, using three energy-efficient pressure-swing distillation processes to address the problem of high energy consumption in traditional pressure-swing distillation. The heat integration and heat pump, with a capital payback time of 3 years, may save 31.44% and 51.30% of the total yearly cost when compared to the planned traditional pressure-swing distillation, respectively Zhai et al., (2023). Liang et al (2023), in this research, an equation-based optimization framework is presented for the simultaneous heat integration and flowsheet optimization of the combined cooling, heating, and power system based on the methanol-steam-reforming proton exchange membrane fuel cell. Researchers applied the framework to a 1000 kW combined cooling, heating, and power generation system, and the integrated design produced a levelized cost of electricity of 0.2374 $/kWh and an energy efficiency of 88.50%. The results indicate that, in comparison to a conventional design, simultaneous heat integration and flowsheet optimization can improve the system's energy efficiency by 5.45 percentage points, exergy efficiency by 2.22 percentage points, and the levelized cost of electricity by 4.50% Liang et al., (2023).

When the literature is examined, synthetic fuel production processes generally focus on issues such as production efficiency, energy consumption of systems and production costs, but issues such as thermal processes in these processes, heat exchanger networks and optimization of thermal load distribution have not been examined much. Since more than one heat exchanger interacts with each other directly or indirectly in long processes such as synthetic moxibustion production, the thermal load of the process should be calculated clearly and whether the system has a thermal requirement from an external source should be examined. In this study, the heat exchanger network of a methanol production facility was considered, and the thermal loads required to maintain the system were calculated. Afterwards, the heat exchanger network was optimized using pinch analysis, and external heat input was eliminated by preventing heat rejections from the process.

2. Material and Methods

Methanol production is important for several reasons. Firstly, methanol is a versatile chemical compound that can be used as a building block for obtaining more complex chemical structures and as a clean-burning fuel with a high-octane number Dalena et al., (2018). Secondly, the biological conversion of methanol through natural and synthetic methylotrophs expands the chemical repertoire and contributes to a one-carbon (C1)-based chemical economy Chen & Lan, (2020). Thirdly, methanol production based on renewable energy provides a sustainable option for fuel production and is extensively used in the chemical industry Vesterinen, (2018). Additionally, methanol can be produced from carbon dioxide, which is abundant due to anthropogenic activities, offering a potential solution for reducing greenhouse gas emissions Sivadinarayana et al., (2020). Overall, methanol production plays a crucial role in various industries and offers potential solutions for reducing environmental impact and meeting energy demands. Thermal energy plays a crucial role in methanol production systems. Concentrated solar thermal technology can be used to produce methanol by utilizing solar heat to generate hydrogen and carbon monoxide, which are the main constituents of synthesis gas Monnerie et al., (2020). Additionally, the use of solar energy in a thermochemical reactor can reenergize carbon dioxide into carbon monoxide, which can then be used in the methanol synthesis process (Mancusi et al., 2021). The integration of different systems, such as catalytic partial oxidation reactors and fluidized bed systems, can optimize the production process and improve energy efficiency Kim et al., (2011); MACHIDA et al., (1998).

The fresh wet hydrogen supply from chlorine generation by salt electrolysis is compressed to 45 bar in (I). The mixture from the methanol plant (VI) and the carbon dioxide from the carbon capture plant are mixed in the mixing chamber and the resultant gas mixture (VII) is heated in the FEHE by the reactor outlet stream (XI) before being fed to a reactor that is isothermally operated at 50 bar. The reactor outlet stream (XII) is cooled down in the FEHE unit and another cooler (XIII) before being flashed in a separator to separate the recycled non-condensable gas components such as CO, CO2, and H2, from the methanol and liquid water liquid. A second compressor receives the recycle stream after it has been purged and combined with the fresh CO2 feed stream. The compressed wet hydrogen stream (I) is fed in counter-current mode to a Stripping Column (SC), where the liquid stream of the flash is transmitted. In addition to drying the hydrogen feed and removing the light ends like CO2 and CO, which are totally recycled, this also eliminates water from the reactor feed. The distillation column (DC), which separates water as the bottom product from methanol as the top distillate, receives the liquid bottom stream from the stripper (XIV-XV). It is important to keep in mind that employing the stripper unit results in a higher-temperature liquid outflow that contains a methanol-water mixture. As a result, the reboiler duty is lowered. A partial condenser that can yield a vapor distillate (lights), a high purity liquid methanol distillate (XVI), and water (XVII) as a bottom product is used to separate the methanol-water stream in a single distillation column. Overall layout of the process was provided in Fig 1.Kiss et al., (2016); Ozcan & Kayabasi, (2021).

