International Journal of Natural Sciences Research
2021 Vol. 9, No. 1, pp. 1-11
ISSN(e): 2311-4746
ISSN(p): 2311-7435
DOI: 10.18488/journal.63.2021.91.1.11

OPTIMIZATION OF THE TOTAL ANNUAL COST IN HEAT EXCHANGER NETWORKS WITH MULTIPLE UTILITIES

E.C. Udochukwu[1+]
B.U Ogbonnaya[2]
O.S. Azeez[3]

[1]*Department of Chemical Engineering, Federal University Otuoke, Bayelsa State, Nigeria.*
[1]*Email: udochukwuec@fuotuoke.edu.ng Tel: +2348036295880*
[2,3]*Department of Chemical Engineering, Federal University of Technology, Minna, Niger State, Nigeria.*
[2]*Email: blessing0ogbonnaya@gmail.com Tel: +2348098132961*
[3]*Email: tosin.azeez@futminna.edu.ng Tel: +2348068360923*


(+ Corresponding author)

Article History
Received: 5 April 2021
Revised: 10 May 2021
Accepted: 1 June 2021
Published: 24 June 2021

Keywords
Pinch analysis
Heat exchanger networks
Multiple utilities
Super targeting
Total annual cost
Supertargeting
Energy.

ABSTRACT

This research work was focused on optimizing heat exchanger network problems from literature involving multiple utilities with the objective function of minimizing the Total Annual Costs of the designed networks. This was achieved through the use of pinch methodology on Aspen Pinch software, Version 11.1. Supertargeting was used to obtain the minimum temperature difference for two case studies and the networks were designed on Grid Diagrams. The design of the networks was focused on the energy-capital costs tradeoffs, preventing the use of extra heat exchanger units to reduce energy costs at the expense of capital costs. This paid off as the networks designed in this research obtained the lowest total annual costs (TACs) when compared with the results obtained by other researchers on the case studies under review.

Contribution/Originality: This study contributes to the existing literature on problems involving multiple utilities and is able to achieve lower total annual costs through the optimization of the utilities usage using the combined traditional pinch technique and mathematical provisions as available in ASPEN pinch.

1. INTRODUCTION

Optimization of energy consumption in industrial chemical processes is extremely important due to the volatile nature of energy costs. This would reduce production costs, improve product quality, it will also bring about a process that meets safety requirements and complies with environmental regulations as well. However, the main goal of Process Optimization is economics using the lowest amount of resources/input to bring about the best possible product/outcome. This can be seen in the minimization of Total Annual Cost (TAC) in processes by the design of Heat Exchanger Networks (HENs) that maximizes inter-process energy recovery while minimizing the use of external utilities [1].

Process Integration is well developed in literature and involves various methods of HEN synthesis based on heuristics, mathematical programming, and genetic algorithms. These methods can be grouped into; simultaneous methods, sequential methods and hybrid methods. The former involves the solving of the process integration problem using mathematical programming, algorithms or superstructures in a single step. Some examples include Cheapest Utility Principle by Shenoy, et al. [2] Stage wise Superstructure by Yee and Grossmann [3] Supply Based Superstructure by Azeez, et al. [4] Supply and Target based Superstructure by Azeez, et al. [5] Interval based multiple integer non-linear programming (MINLP) superstructure by Isafiade and Fraser [6] among many others [7].

In sequential methods, the problem is broken down into steps which are solved separately using heuristics to determine the optimum network. An example is Pinch Analysis which can be used to solve HEN problems by following the laws of thermodynamics using simple temperature - enthalpy (composite) graphs or problem table algorithm to analyze the stream data to discover a pinch point, a minimum approach temperature between streams in a heat exchanger (ΔT_{min}), energy, cost and other targets are also calculated for the process. The actual heat exchanger network is then designed on a grid diagram following the rules of pinch design method. Hybrid methods combine both previously stated methods with the use of heuristics from sequential methods to determine the ΔT_{min} value and other targets as well as mathematical programming from simultaneous methods to design the HEN or optimize the network designed from sequential methods [7].

In Pinch Analysis, Composite curves are temperature – enthalpy graphs used to visualize the energy needs of a system by plotting the process streams as seen in Figure 1, for the purpose of determining the inter process heat transfer potential of a particular process. The hot composite curve representing the hot streams is plotted above the cold streams in a cold composite curve and the pinch point exists at the closest approach point between both curves and the vertical distance at this point is the minimum temperature difference (ΔT_{min}) of the network. The horizontal difference at the top of the graph shows the hot utility needs of the system while the difference at the base shows the cold utility needs [8].

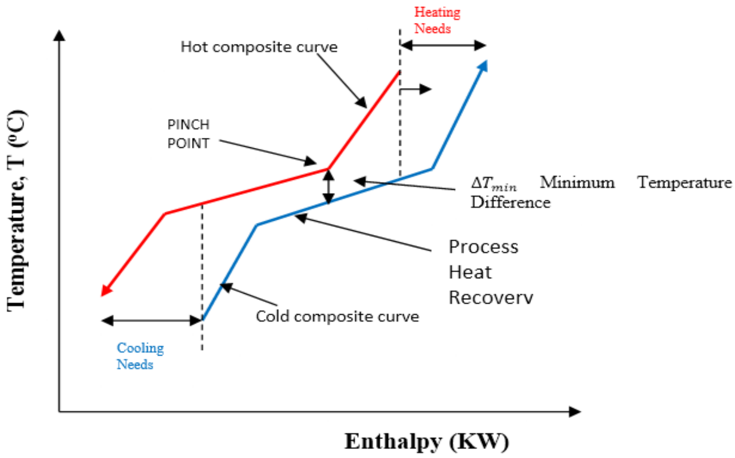

Figure-1. The Composite Curves.

While the composite curves show the amount of energy needed after the process – process heat transfer for remaining heating or cooling needs of the system, their capabilities end there. In situations where either cost of utilities, their availability or stream target temperatures demand for the use of more than one heating or cooling utilities (multiple utilities), they are unable to give further information.

Linnhoff, et al. [9] developed the grand composite curve (GCC) to represent the utilities based on both the enthalpy and temperature levels. It is created by adjusting interval temperatures by $\frac{1}{2}\Delta T_{min}$ and plotting that against cumulative enthalpy as shown in Figure 2. It gives the information on utility needs as well as temperature levels at which they are required. The tool is also useful for effective integration through profile matching and solving of multiple utilities problems in Pinch Analysis. Other sequential and simultaneous methods have been developed by researchers over the years to solve multiple utility problems [8].

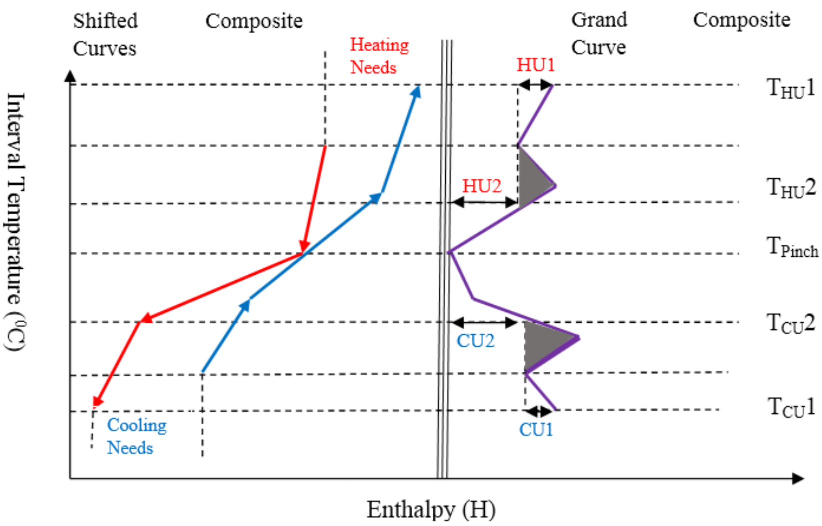

Figure-2. The shifted and grand composite curves.

