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IMPROVING THE EFFICIENCY OF NIGERIAN REFINERIES USING PINCH TECHNOLOGY A CASE STUDY OF THE CRUDE DISTILLATION UNIT OF PORT HARCOURT REFINERY, ALESA ELEME

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ABSTRACT

The crude distillation unit (CDU) of the New Port Harcourt Refinery, with a processing capacity of 150,000 barrels per day, was adopted as the case study for this project. The research was motivated by measurable production and energy losses arising from frequent plant downtime, inefficient energy utilization, and inadequacies in process network dynamics and control. Pinch Analysis was applied to the heat exchanger network (HEN) of the CDU using Aspen Pinch 11.1, a commercial process integration software. The study involved the collection of relevant process data, including the CDU process flow diagram, energy balance flow sheets, plant operating records, plant information system (PI) data, and heat exchanger operational data obtained from the PI system. From these sources, the required data for pinch analysis were extracted and converted into pinch-compatible thermal data. The analysis procedure included the development of problem tables, construction of composite and grand composite curves, determination of the pinch point, energy and area targets, and grid representation of the heat exchanger networks. This approach enabled the identification of heat exchangers that crossed the pinch, violated pinch design rules, and contributed to energy penalties. The total computational time for the analysis was 141,039 CPU seconds, executed on a 3.2 GHz Intel® Core™2 T5200 laptop with 1024 MB RAM. The analysis was conducted at minimum temperature differences (ΔTmin) ranging from 20 to 40 °C, consistent with values established for the oil refining industry. A flowsheet comprising 23 heat exchangers distributed across three networks formed the basis of the study: HEN-1 with 7 exchangers and 25 nodes, HEN-2 with 12 exchangers and 36 nodes, and HEN-3 with 4 exchangers and 18 nodes. Results showed that HEN-1 exhibited poor and unclear grid representation, leading to uncertainties in pinch location, cross-pinch effects, penalties, and stream matching. HEN-2 demonstrated a clearer grid structure, allowing accurate identification of pinch location, cross-pinch effects, and exchangers violating pinch rules. At ΔTmin = 20 °C, HEN-2 achieved heat balance, optimal stream matching, and zero cross-pinch effect, requiring only minimal retrofitting. Conversely, HEN-3 produced unsatisfactory results across all ΔTmin values, indicating the need for complete retrofitting. Even then, optimal performance may not be achievable due to its low potential for process-to-process heat recovery. Overall, the study revealed heat imbalance, poor stream matching, and moderate cross-pinch effects across the CDU HEN, confirming the need for total network retrofitting. The findings further demonstrate that the design of an energy-efficient HEN is highly dependent on the selected ΔTmin, with each network exhibiting unique performance characteristics under different conditions.

INTRODUCTION

It is predicted that the world's energy would be exhausted within a century. In this situation, the countries that have energy resources like OPECs are trying to keep their own resources for use in the emergency case. This leads to decrease in the production of oil and natural gas which results in the petroleum price increasing everyday. Petroleum is a major source of energy in our life. The new industrial countries (NICs') have very large energy consumption; the energy sources from these countries are imported from foreign countries to meet the domestic consumptions. All of these NICs' suffer from the high price of petroleum. To resolve the problem, the energy consumption has to be reduced. On the global scene, government has issued many energy conservations plans for reducing the energy consumption. With the latest plan, the energy consumption is being cut down in factories and buildings, and promoting the line of renewable energy. The industrial sector, which consumes a large amount of energy, steadily looks for new ways of utilizing the energy efficiently.

Pinch technology is one of the energy optimization methods. Pinch technology is the most practical method for applying process integration. Process integration is a very important means of improving energy efficiency of industrial and manufacturing processes while minimizing their environmental impact. By analyzing the thermodynamics of a process, engineers can quantify the process, identify the regions where energy can be better utilized and define the minimum targets for energy consumption. Pinch technology is used mostly for heat exchanger network synthesis (HENS). It can also be applied for distillation column design, mass exchanger network synthesis (MENS), batch scheduling, total utilities system design, etc. The process pinch points refers to the energy optimum point in the process design, the temperature level above this point acts as a heat sink, and the one below acts as heat source. Based on rigorous thermodynamics principles, pinch technology matches cold streams that need to be heated with hot streams which need to be cooled, causing high degree of energy recovery. Thus, pinch technology can be used to determine the minimum requirement for both hot and cold utilities in a process and enhance process integration.

HISTORICAL BACKGROUND OF THE PORT-HARCOURT REFINERY

The crude distillation unit (CDU) of Port-Harcourt Refinery Company (PHRC) has been chosen for this work. PHRC is one of the eleven subsidiary companies owned by the Nigerian National Petroleum Corporation (NNPC). The Refinery complex is comprised of 2 refineries:

a. Old Port Harcourt Refinery (OPHR) with a processing capacity of 60,000 BPD built in 1965.
b. New Port Harcourt Refinery (NPHR) with processing capacity of 150,000 BPD built in 1989. This is the case study for this project work.

The combined refinery capacity of the complex is 210,000 BPD.