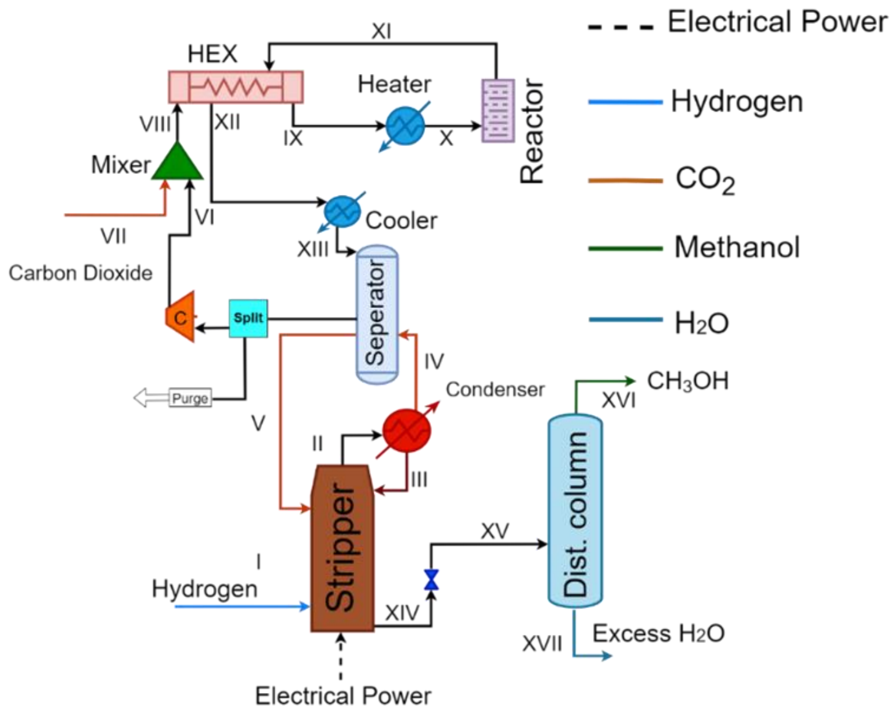

Figure 1. *Flow chart of Methanol production unit with heat integration.*

Oil refineries consist of systems where significant amounts of oil are processed, and product streams carry high amounts of thermal energy. Therefore, process flow and energy balance are widely used to reduce energy costs between thermal processes. Turton et al., (2008). The total number of utilities required to perform energy transfers in these processes can be reduced or, more precisely, increased by the heat integration method for matching the addition and removal of heat.

In this study, a general algorithm was used to determine the minimum thermal resource (utility) required for the given minimum temperature difference. In a HEN, the optimization process is, respectively, determining the lowest approach temperature, temperature diagram showing the temperature ranges, cascade diagram where the pinch temperature is determined, minimum utility requirement and finally calculating the lowest number of heat exchangers. Considering the logarithmic mean temperature difference $(\Delta T_m)_{ln}$ and the overall heat transfer coefficient (U), the heat transfer (Q) equation can be written as:

$$Q = UA(\Delta T_m)_{ln} \tag{1}$$

The ΔT_m is defined as logarithmic mean temperature difference that is indicating any logarithmic mean temperature value between the flows as below:

$$\Delta T_m = \frac{\Delta T_1 - \Delta T_2}{ln\frac{\Delta T_1}{\Delta T_2}} \tag{2}$$

The following relation can be constructed to determine the least number of HXs is employed:

$$N_{min} = N_h + N_c + N_u - 1 \tag{3}$$

Here, N_h, N_c, N_u are number of hot flows, number of cold flows and number of utilities respectively Turton et al., (2018).