Fraser [10] presented a technique where the fraction of a utility relative to the limit feasible be used while optimizing on the basis of minimum flux or the ΔT_{min} value. The problem could not reconcile the relationship between the minimum exchanger area and the capital cost. The method also suggested that the linearized cost function do not perfectly represent the associated capital cost and area. The Cheapest Utility Principle (CUP) is a pinch based utility optimization method introduced by Shenoy, et al. [2] to determine optimum utility loads for multiple utility systems based on both utility and capital costs [2, 6].

José, et al. [11] adapted Yee and Grossmann [3] Stage wise superstructure to optimize multiple utility problems. In José, et al. [11] method, process streams can be matched with utility streams at any stage of the superstructure in contrary to Yee and Grossmann's method that was adapted where this is only possible at the ends of the superstructure. Supply Based Superstructure [4] and Supply and Target based Superstructure [5] have also been used for the optimization of total investment costs when using multiple utilities in simultaneous approaches.

Aside from the choice of the right utilities in Multiple Utility HEN problems it is also necessary to optimize the network's TAC by accurately targeting energy and capital costs, minimum number of units, area targets etc. This can only be achieved using the optimum ΔT_{min} value, which can be obtained through Supertargeting by trading off of energy and capital costs at different values of ΔT_{min}. A small ΔT_{min} value leads to a low external utility target and an equally low energy cost but area target will be high as will the capital cost. A high value of ΔT_{min}, will result in high utility targets and costs as well as low heat exchanger areas and capital costs. The optimal value of ΔT_{min} for a given network or process will balance both energy and capital costs in a way that ensures a minimum Total cost for the network. Hence, Supertargeting is necessary to design a globally optimal network with minimum TAC [12].

In this research, energy optimization tool (Aspen Pinch Version11.1) was used to analyze two literature problems. This optimization tool utilizes the composite curve, the GCC and the balanced GCC as well as supertargeting that are available in pinch analysis for the optimization task as discussed in the introduction above. The stream and cost data for each case study were used to set targets and the networks were designed on the software's grid diagram. The technique has been used to investigate the choice and optimization of utility usage in this research and the obtained results were compared with those from other methods and researchers.

2. CASE STUDY 1

This 3-stream problem was first solved by Shenoy, et al. [2] it involved 3 levels of steam as hot utilities and 1 cold utility in form of cooling water as shown in Table 1.

In this research, this problem was solved using pinch analysis on Aspen Pinch 11.1, the composite curves were constructed and supertargeting was carried out using stream data to obtain an optimum ΔT_{min} value of 15ºC. With this value and the data in Table 1, targets were set for the network and HEN was designed on a grid diagram following pinch design rules. The designed network (Figure 3), utilized 5 heat exchangers; 3 inter process, 1 cooler and a single heater using only the high-pressure steam to heat up the cold stream. Unlike other researchers that have solved this same problem, this research's focus was on minimizing TAC of the entire network, not just minimizing the use of expensive utilities and maximizing use of cheaper utilities. From the streams temperatures in the process data Table 1 and the grid diagram Figure 1 the target temperature of the cold stream is 185ºC; which is above the supply temperature of the other two hot utilities (Medium (MP) and Low Pressure (LP) Steams. While a match between the cold stream and any of these utilities will lead to a lower operating (energy) cost, there would still be extra cooling needs left behind that would require a match with the High-Pressure Steam (HP) to satisfy. The cost of installing this extra exchanger(s) will raise the capital cost of the network and in turn the network's TAC.

Table-1. Stream and Cost Data for Case Study 1

Stream	T_{supply} (ºC)	T_{target} (ºC)	MCp (kW/ºC)	h (kW/m²ºC)	Cost (£/kW.yr)
H1	105.00	25.00	10.00	0.50	-
H2	185.00	35.00	5.00	0.50	-
C1	25.00	185.00	7.50	0.50	-
HP Steam	210.00	209.00	-	5.00	160.00
MP Steam	160.00	159.00	-	5.00	110.00
LP Steam	130.00	129.00	-	5.00	50.00
CW	5.00	6.00	-	2.60	10.00

Note: Heat Exchanger Capital Cost (£) = 800 × area (m²); Annualization factor = 0.298 (/yr).

The 5-unit network designed in this research gave the lowest TAC of $81,410.70/year when compared with other solutions proposed by various researchers as seen in Table 2, while Figure 2 shows a graphical comparison of the TACs achieved by various networks. Further results for this study are shown in Appendix A.

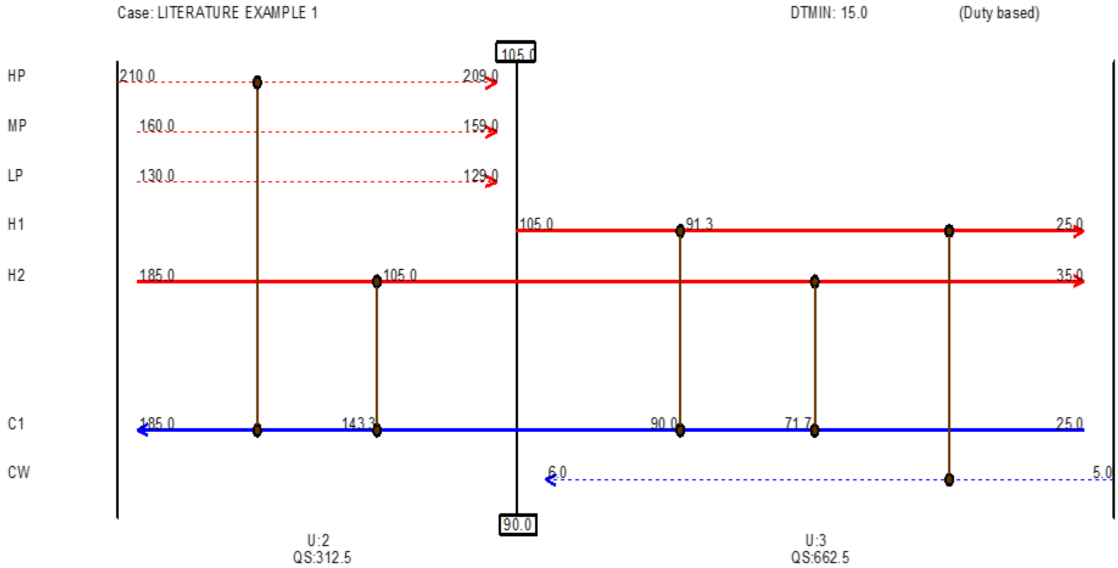

Figure-3. Heat Exchanger Network for Case Study 1.