GOAL AND MOTIVATION

The refineries keep breaking down and refusing to operate efficiently because of excessive energy; and poor process network, dynamics and control. In the light of the above setbacks, the quest for effective optimal refining has gingered this study of the heat exchanger network synthesis in crude distillation units of refineries with specific reference to the NPHRC. A goal in this research work will be to successfully develop a unifying approach to process integration through pinch technology. In addition, the merits of advanced commercial software tools for process integration (e.g., Aspen Pinch) will be evaluated, for applications to real industrial and process problems.

RESEARCH TASKS AND OBJECTIVES

The cardinal objective of this research work is to study the application for minimum thermodynamics conditions by using pinch technology; find the conditions for minimum energy requirements in a heat exchanger network and find the networks design that satisfy the minimum energy targets.

METHODOLOGY

For this research work, practical part will be started with:

1. Acquisition of process data which include one or more of the following:
    a. Process flow diagram of CDU of NPHRC
    b. Energy balance flow sheet of CDU
    c. Plant operating records
    d. Plant information system (P.I.)
    e. Heat exchanger Network (HEN) operative data from P.I.
2. Data Extraction from flow sheets to pinch data
3. Formation of problem table or thermal data
4. Plotting composite curves and grand composite curves by using process simulation tool to find the pinch point, energy targets and area target of the process.
5. Grid representation of the heat exchanger network to identify heats exchangers crossing the pinch, or violating the pinch rule.
6. Identification of cross pinch exchangers and penalties.

SIGNIFICANCE OF THE RESEARCH

Until this time, limited publications have presented issues on the applications of pinch technology to retrofitting the Nigerian refineries; most documented works are also directed towards steady state integration of the heat exchangers to achieve target temperatures. In view of current policies and indigenous research works so far, only replacements of broken down components and the usual turn around maintenance which involves the cleaning of heat exchangers to remove scales depositions due to fouling have been practiced in our refineries. As will be discovered soonest in this detailed research work, the refineries keep breaking down and refusing to operate efficiently because of excessive energy that is used to claim the process and poor process network. In the light of the above setbacks, the quest for effective optimal refining has gingered this study of the heat exchanger network synthesis in distillation units of refineries with specific reference to the NPHRC.

EARLIER WORKS TO IMPROVE THE ENERGY EFFICIENCY OF REFINERIES

Numerous investigations have been carried out to improve the performance of heat exchanger networks. The HEN design approaches can be grouped into 3 categories:

a. Pinch Analysis Method
b. Mathematical programming methods and;
c. Stochastic methods

Linnhoff and Hindmarsh (1983) developed a method of design for the minimum hot and cold utility demand, for a set of hot and cold streams and a selected minimum temperature approach (DT min) based on several heuristic rules. Because pinch analysis is difficult to apply to large scale problems, mathematical modeling methods were developed. Optimization of HEN is generally formulated on a mixed-integer non-linear programming (MINLP). To avoid being trapped into local optimum, simplifications are made to convert the MTNLP into linear programming (LP) (Papoulias and Grossmann, 1983; Cerda and Westerberg, (1983), or Non-linear Programming (NLP) as contained in the work of Yee, (1990). Other attempts have been made to reduce the size of the problem, using ''block'' (Zhu, 1995) and ''stage'' (Asante and Zhu, 1996) concepts. Compared to others, stochastic methods have more chance finding the global optimization for MINLP problems, due to the random nature of the optimization methods. Commonly used algorithms in the synthesis of HENs are Genetic Algorithms (Wang, 1998; Lewin,

1998) and simulated Annealing (SA). However, not all of the researches above are suitable for HEN retrofit. Moreover, there has been no work which considered the varying thermal property (e.g. heat capacities) issue of process streams. Non-constant thermal proportions often arise when multi- component streams are cooled down or heated up, such as in refining preheat trains. The network pinch method (Asante and Zhu, 1996) combined physical insights into retrofit problems and mathematical techniques. The bottlenecks of the existing network configuration is first identified by redistributing the heat loads of existing exchangers, which is referred to as providing the existing network. Then each candidate structural modification that may overcome the bottleneck of the HEN configuration is optimized at a time for maximum heat recovery. A list is generated after all suggested modifications are optimized, showing the corresponding maximum heat recovery for a given modified HEN topology. The difficult MINLP problem is decomposed into MILP problem and NLP problem. Although it is sequential approach, it explores possible topology modifications in a systematic way and at the same time allows inner integrations in the design procedure.

However, the existing networks pinch approach assumed content thermal properties with temperature in the design of HENs and stream split fractions are not considered in pinching existing networks. Moreover, the existing approach only carries out cost-optimization in the optimization stage after the diagnosis stage. The design with minimum cost cannot be guaranteed since the selection of the potential modification is not based on costs but energy demands. In this project, the network pinch design methods are modified to overcome these limitations. Considering beyond the networks, retrofits of refinery distillation system has been studied by a number of researchers. Early research concentrated on proposing modifications to the distillation columns and the heat exchanger network in other to reduce energy consumption. Sittig (1978) suggested that in order to improve the efficiency of the distillation system, new intervals with higher efficiency should be installed and recommended the use of intermediate reboilers. Bannon and Marple (1978) proposed other column modifications such as the installations of pump-around.

Pinch analysis principles guided many researchers to identify modifications to distillation columns for reducing energy consumption and improving the performance of refinery distillation columns, based on insights derived from pinch analysis.