The principles for coupling hot flows and cold flows for blocks above the pinch point based on a diagram of temperature ranges that includes all blocks above the pinch point, starting with the lower block and working upward, transferring heat horizontally from the hot side to the cold side. Heat transfer can occur diagonally downwards, but never diagonally upwards. First the hot flow is matched with the product of the smallest heat capacity and temperature difference ($\dot{m}C_p\Delta T$), for flows touching the pinch point $\dot{m}C_{p,hot}\Delta T \leq \dot{m}C_{p,cold}\Delta T$. If this condition is not met, the condition must be met by reducing the heat capacities by dividing the hot flow into two or three. For blocks below the pinch point, a temperature range diagram is drawn up that includes all blocks below the pinch point, and the flows are matched to each other, starting with the upper block and downward, transferring heat horizontally or diagonally downward from the hot side to the cold side. However, it is never matched diagonally upwards. First, the hot flow is matched to the smallest $\dot{m}C_p\Delta T$. For flows touching the pinch point, $\dot{m}C_{p,hot}\Delta T$ must $\leq \dot{m}C_{p,cold}\Delta T$. If this condition is not met, the cold flow heat capacities must be divided into two or three to ensure the condition.

The emissions are estimated using the quantity of fuel utilized in the combustion processes and the average emission factor depending on the process type listed in the related tables in the reports of IPCC. Equation 4 illustrates how the IPCC Tier 1 technique was used to get the C emissions factor from coal IPCC, (1996).

$$C_C = 32.15 - (0.234 \times H_V) \tag{4}$$

Here, H_V is the gross calorific value of coal, which varies from 31 to 37 TJ/kiloton on a dry, mineral-free basis, and C_C is the carbon emission factor in t C/TJ. The system uses a lot of carbon dioxide, which results in a large reduction in GHG emissions. However, there are a lot of indirect greenhouse gas emissions since the system depends so largely on thermal energy. The CO2 reduction capacity of the system may then be computed using Eq. 5.

$$ER_{net} = ER_{utilization} - ER_{generation} \quad (5)$$

Here, $ER_{generation}$ is the quantity of carbon dioxide created during the process, $ER_{utilization}$ is the amount of carbon dioxide utilized in system processes, Total carbon dioxide emissions are represented by ER_{net}.

3. Results and Discussions

We examined the heat Exchange network based on the pinch theory and the thorough instructions supplied by Turton Turton et al., (2018) in order to optimize the energy recovery and decrease the utility consumption of the methanol production system. The minimum heat transfer temperature differential, also known as the minimum driving force for heat exchange, was adjusted to 10°C after taking into account the actual operating circumstances, financial advantages, and heat exchange area of the methanol production system. Following the integration of the process heat, the system's optimized HEN was created. In Fig. 2 and Fig. 3, it is seen that the pinch temperature is 320 °C.

Table 1. Thermal data for streams.

Stream No.	Flow Type	ṁ (kg/s)	Cp (kJ/kg °C)	ṁ×Cp (kW/°C)	T_{in} (°C)	T_{out} (°C)	$\dot{Q}$ (kW)
1	Hot	354	2.44	863	523	304	189163
2	Hot	11	8	88	320	303	1496
3	Cold	354	2.65	938	301.2	498	-184757
Total							5902

Every stream was represented as a vertical line in a graphic of temperature intervals, with the streams that required cooling on the left and the streams that required heating on the right. The temperature interval plot is displayed in Fig. 2.