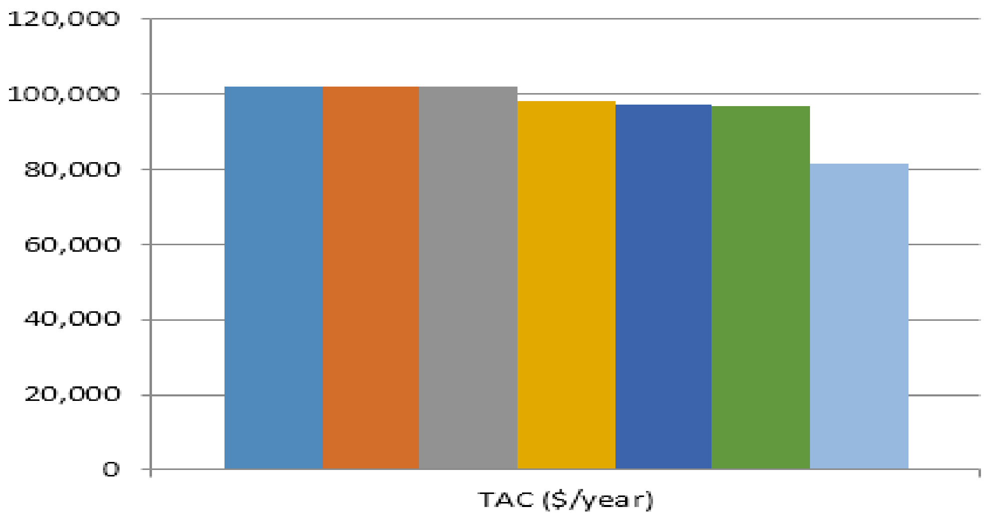

Figure-4. Graphical Comparisons for TAC (Case Study 1).

- T&SBS [5].
- S&TBS [5].
- SBS [4].
- CUP [2].
- IBMS [6].

Table-2. Summary and Comparison of Results for Case Study 1.

Method	Number of Units	TAC ($/year)	Percentage Difference (%)
T&SBS [5]	7	101,893.0	25.16
S&TBS [5]	6	101,889.0	25.15
SBS [4]	7	101,889.0	25.15
CUP [2]	9	98,263.0	20.70
IBMS [6]	9	97,211.0	19.41
SWS [11]	7	97,079.0	19.25
This Study	5	81,410.7	0.00

3. CASE STUDY 2

This problem involved 4 process streams, 3 hot utilities (steam at 3 pressure levels and 2 cold utilities; cooling water (CW) and air cooling (AC). The stream and cost data extracted from Shenoy, et al. [2] for the problem are presented in Table 3.

Table-3. Stream and Cost Data for Case Study 2.

Streams	T_{supply} (°C)	T_{target} (°C)	MCp (kW/°C)	h (kW/m²°C)	Cost (£/kW.yr)
H1	155.00	85.0	150	0.5	
H2	230.00	40.0	85	0.5	
C1	115.00	210.0	140	0.5	
C2	50.00	180.0	55	0.5	
C3	60.00	175.0	60	0.5	
HP Steam	255.00	254.0		0.5	70
MP Steam	205.00	204.0		0.5	50
LP Steam	150.00	149.0		0.5	20
CW	30.00	40.0		0.5	10
AC	40.00	65.0		0.5	5

Note: Heat Exchanger Capital Cost (£) = 13000 + 1000 (area) (m²); Annualization factor = 0.322 (/yr).

For this problem, the supertargeting produced an optimum $\Delta T_{min}\Delta T_{min}$ value of 20.0°C, which was used to set targets along with the process data in Table 3 and design a network for the problem. The HEN designed for this case study in Figure 5 involved 9 heat exchangers; 4 inter process, 1 heater and 4 coolers. Similar to Case Study 1, the target temperature of C1, 210.0°C was higher than the supply temperatures of MP and LP steams so a single heater matched with HP steam was used to cool it as this was more economically beneficial than using more than one heat exchanger to match with the cheaper utilities first and finally, the more expensive one. The two hot streams above pinch were split as their heat capacities of 150 and 85 kW/°C were much higher than those of the cold streams 55 and 60 kW/ °C. Air cooling (AC) was not used on stream H2 as its target temperature, 40°C was the same as the supply temp limit of AC. Hence, AC would have been unable to satisfy its heat load, a match between AC and H2 would have left some of H2's cooling needs to be satisfied by Cooling Water (CW) with a supply temperature of 30 °C. Upon consideration of the additional capital cost the dual utility matching would result in, CW was used to satisfy the remaining cooling needs of H2 despite it being the more expensive cold utility. This trade paid off as can be seen in the Low TAC obtained by the network.

The TAC of this network was compared with those of others who have solved this same problem in Table 4 and Figure 6 show their graphical comparison. This study produced the lowest TAC followed closely by the result obtained from SWS [10] which was 0.97% higher than $1,110,403.10/year obtained by this study. The complete results for this case study as well as the graphs plotted are shown in Appendix B.

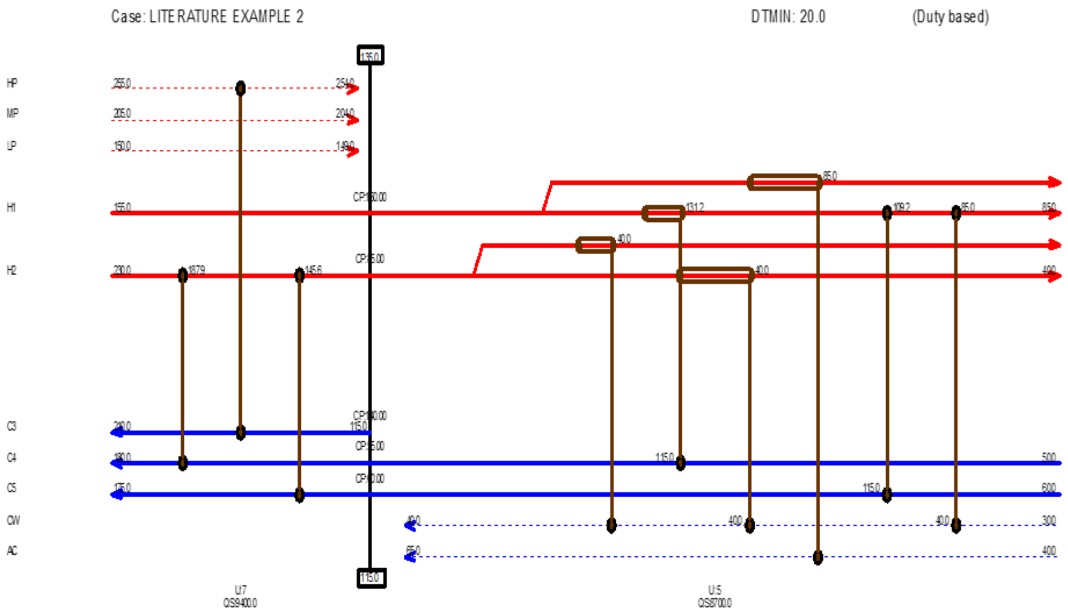

Figure-5. Heat Exchanger Network Design for Case Study 2.

Table-4. Summary and Comparison of Results of Case Study 2.