PROCESS OVERVIEW OF REFINERY UNDER STUDY

There exists 2 CDUs in PHRC. The first is the atmospheric crude distillation unit (area 1) indicated by unit no 10. Built in 1989, it has a producing capacity of 150,000 BPD and is situated in the NPHR complex. This unit specifically is the focal points of the project under study. Meanwhile, the second is the crude distillation unit (area 5) indicated by unit no 510. Built in 1965, it has a processing capacity of 60,000 BPD and is the main unit in the OPHR complex, (Port Harcourt Refinery Company Limited Brochure, 2005). Once more, our focus is on the CDU (Area 1). Raw crude oil is pumped to the CDU after setting and dewatering at the tank farm. It passes through a heat exchanger train, the desalter (for removal of salt and sediments), the pre-flash column (for removal of lighter ends), and the main crude heater where it is heated up, then to the main fractionating column or fractionator. This is also the distillation tower in which the distillation trays ensure thorough mixing and separation of liquids from vapours. The vapours are removed from the top of the fractionator, condensed and sent to saturated gas concentration unit (SGCU) for further separation and production of LPG or cooking gas.

The liquids are withdrawn from the side of the fractionators, based on the boiling point ranges as products. The liquid products are as follows:

1. Whole naphtha
2. Straight run kerosene
3. Light diesel oil
4. Heavy diesel oil
5. Atmospheric residue

These products are classified as either finished or semi-finished. The semi-finished products are further subjected to secondary process to obtain finished products. The whole naphtha is stabilized by stripping it further of lighter components (C1, C2, C3 & C4), then split into straight run gasoline (SRG) and straight run naphtha (SRN). The SRG is sent to intermediate products storage as one of the components to be blended to produce premium motor spirits (PMS). The SRN is sent to naphtha hydro treating and catalytic reforming units (NHU/CRU) to produce reformate used as a components for PMS blending. The reformate has a higher octane number (a critical measure of PMS quality) than the SRN. The SRK, also known as Dual Purpose Kerosene (DPK) is used either directly as household kerosene or as aviation fuel after further processing and introduction of additives. For the production of aviation turbine kerosene (jets al), a part of the SRK is sent to the kerosene Hydro treating Unit (KHU) for improvements of the smoke points, etc. The lighter diesel oil is a finished product and is used directly on Automatic Gas Oil (AGO) or Diesel. The heavy diesel oil (HDO) forms part of the feedstock for the fluid catalytic cracking unit (FCCU) and is sent to storage. The last fraction is the atmospheric residue (AR) and thus is sent to the vacuum distillation unit (VDU) to obtain feedstock for FCCU. Due to energy and economic crises, one way to improve energy efficiency of the refinery having crude distillation units (CDU), high energy consuming units, with complex heat exchanger networks (HENs) is to reduce energy consumption at crude furnaces and product coolers. Such refinery, like the PHRC, can be retrofitted by applying pinch analysis and stage model.
For the retrofits design with minimal network changer, the stage model and heat-demand- supply diagram can be applied by fixing the same location of exchangers on the existing one and varying the exchanger minimum temperature approach (EMAT) in the model. The result showed minimal additional exchanger areas will be added to receiver heat for preheating crude and also increase the furnace inlet temperatures, resulting in energy savings at furnace and coolers about 1.3% and 2.8% respectively. Heat exchanger network retrofit of CDU is to modify the existing exchanger network with minimal changer resulting in energy saving on crude furnace and product coolers. The modification can be adding new exchangers or more exchanger area to the existing HEN, or relocating the existing exchangers. An outstanding approach to HEN synthesis is the use of optimization model called stage model to do the grassroots design of HEN.

The CDU is one of the largest energy-consuming units having the crude preheating trans or HEN transferring heat from pump-around and hot product streams; Naphtha (OVHD), kerosene (KERO), light and heavy gas oil (LGO, HGO) and Long Residue (LR), to the crude feed (CRUDE) as shown in the figure 2.1 . Preheating the crude by HEN helps
reduce fuel consumption at the crude furnace.