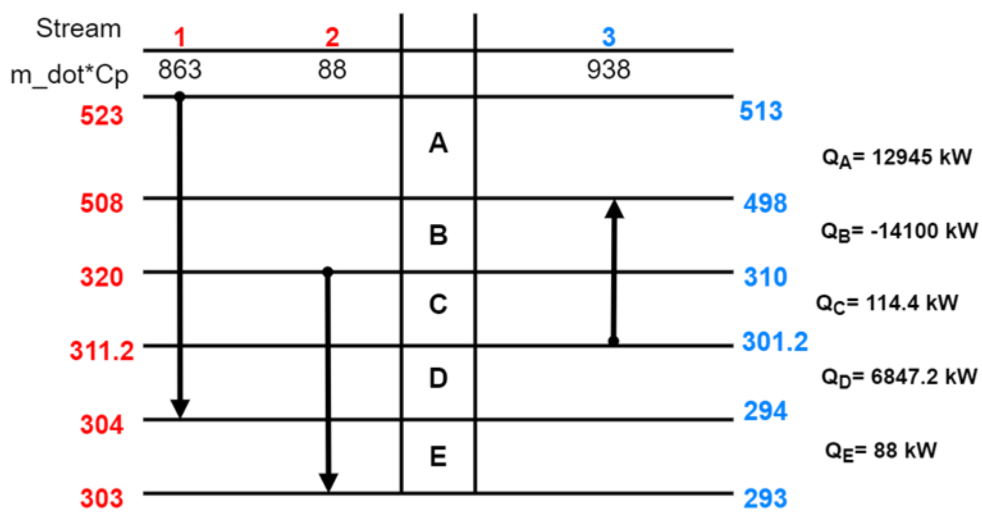

Figure 2. Diagram of temperature intervals.

5894.6 kW is the total enthalpy excess for all streams, as indicated in the right column. The net energy from hot streams to cold streams in each temperature interval is 7049.6 kW, as Fig. 3 illustrates. Point B is where the pinch point appears. Heat is transferred via temperature gradients; if energy is abundant, the hot utility will ultimately need to transfer its excess heat to the cold utility.

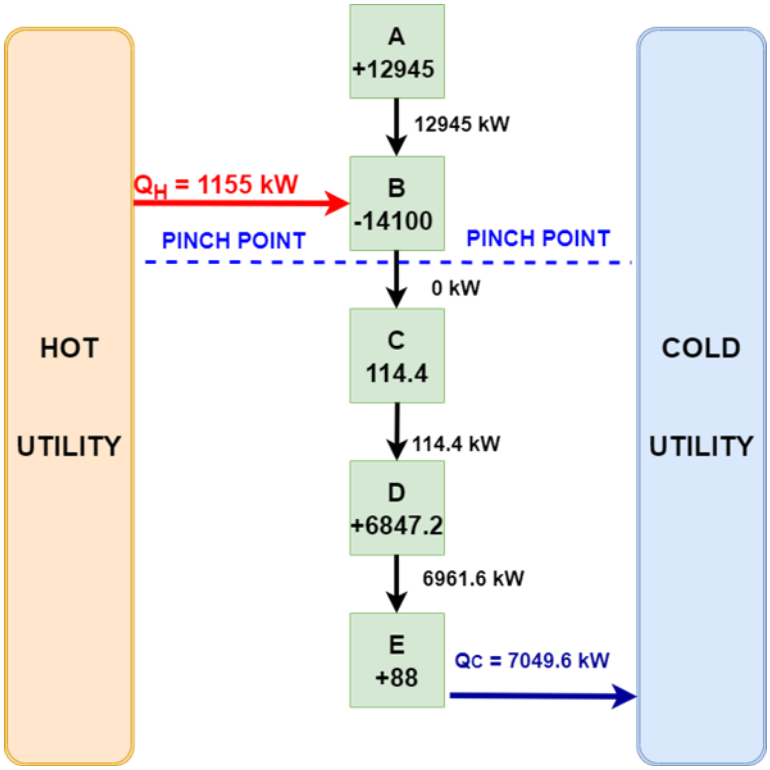

Figure 3. Cascade diagram of HXs.

As seen in Fig. 4, the system's optimal HEN and the least number of HXs required to transmit heat to the minimum facility design were established after the heat integration procedure.