Method	No. of Units	TAC ($/year)	Percentage Difference (%)
T&SBS [5]	8	1,226,806.00	10.48
CUP [2]	9	1,158,500.00	4.33
IBMS [6]	7	1,150,460.00	3.61
S&TBS [5]	7	1,150,303.00	3.59

SBS [4]	8	1,125,417.00	1.35
SWS [11]	8	1,121,175.00	0.97
This Study	9	1,110,403.10	0.00

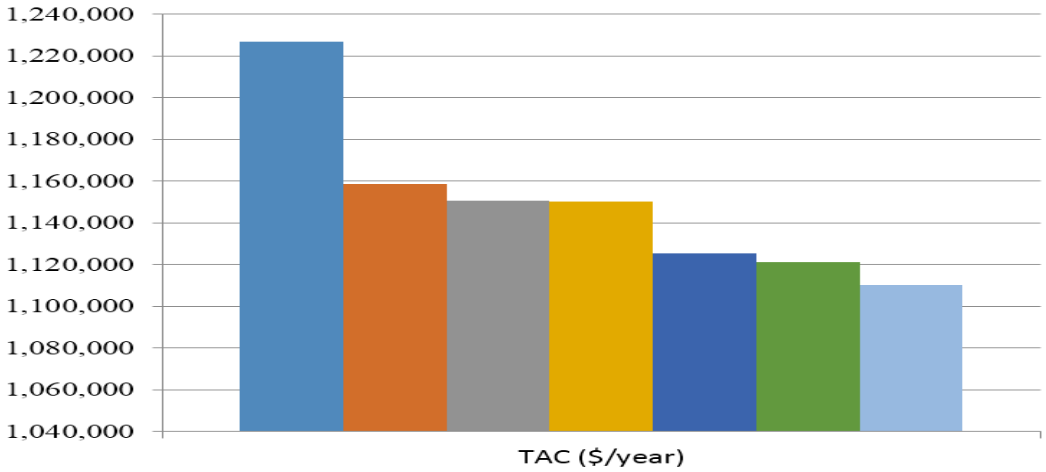

Figure-6. Graphical comparisons for total annual cost (case study 2).

- T&SBS [5].
- CUP [2].
- IBMS [6].
- S&TBS [5].
- SBS [4].
- SWS [11].
- This study.

4. CONCLUSION

This study focused on the solving of HENS problems involving multiple utilities. The minimum TACs obtained in both examples one and two were lower than any of those obtained by other researchers for the case studies. This research proves that merely shifting heat load from costlier utilities to their cheaper alternatives does not guarantee a globally optimal solution. Especially without considering the impact of such choices on the capital cost of the network, in terms of the cost of installing the new heat exchangers that would be needed to distribute heat loads between multiple utilities. It also showed the importance of supertargeting as the optimal TACs achieved in this study would have been impossible to get using a non optimal value of ΔT_{min}.

Funding: This study received no specific financial support.
Competing Interests: The authors declare that they have no competing interests.
Acknowledgement: All authors contributed equally to the conception and design of the study.

REFERENCES

[1] Y. Lukman, B. Suleiman, and O. Azeez, "Evaluation of total annual costs of heat exchanger networks using modified pinch analysis," *Nigerian Journal of Technology*, vol. 35, pp. 537-541, 2016.Available at: https://doi.org/10.4314/njt.v35i3.10.

[2] U. Shenoy, A. Sinha, and S. Bandyopadhyay, "Multiple utilities targeting for heat exchanger networks," *Chemical Engineering Research and Design*, vol. 76, pp. 259-272, 1998.Available at: https://doi.org/10.1205/026387698524910.

[3] T. F. Yee and I. E. Grossmann, "Simultaneous optimization models for heat integration—II. Heat exchanger network synthesis," *Computers & Chemical Engineering*, vol. 14, pp. 1165-1184, 1990.Available at: https://doi.org/10.1016/0098-1354(90)85010-8.

[4] O. Azeez, A. J. Isafiade, and D. M. Fraser, "Supply-based superstructure synthesis of heat and mass exchange networks," *Computers & Chemical Engineering*, vol. 56, pp. 184-201, 2013.Available at: https://doi.org/10.1016/j.compchemeng.2013.05.010.

[5] O. S. Azeez, A. Isafiade, and D. Fraser, "Supply and target based superstructure synthesis of heat and mass exchanger networks," *Chemical Engineering Research and Design*, vol. 90, pp. 266-287, 2012.Available at: https://doi.org/10.1016/j.cherd.2011.07.004.

[6] A. J. Isafiade and D. M. Fraser, "Interval –based MINLP superstructure synthesis of heat exchange networks," *Chemical Engineering Research and Design*, vol. 86, pp. 245-257, 2008.Available at: https://doi.org/10.1016/j.cherd.2007.11.001.

[7] B. Ogbonnaya, O. Azeez, H. Akande, and E. Muzenda, "Investigation of loops and paths as optimization tools for total annual cost in heat exchanger networks," *International Journal of Energy and Environmental Engineering*, vol. 12, pp. 281-293, 2021.Available at: https://doi.org/10.1007/s40095-020-00374-w.

[8] E. M. Ukpo, "Heat exchanger network design for minimum total annual cost using pinch analysis-case study of catalytic reforming unit of Kaduna refinery," Unpublished Master's Thesis), Federal University of Technology, Minna, Niger State, Nigeria, 2017.

[9] B. Linnhoff, D. W. Townsend, D. Boland, G. F. Hewitt, B. E. A. Thomas, A. R. Guy, and R. H. Marsland, *A user guide on process integration for the efficient use of energy*. U.K: The Institute of Chemical Engineering, 1982.

[10] D. M. Fraser, "Multiple utilities in heat exchanger network synthesis," in *Proceedings CHEMECA '94 Conference, Perth*, 1994, pp. 789-796.

[11] P.-O. M. José, M. Serna-González, and A. Jiménez-Gutiérrez, "Synthesis of heat exchanger networks with optimal placement of multiple utilities," *Industrial & Engineering Chemistry Research*, vol. 49, pp. 2849-2856, 2010.Available at: https://doi.org/10.1021/ie901750a.

[12] O. Azeez, O. Blessing, E. Onyinye, and A. Hassan, "Effect of supertargeting and non isothermal stream mixing in heat exchanger network design using modified pinch analysis," *International Journal of Energy and Environmental Science*, vol. 4, pp. 18-20, 2019.Available at: https://doi.org/10.11648/j.ijees.20190401.13.

Appendix A

Table-A1. Network results for Case Study 1.

Total number of exchangers	5
Total heat exchanger area	217.0 m^2
Total hot Utility	312.5 kW
Total hot Utility cost	70749.32 $/yr
Total cold Utility	662.5 kW
Total cold Utility cost	9327.91 $/yr
Annual capital cost	1333.47 $/yr
Annual Utility cost	80077.23 $/yr
Total annual cost	81410.70 $/yr

Source: Ukpo [8].