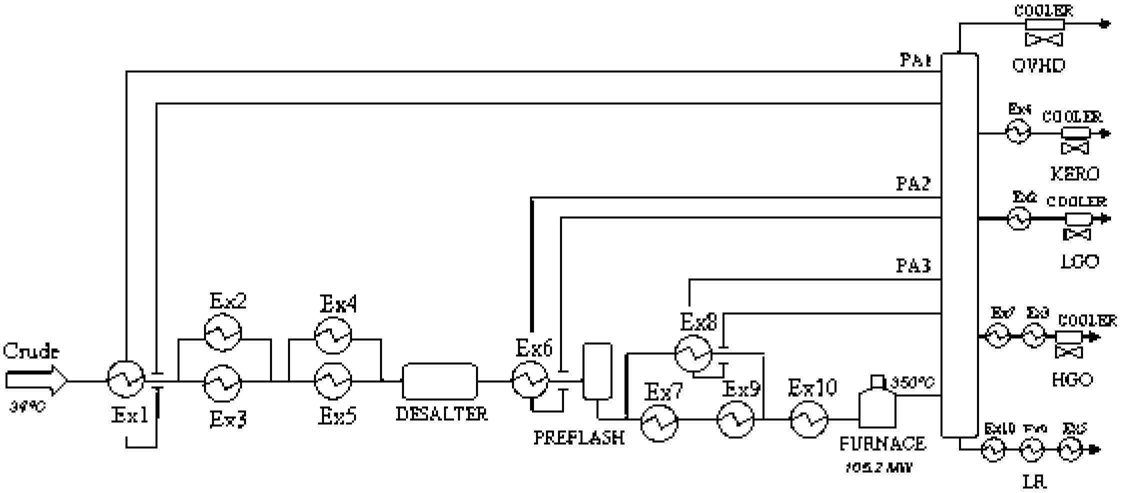


Fig. 2.1: *A typical HEN of crude preheating train (Promvitak, 2001).*

Furthermore, for any heat exchanger networks design, the first and second laws of thermodynamics must be satisfied. And before one can proceed with the actual design, the minimum heating and cooling energy requirements and the number of heat exchangers must be known. According to Linnhoff and Hindmarsh (1983), the appropriate procedure is to design two sub networks of exchangers: - one is above the pinch temperature, and the other below the pinch.

PINCH ANALYSIS

BASIC PINCH ANALYSIS CONCEPTS

The pinch analysis concept is originated to design the heat recovery network for a specified design task. The pinch analysis starts with the heat and material balances data of the process which is obtained after the core process, i.e. reaction and separation system, has been designed. Using thermal data from the process, we can set the target for energy saving prior to the design of the heat exchanger networks. The necessary thermal data are the source and target temperature and heat capacity flow rate for each stream as exemplified in table 2.1 below.

Table 2.1: *Thermal data for process streams (Linnhoff and Hindmarsh, 1983)*

No.	type	Temperature(T_S), ^oC	Temperature(T_t), ^oC	flowrate (CP), kW/^oC
1	Hot	150	60	2
2	Hot	90	60	8
3	Cold	20	125	2.5
4	Cold	25	100	3

Here, the hot streams are referred to the streams that required cooling, i.e. the source temperature is higher than the target. While the cold streams are referred to those required heating, i.e. the target temperature is higher than the supply. Heat capacity flow rate is defined as specific heat capacity times mass flow rate as shown below:

$$CP = Cp \times F \qquad - \quad - \quad - \quad - \qquad 2.1$$

Where CP = heat capacity flow rate (kW/^{O}C)

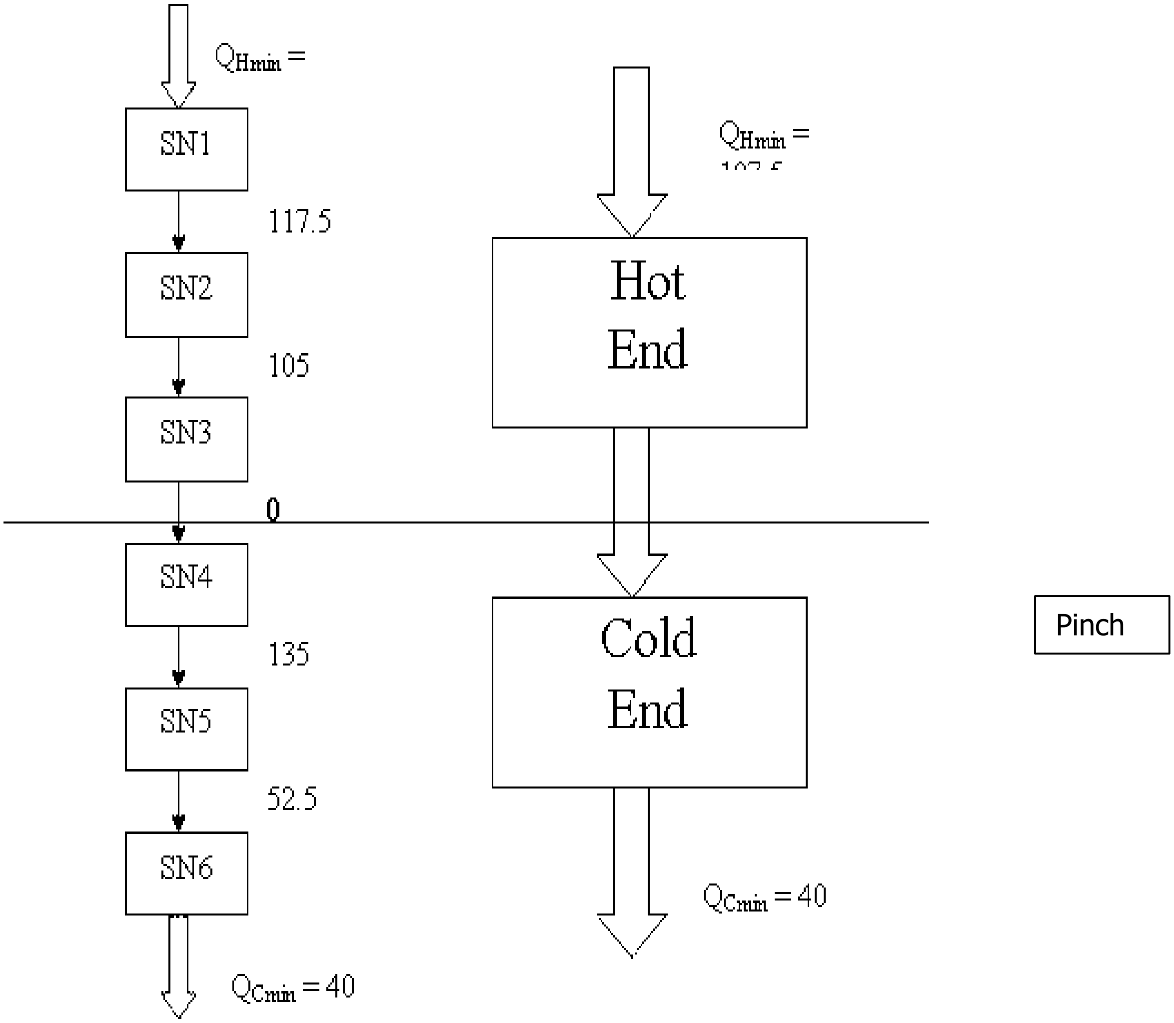
Cp = specific heat capacity of the stream (kJ/ kg ^{O}C)
F = mass flow rate of the stream (kg/s)
The data using here is based on the assumption that the heat capacity flow rate is constant. The location of pinch and the minimum utility requirement can be calculated by using the problem table algorithm (Linnhoff and Flower, 1979) for a specified minimum temperature difference, ΔT_{min}.