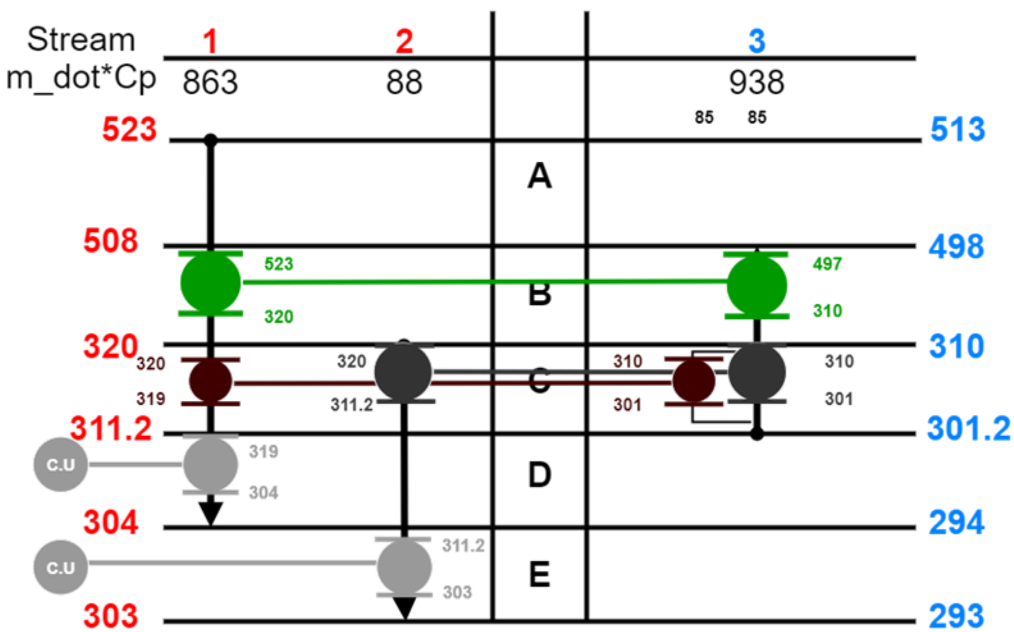

Figure 4. Design of HEN.

For each process HX in networks 1, 2, and 3, the $(\Delta T_m)_{ln}$, surface area, heat transfer, and overall heat transfer coefficient were calculated using Eq. 2. A thorough flow diagram of the HEN is displayed in Fig. 5, and a summary of these results is given in Table 2:

Table 2. Summary of findings for exchangers.

Heat Exchanger	$(\Delta T_m)_{ln}$ (K)	U (kW/m^{2}K)	Q (kW)	A (m^2)
1	16.74	0.5	175189	20924
2	13.61	0.5	863	126.8
3	10.1	0.5	774.4	153.4
Total				21204.2

The final HEN is shown in Fig. 5. This network has the minimum number of HXs, for the minimum utility requirements, using a minimum approach temperature, for ΔT = 10°C.

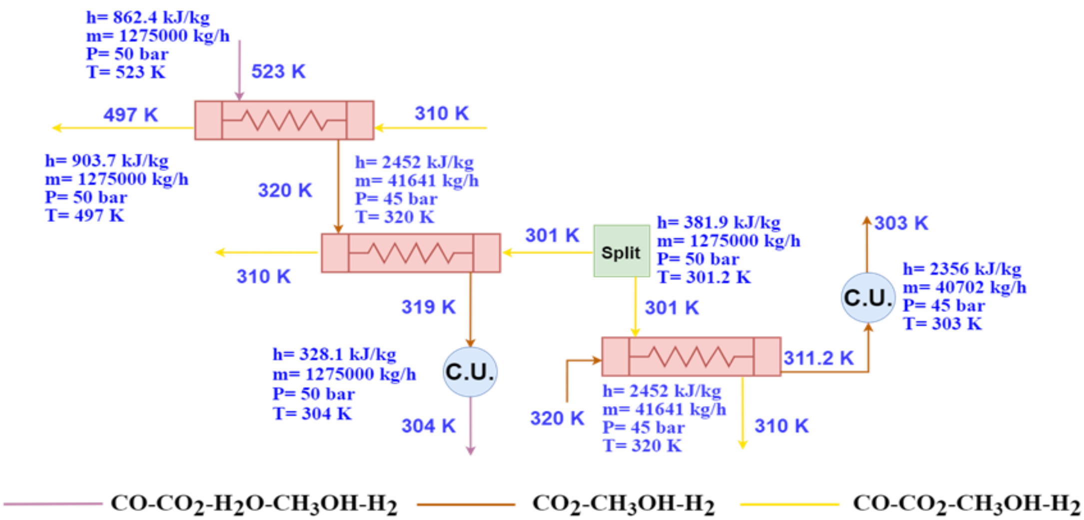

Figure 5. Detailed flow diagram of HEN after heat integration.