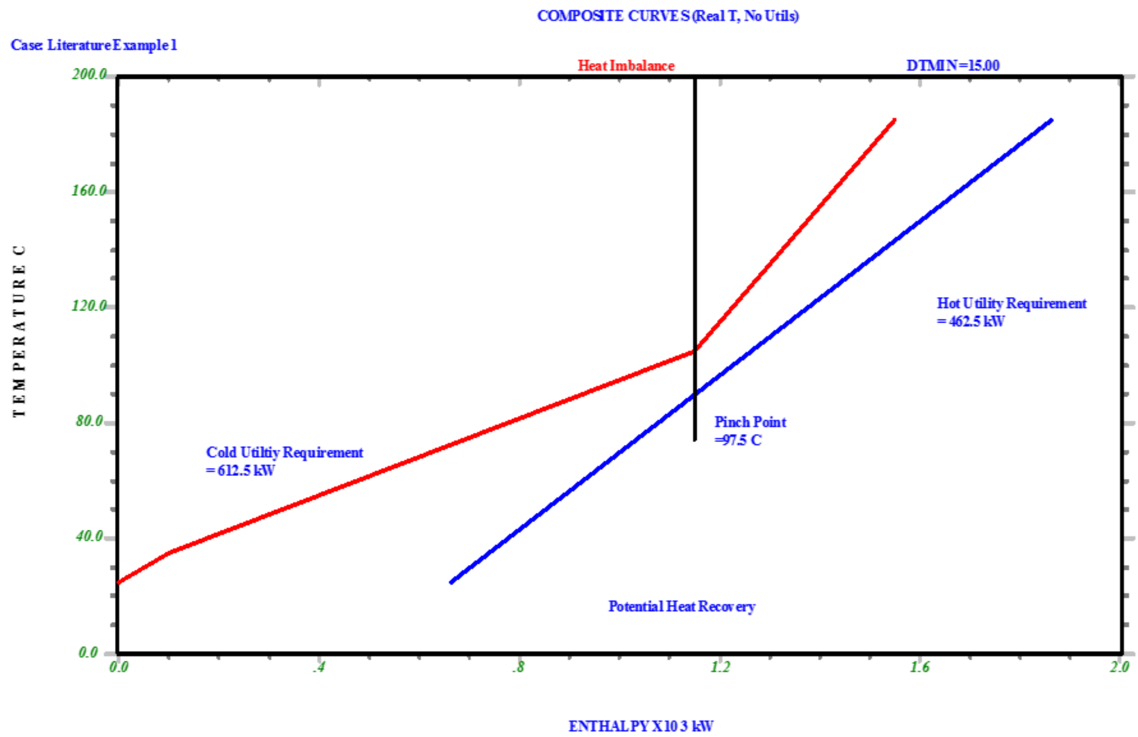

Figure-A.1. Composite curves for case study 1.

Source: Ukpo [8].

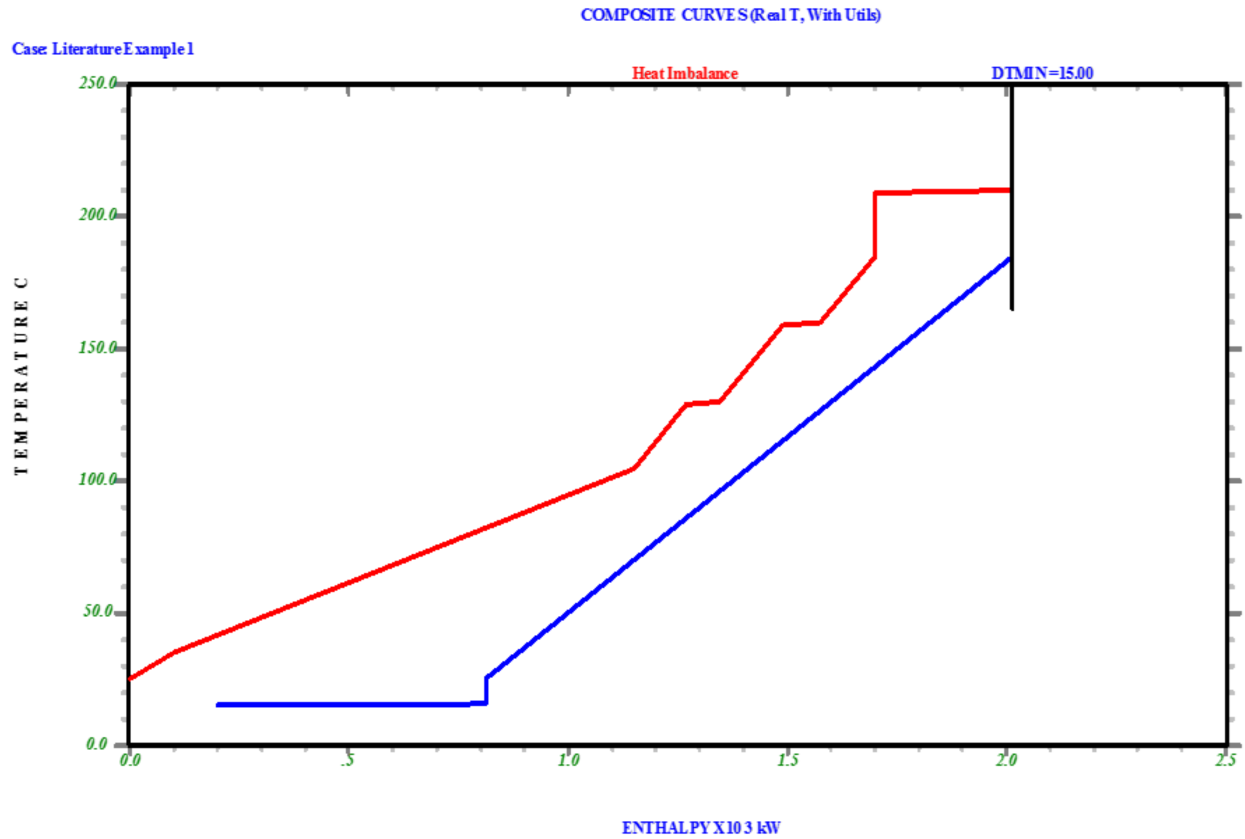

Figure-A.2. Balanced Composite for Case Study 1.

Source: Ukpo [8].