For a ΔT_{min} of 20 ^{O}C, the results from this method are shown in Table 2.2.

Table 2.2*: Problem table for data given in Table 2.0. (Linnhoff and Hindmarsh, 1983)*

	Streams and temperature					Accumulated		Heat Flows	
Subnetwork	Cold streams	T(^{O}C)		Hot Streams	Heat Deficit	Input	Output	Input	Output
	(4)	(3)	150	(1) (2)					
SN1		125	145		-10	0	+10	107.5	117.5
SN2		100	120		+12.5	+10	-2.5	117.5	105
SN3		70	90		+105	-2.5	-107.5	105	0
SN4		40	60		-135	-107.5	+27.5	0	135
SN5		25			+82.5	+27.5	-55	135	52.5
SN6		20			+12.5	-55	-67.5	52.5	40

In the table the stream data are shown on the left. The network is divided into six sub- networks (SN1-SN6) corresponding to the temperature interval. The interval is defined by process stream supply and target temperatures. For example, SN2 is defined by the target temperature of stream No.3 and No. 4. The important feature of this method is the separation between hot and cold streams by ΔT_{min}. This feature ensures the feasibility of complete heat exchange between the hot and cold streams. In other words, for each sub- network there will be either a net heat deficit or surplus as shown in Heat Deficit column (column 1) in Table 2.2. The sign convention for heat deficit is positive while the negative is used for heat surplus. The results of the problem table algorithm can be shown diagrammatically called "Trans- shipment heat flow diagram" as shown in Figure 2.1(a). All heat flows are calculated by problem table algorithm. It can be seen from this diagram, the heat flow from SN3 to SN4 is zero while other flows are positive. The point where the heat flow is zero represents the pinch point. The significance of the pinch is shown in Figure 2.2(b). The pinch separates the problem into two thermodynamic regions, namely, hot end and cold end. The hot end is the region comprising all streams or parts of streams above the pinch temperature. Only hot utility is required in this region but not cold utility. The cold end is the region comprising all streams or parts of streams below the pinch temperature. Cold utility is required in this region but not for hot utility. There is no heat transferring across the pinch, therefore, the utility requirement is the minimum.



(a) (b)

Figure 2.2: *(a) Transshipment heat flow diagram for data in Table 2.1. (b) Sub-networks combined into a hot and cold region (Linnhoff and Hindmarsh, 1983)*

As described previously, the hot end requires only hot utility so it acts as a heat sink while the cold end requires only cold utility so it acts as a heat source. To achieve this minimum requirement, the design has to obey the pinch principle. The pinch principle comprises of:

(1) There must not be heat across the pinch
(2) There must not be external utility cooling above the pinch
(3) There must not be external utility heating below the pinch.

Violating this principle will increase the utility requirement as shown in Figure 2.3. The effect of transferring heat, X, across pinch is shown in Figure 2.3(a). Any heat transferred must, by enthalpy balance around the sink, be supplied from hot utility in addition to the minimum requirement.

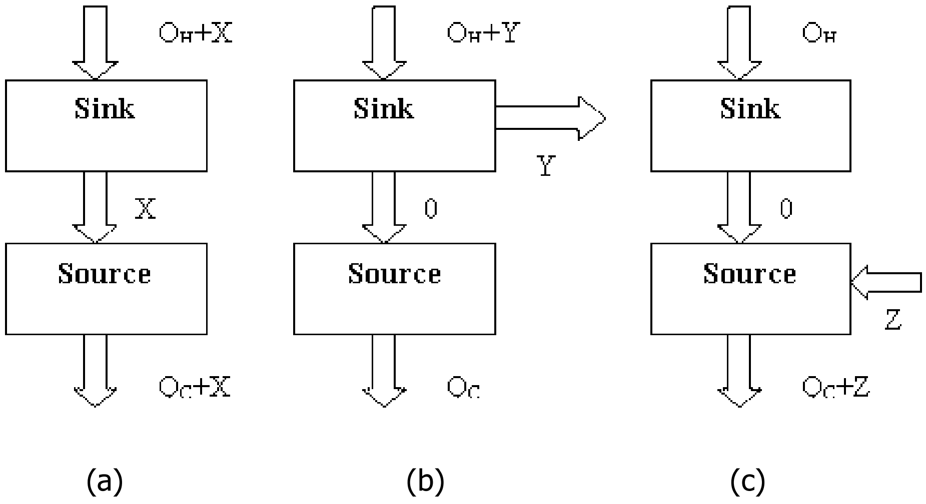


Figure 2.3: *(a) Effect of heat transfer across the pinch, (b) Effect of utility cooling above the pinch, (c) Effect of utility heating below the pinch (Linnhoff and Hindmarsh, 1983)*