Emission reduction before and after heat integration is given in Fig. 6. After the heat integration, it has been revealed that all of the fuel spent to meet the heat need in the facility can be derived from the heat produced in the facility. Accordingly, after heat integration, an increase of 377 tons/day is observed in emission reduction.

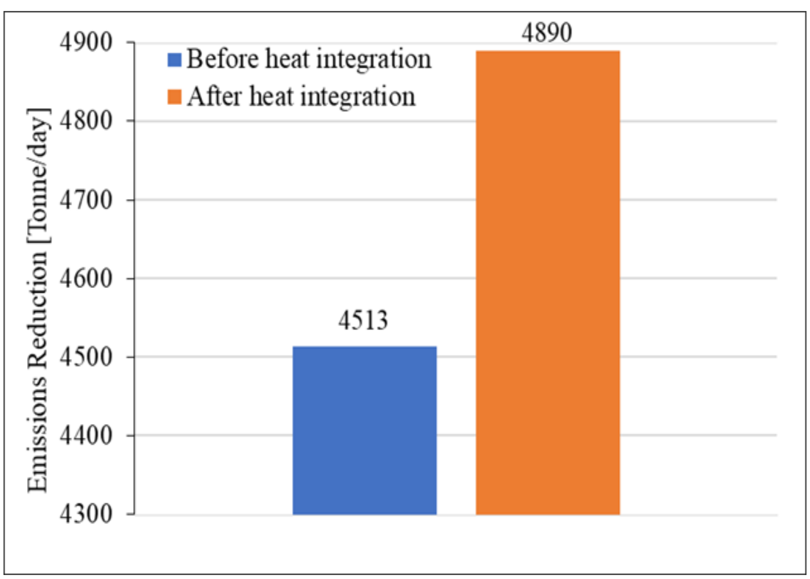

Figure 6. Emissions reduction before and after heat integration.

4. Conclusion

As a result of this study, the application of pinch theory and heat exchange network optimization to the methanol production system has yielded substantial benefits. By carefully matching heat additions and removals within the process, we have achieved a remarkable reduction in utility consumption and emissions. The optimized HEN, designed with a minimum approach temperature of 10°C, effectively utilizes available thermal energy within the system, reducing the reliance on external utilities. This integration not only enhances energy recovery but also contributes to a more sustainable and environmentally friendly methanol production process. The findings highlight the importance of considering heat integration strategies in industrial processes to improve energy efficiency and reduce environmental impact.

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References

Besevli, B., Kayabasi, E., Akroot, A., Talal, W., Alfaris, A., Assaf, Y. H., Nawaf, M. Y., Bdaiwi, M., & Khudhur, J. (2024). *applied sciences Technoeconomic Analysis of Oxygen-Supported Combined Systems for Recovering Waste Heat in an Iron-Steel Facility*.

Boldyryev, S. (2018). *Heat Integration in a Cement Production* (H. E.-D. M. Saleh & R. O. A. Rahman (eds.); p. Ch. 7). IntechOpen. https://doi.org/10.5772/intechopen.75820

Chen, A. Y., & Lan, E. I. (2020). Chemical Production from Methanol Using Natural and Synthetic Methylotrophs. *Biotechnology Journal*, *15*(6). https://doi.org/10.1002/biot.201900356

Dalena, F., Senatore, A., Marino, A., Gordano, A., Basile, M., & Basile, A. (2018). Methanol Production and Applications: An Overview. In *Methanol* (pp. 3–28). Elsevier. https://doi.org/10.1016/B978-0-444-63903-5.00001-7

IPCC. (1996). Vol. 3: Chapter 1 Energy. In *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual* (Issue 1996, pp. 1–40).