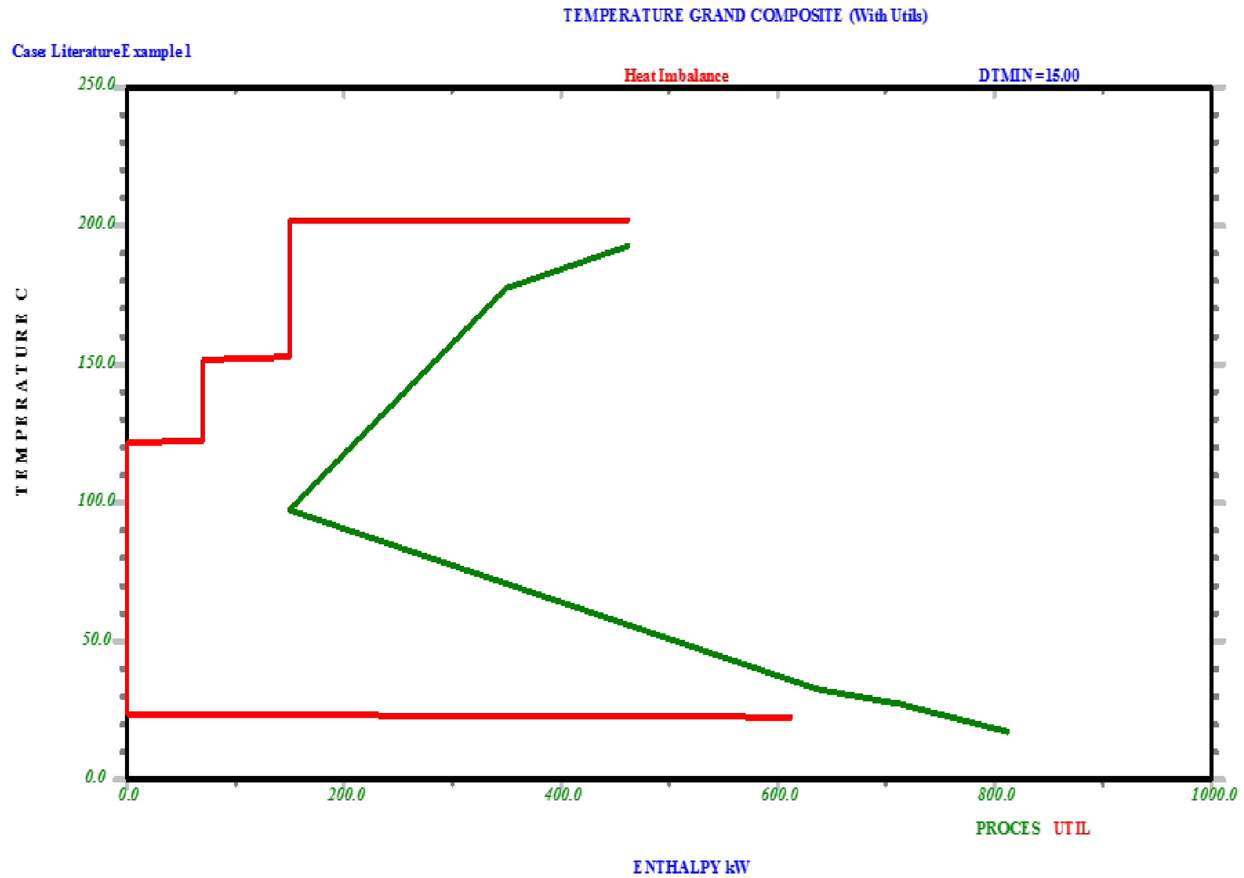

Figure-A.3. Grand Composite Curve for Case Study 1.

Source: Ukpo [8].

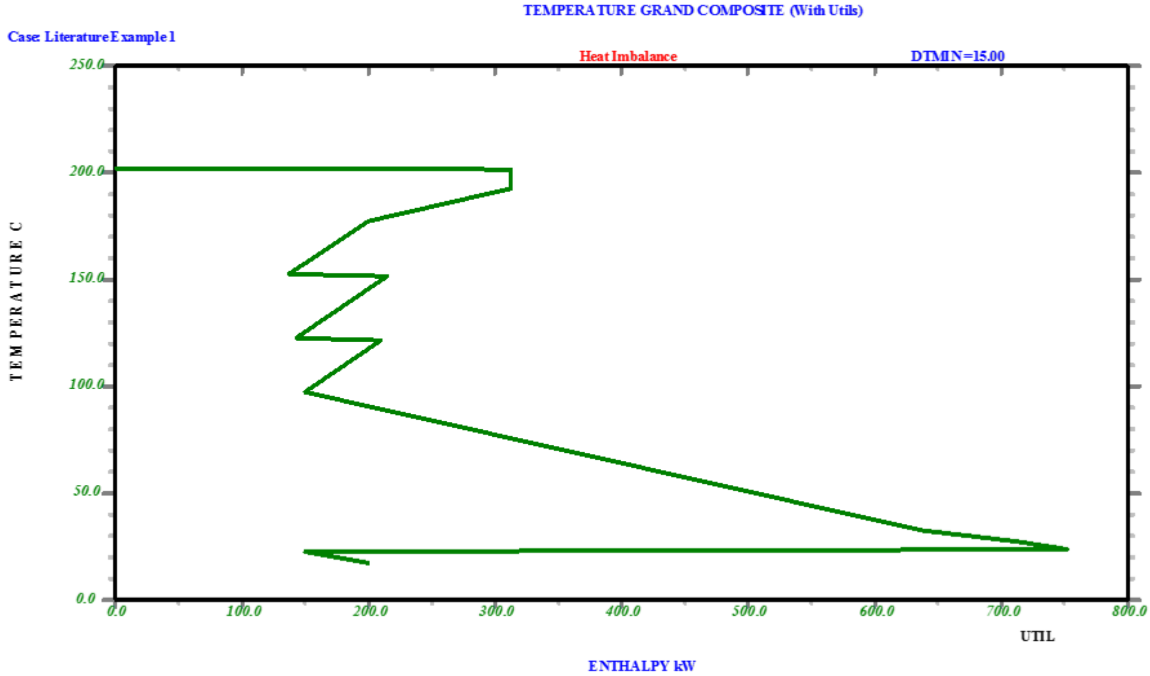

Figure-A.4. Balanced grand composite curve for case study 1.

Source: Ukpo [8].

Appendix B

Table-A1. Network results for case study 1.

Total number of exchangers	**9**
Total heat exchanger area	3386.1 m^2
Total hot Utility	13300.0 kW
Total hot Utility cost	1013450.10 US$/yr
Total cold Utility	12600.0 kW
Total cold Utility cost	61061.74 $/yr
Annual capital cost	35891.26 $/yr
Annual Utility cost	1074511.84 $/yr
Total annual cost	1110403.10 $/yr

Source: Ukpo [8].

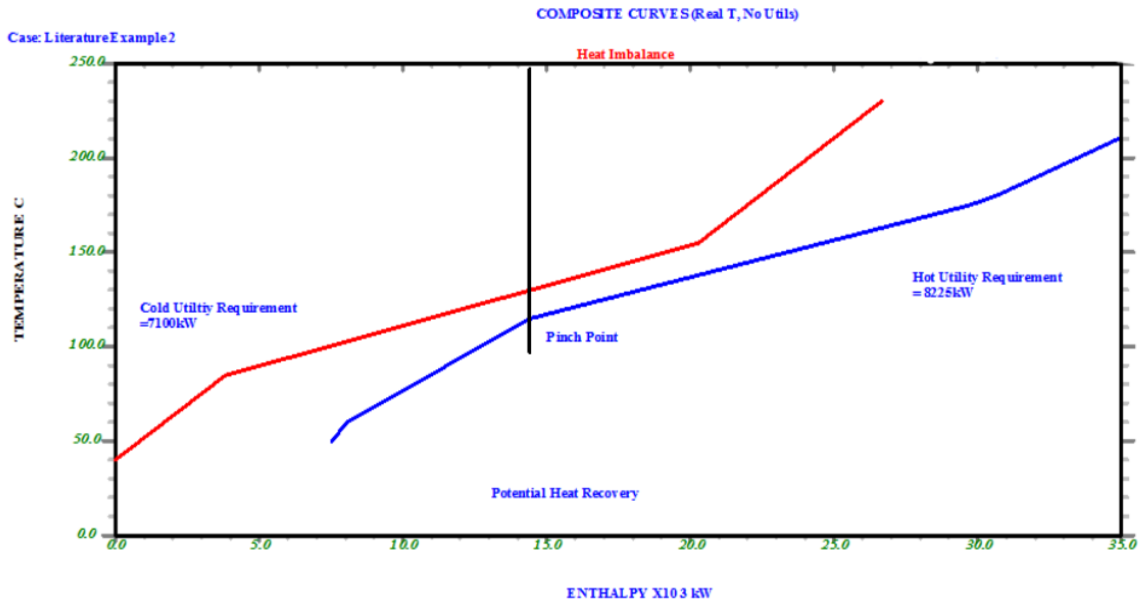

Figure-B.1. Composite Curves without Utiltiies Case Study 2.