The same argument is applied for the assessment of the effect of cooling above and heating below the pinch. Consider Figure 2.3(b), if we let the heat Y to be removed from the sink, again by enthalpy balance, the utility heating has to be increased to balance the rejected heat. Likewise, in Figure 2.3(c) if we input the heat to the source, the utility cooling has to be increased in order to reject the external heat. Thus, to achieve the minimum utility requirement, the pinch principle must not be violated. The principle is very useful to the retrofit studies. Using the above argument, the designer can find which exchangers are placed at fault position.

THE GRID REPRESENTATION

In network design development, it is desirable to do on a representation which shows the stream data and the pinch together. In addition, the presentation ought to be sufficiently flexible to allow easy manipulation of matches. The grid representation can be modified to achieve these objectives. The illustration of grid representation is shown in Figure 2.4 for the data given in Table 2.1. In the grid representation, the hot streams are grouped running from their supply (left) to target (right) temperatures. Cold streams are located beneath, running counter-currently. The pinch division is represented in the diagram by dividing the stream data at the pinch temperature. Note that the hot and cold streams are separated by ·T_{min}. The heat exchangers are represented by vertical lines and circle on the streams matched as shown in Figure 2.5. Heaters and Coolers are represented by the circles placed on cold and hot streams, respectively. The duty load of the exchangers is dictated below the circles.

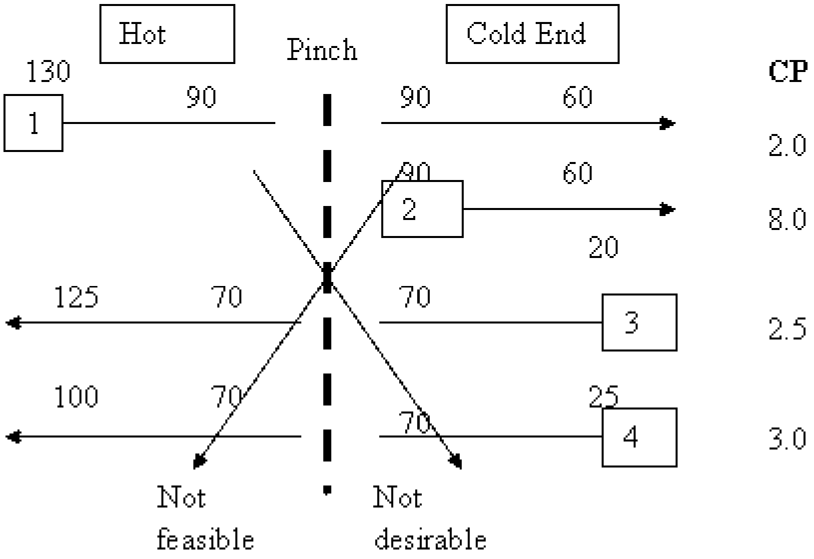


Figure 2.4: *Grid representation (Linnhoff and Hindmarsh, 1983)*

Consider figure 2.4, heat exchanger from cold end to the hot end is not feasible while the exchange from hot to cold end is not desirable as this would constitute heat transfer across pinch. Therefore, the grid shown in Figure 2.4 provides a completely separate design tasks, the hot end and the cold end.

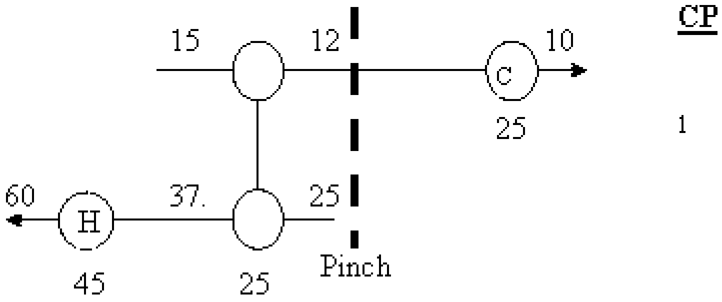


Figure 2.5: *Heat exchangers representation in grid diagram (Linnhoff and Hindmarsh, 1983)*

COMPOSITE CURVES (CCs)

The energy targets are calculated by problem table algorithm as described previously. They can also be obtained using a tool called the "composite curves", the curves consist of temperature-enthalpy (T-H) profiles of heat availability in the process (the hot composite curve) and heat demands in the process (the cold composite curve) together in a graphical representation. Figure 2.6 demonstrates the construction of the hot composite curve. The result for a set of hot and cold streams is a plot of two composite curves as shown in Figure 2.7. The overlap between the composite curves represents the maximum amount of heat recovery possible within the process.