Kim, J., Henao, C. A., Johnson, T. A., Dedrick, D. E., Miller, J. E., Stechel, E. B., & Maravelias, C. T. (2011). Methanol production from CO2 using solar-thermal energy: process development and techno-economic analysis. *Energy & Environmental Science*, *4*(9), 3122. https://doi.org/10.1039/c1ee01311d

Kiss, A. A., Pragt, J. J., Vos, H. J., Bargeman, G., & de Groot, M. T. (2016). Novel efficient process for methanol synthesis by CO 2 hydrogenation. *Chemical Engineering Journal*, *284*, 260–269. https://doi.org/10.1016/j.cej.2015.08.101

Liang, Z., Liang, Y., Luo, X., Wang, H., Wu, W., Chen, J., & Chen, Y. (2023). Integration and optimization of methanol-reforming proton exchange membrane fuel cell system for distributed generation with combined cooling, heating and power. *Journal of Cleaner Production*, *411*, 137342. https://doi.org/https://doi.org/10.1016/j.jclepro.2023.137342

MACHIDA, S., AKIYAMA, T., & YAGI, J.-I. (1998). Exergy Analysis of Methanol Production System. *KAGAKU KOGAKU RONBUNSHU*, *24*(3), 462–470. https://doi.org/10.1252/kakoronbunshu.24.462

Malekli, M., Aslani, A., Zolfaghari, Z., & Zahedi, R. (2023). CO2 capture and sequestration from a mixture of direct air and industrial exhaust gases using MDEA/PZ: Optimal design by process integration with organic rankine cycle. *Energy Reports*, *9*, 4701–4712. https://doi.org/10.1016/j.egyr.2023.03.115

Mancusi, E., Bareschino, P., Brachi, P., Coppola, A., Ruoppolo, G., Urciuolo, M., & Pepe, F. (2021). Feasibility of an integrated biomass-based CLC combustion and a renewable-energy-based methanol production systems. *Renewable Energy*, *179*, 29–36. https://doi.org/10.1016/j.renene.2021.06.114

Masso, A. H., & Rudd, D. F. (1969). The synthesis of system designs. II. Heuristic structuring. *AIChE Journal*, *15*(1), 10–17. https://doi.org/10.1002/aic.690150108

Monnerie, N., Gan, P. G., Roeb, M., & Sattler, C. (2020). Methanol production using hydrogen from concentrated solar energy.

International Journal of Hydrogen Energy, *45*(49), 26117–26125. https://doi.org/10.1016/j.ijhydene.2019.12.200

Ozcan, H., & Kayabasi, E. (2021). Thermodynamic and economic analysis of a synthetic fuel production plant via CO2 hydrogenation using waste heat from an iron-steel facility. *Energy Conversion and Management*, *236*(February), 114074. https://doi.org/10.1016/j.enconman.2021.114074

Paiva, A. P. R., Santos, R. O., Maia, M. P., & Prata, D. M. (2023). Improvement of the monochlorobenzene separation process through heat integration: A sustainability-based assessment. *Chemical Industry and Chemical Engineering Quarterly*, *29*(1), 31–42.

Roetzel, W., Luo, X., & Chen, D. (2020). *Chapter 6 - Optimal design of heat exchanger networks* (W. Roetzel, X. Luo, & D. B. T.-D. and O. of H. E. and their N. Chen (eds.); pp. 231–317). Academic Press. https://doi.org/https://doi.org/10.1016/B978-0-12-817894-2.00006-6

Sivadinarayana, C., Miasser, A.-G., Atul, P., Ravichander, N., Saud, A.-H., & Arwa, R. (2020). *Methanol production process*.

Turton, R., Bailie, R. C., Whiting, W. B., & Shaeiwitz, J. A. (2008). *Analysis, synthesis and design of chemical processes* (R. Turton (ed.); 5th Editio). Pearson Education.

Turton, R., Shaeiwitz, K. A., & Bhattacharyya, D. (2018). *Analysis, Synthesis, and Design of Chemical Processes* (W. B. Whiting (ed.); 5th Editio). Pearson Education.

Vesterinen, E. (2018). *Methanol Production via CO2 Hydrogenation* [Aalto University School of Engineering]. https://aaltodoc.aalto.fi/bitstream/handle/123456789/35555/master_Vesterinen_Eero_2018.pdf?sequence=1&isAllowed=y

Zhai, J., Chen, X., Sun, X., & Xie, H. (2023). Economically and thermodynamically efficient pressure-swing distillation with heat integration and heat pump techniques. *Applied Thermal Engineering*, *218*, 119389. https://doi.org/https://doi.org/10.1016/j.applthermaleng.2022.119389