Source: Ukpo [8].

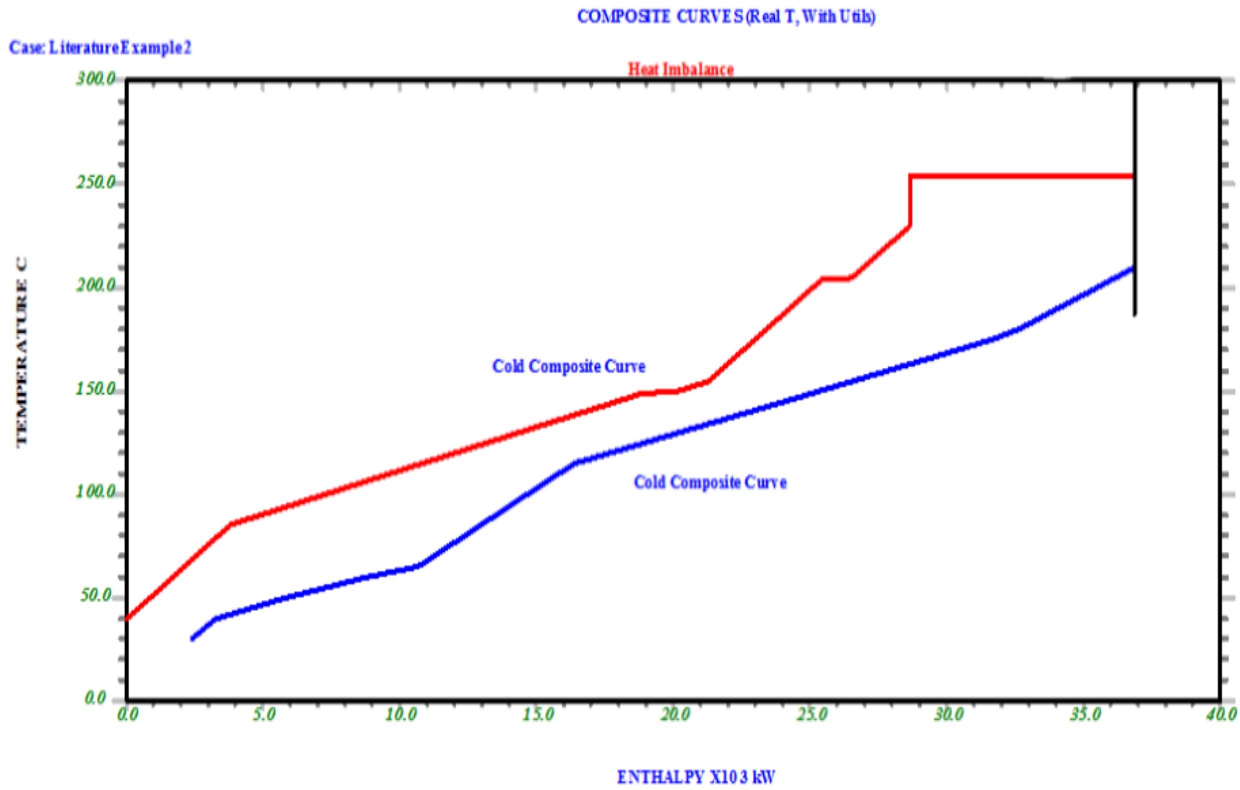

Figure-B.2. Balanced composite curves for example 2.

Source: Ukpo [8].

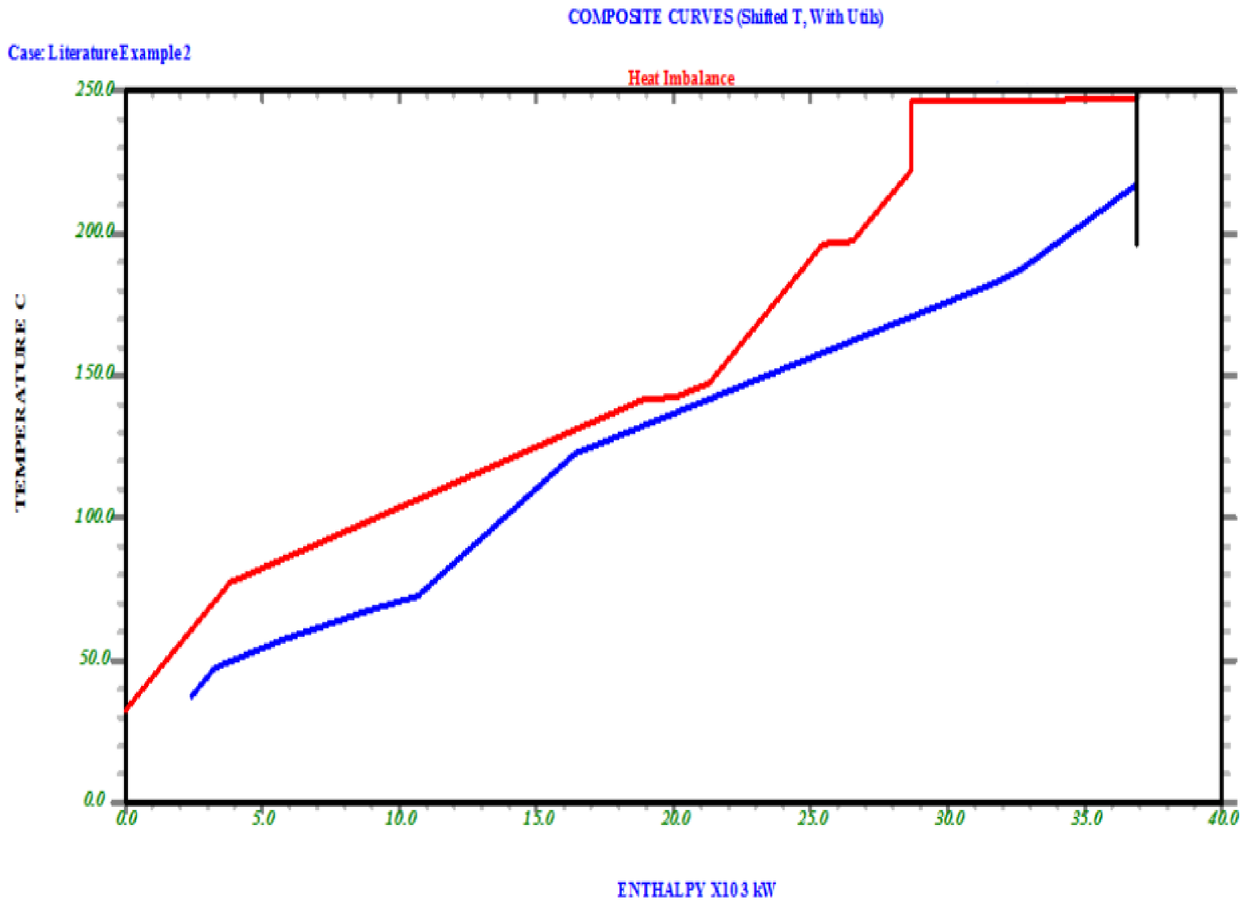

Figure-B.3. Shifted Composite Curve for Case Study 2.