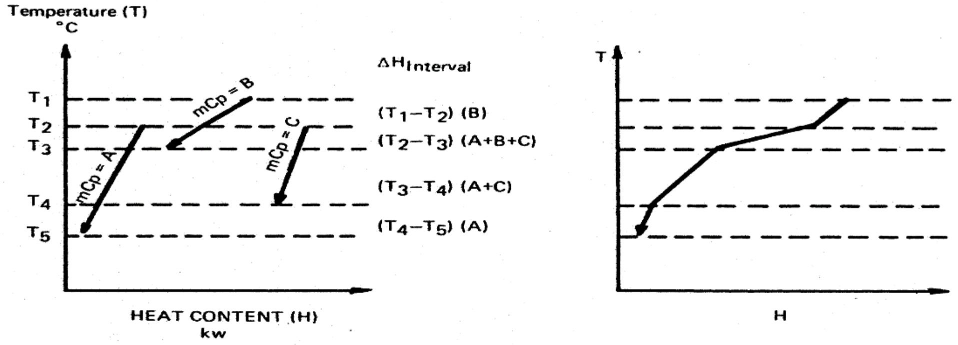


Figure 2.6: *Construction of composite curves (Linnhoff, 1982)*

The "over-shoot" of the hot composite represents the minimum amount of the external cooling required and the "overshoot" of the cold composite represents the minimum amount of external heating. Because of the "kinked" nature of the curve, they approach most closely at one point. This is called the "pinch".

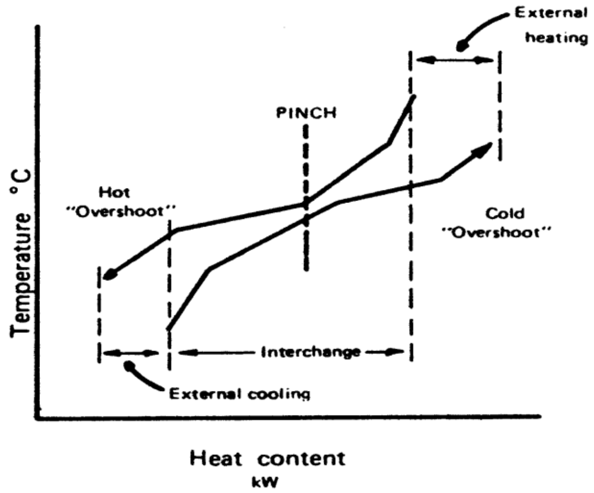
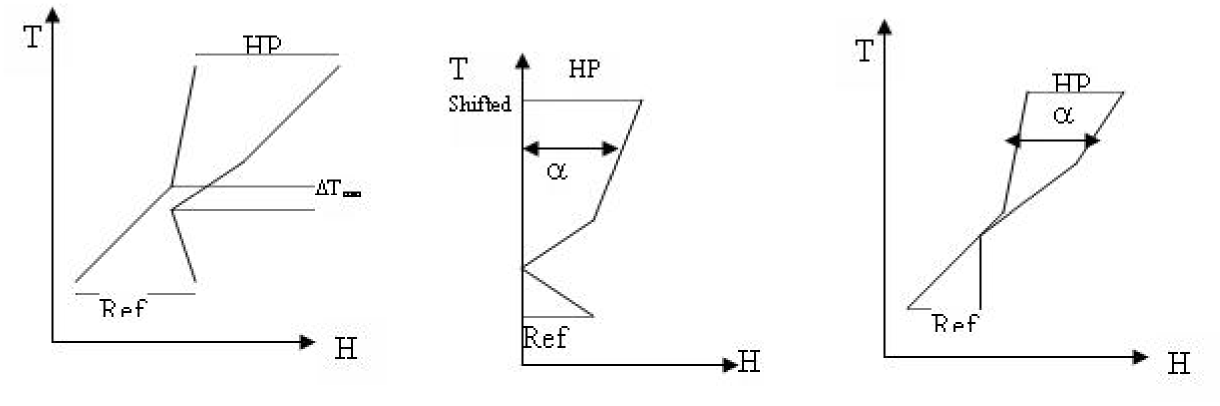


Figure 2.7: *Prediction of energy targets using Composite Curve. (Linnhoff, 1982)*

The transshipment heat flow diagrams (Figure 2.2) can be represented by the temperature- enthalpy plots called the composite curves. The heat flows from the cascade in each temperature interval are plotted against their respective temperature interval boundary. The result is a graph which characterizes the process source and sink in temperature-enthalpy terms, this plot is called "Grand Composite Curve". The construction of which is illustrated in Figure 2.8. The construction starts with the composite curves as shown in Figure 2.8(a). The first step is to make adjustments in the temperatures of the composite curves as shown in Figure 2.8(b). The adjustment is done by increasing the cold composite temperature by ½ ·T_{min} and decreasing the hot composite temperature by ½ ·T_{min}. This temperature shifting of the process streams and utility levels ensures that even when the utility levels touch the grand composite curve, the minimum temperature difference of ·T_{min} is maintained between the utility levels and the process streams. The temperature shifting therefore makes it easier to target for multiple utilities. As a result of this temperature shift, the composite curves touch each other at the pinch. The curves are called "shifted composite curves". The grand composite curve is then constructed from the enthalpy (horizontal) differences between the shifted composite curves at different temperatures (shown by distance · in Figure 2.8(b) and (c)). The grand composite curve provides the same overall energy target as the composite curves, the high pressure steam (HP) and refrigeration (ref.) targets are identical in Figure 2.8(a) and (c). The grand composite curve indicates "shifted" process temperatures. Since the hot process streams are reduced by ½ ·T_{min} and cold process streams are increased by ½ ·T_{min}, the construction of the grand composite curve automatically ensures that there is at least ·T_{min} temperature difference between the hot and cold process streams