Source: Ukpo [8].

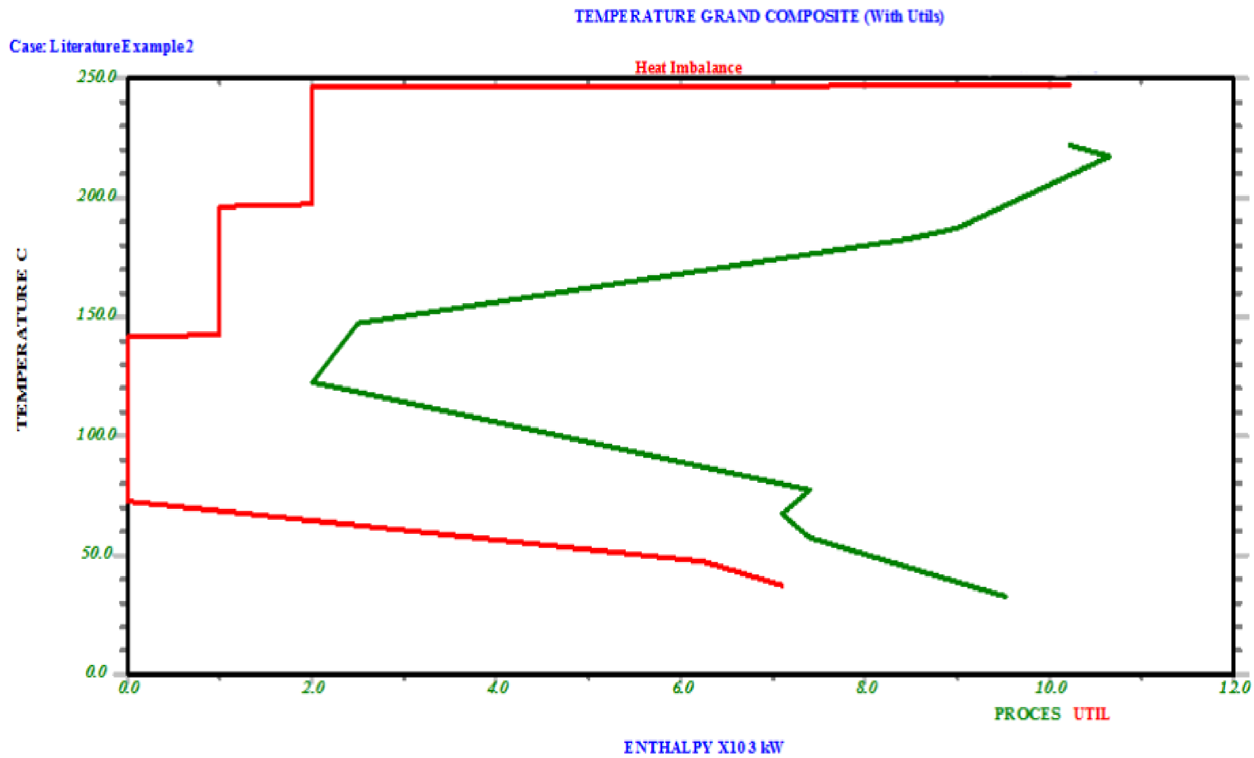

Figure-B.4. Grand composite curves for case study 2.

Source: Ukpo [8].

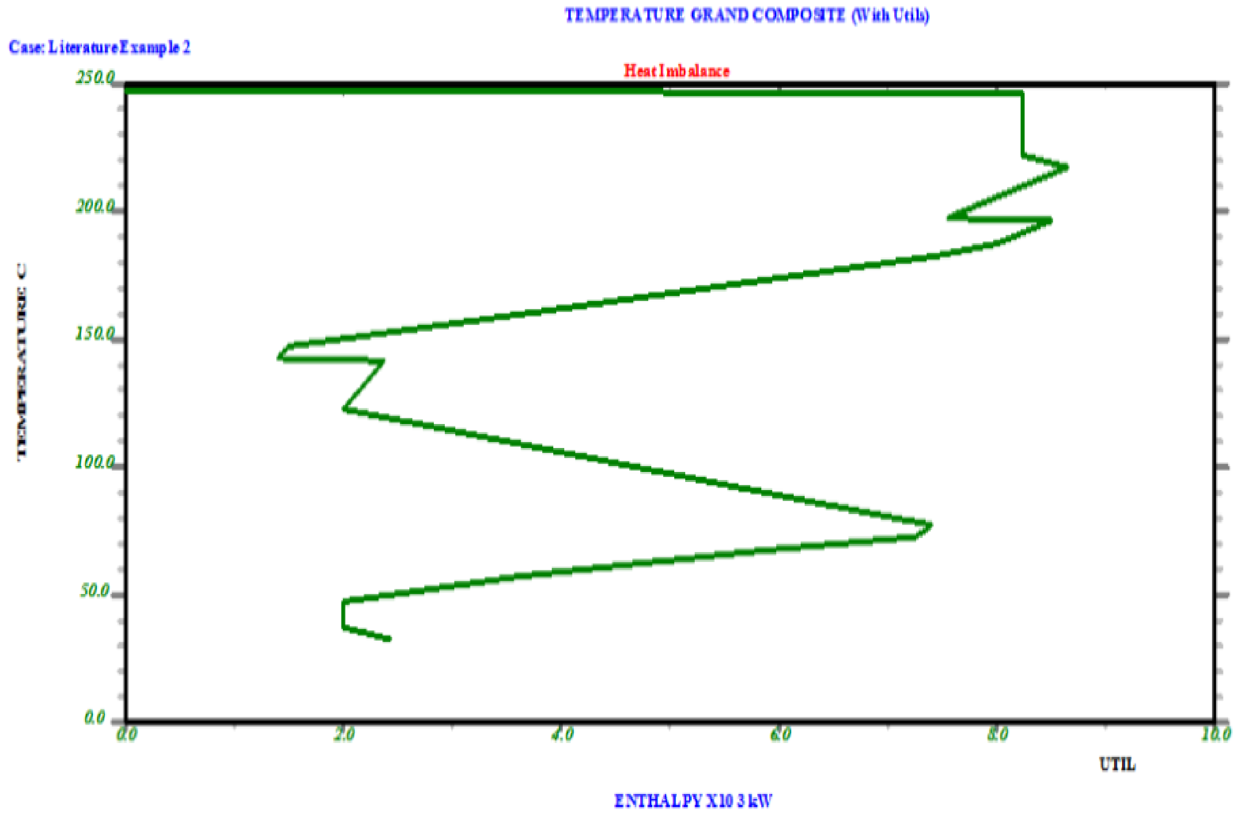

Figure-B.5. Balanced grand composite curves for case study 2.

Source: Ukpo [8].

Views and opinions expressed in this article are the views and opinions of the author(s), International Journal of Natural Sciences Research shall not be responsible or answerable for any loss, damage or liability etc. caused in relation to/arising out of the use of the content.