(a) (b) (c)

Figure 2.8: *Construction of the grand composite curve, (a) Composite curves (b) Shifted composite curves (c) Grand composite curves (Linnhoff, 1982)*

The utility levels when placed against the grand composite curve are also shifted by ½ ·T_{min}- hot utility temperatures decreased by ½ ·T_{min} and cold utility temperature increased by ½ ·T_{min}. This shifting of utilities temperatures ensures that there is a minimum temperature difference of ·T_{min} between the utilities and the corresponding process streams. More importantly, when utility levels touch the grand composite curve, ·T_{min} temperature difference is maintained.

APPLICATIONS OF PINCH TECHNOLOGY

Pinch technology (PT) is proved to be important for engineers to analyze and design chemical processes (Stankiewicz, 1993). By allowing engineers to track the heat or pressure flow all process streams within a plant, PT made it easier to integrate plant design. Rearranging equipment, such as reactors, evaporators, pumps, distillation columns, and separators, can make unit operations more efficient, in energy consumption such as heat exchanger networks. It is available to automate the redesign process and PT is set to move beyond energy, into pressure drop optimization and distillation columns sequencing. Moreover, the pinch concept is also used to develop a procedure to optimize a licensor's design for complex processes with many utilities and unit operations (Trivedi, 1996). The procedure included a method to set the marginal cost for various utility levels. It also illustrates how to use composite and grand composite curves to set the level and load of various. In addition, the method optimizes distillation column using the concepts of column grand composite curves. In addition to the use of PT as a design tool, it can be combined with exergy analysis to develop a method for process modification (Feng and Zhu, 1997). Omega-H diagram was proposed, energy and exergy balance can be represented in this diagram which helps the process analyst to view the performance and set the target for improvement, and modification can be located by viewing the imperfection of the existing process. The same idea was also applied to heat exchanger network analysis (Sorin and Paris, 1997). Process integration (PI) is a major area in which the pinch analysis is applied (Hallale, 2001). PI is not only the pinch analysis and energy integration but it had been extended its uses to various applications. The four major areas of PI are:

1) Efficient use of raw materials

2) Energy efficiency
3) Emission reduction and;
4) Process operations.

Many applications of pinch technology were discussed, they are used in hydrogen management, total site analysis and integration, heat exchanger networks design and retrofit, column analysis and integration and water management. All of these applications start from generating composite curve, locating pinch point, setting targets and then designing or modifying to achieve the targets.

OPERATING PRINCIPLE OF HEAT EXCHANGERS

BASIC THEORY OF HEAT TRANSFER

Heat can be transferred from a source to a receiver by conduction, convection, or radiation. In many cases, the exchange occurs by a combination of two or three of these mechanisms. When the rate of heat transfer remains constant and is unaffected by time, the flow of heat is designated as being in a ***steady*** state; an ***unsteady*** state exists when the rate of heat transfer at any point varies with time, (Adrian B. and Allan K., 2003). Most industrial operations in which heat transfer is involved are carried out under steady-state conditions. However, unsteady-state conditions are encountered in batch processes, cooling and heating of materials such as metals or glass, and certain types of regeneration, curing, or activation processes.

1. **Conductive Heat Transfer:** The transfer of heat through a fixed material is accomplished by the mechanism known as ***conduction.*** The rate of heat flow by conduction is proportional to the area available for the heat transfer and the temperature gradient in the direction of the heat-flow path.

2. **Convective Heat Transfer:** Transfer of heat by physical mixing of the hot and cold portions of a fluid is known as heat transfer by ***convection.*** The mixing can occur as a result of density differences alone, as in ***natural convection,*** or as a result of mechanically induced agitation, as in ***forced convection.***

3. **Radiative Heat Transfer:** When radiant heat energy is transferred from a source to a receiver, the method of heat transfer is designated as ***radiation.*** The rate at which radiant heat energy is

emitted from a source is. Part of the radiant energy intercepted by a receiver is absorbed, and part may be reflected. In addition, the receiver, as well as the source, can emit radiant energy. The engineer is usually interested in the net rate of heat interchange between two bodies. Some of the radiated energy may be returned to the source by reflection from the receiver, and the receiver, of course, emits radiant energy which can be partly or completely absorbed by the source.

SHELL AND TUBE HEAT EXCHANGERS

A *heat exchanger* is defined as any device that transfers heat from one fluid to another or from or to a fluid and the environment. Shell-and-tube heat exchangers are fabricated with round tubes mounted in cylindrical shells with their axes coaxial with the shell axis. The differences between the many variations of this basic type of heat exchanger lie mainly in their construction features and the provisions made for handling differential thermal expansion between tubes and shell.

A widely accepted standard is published by the Tubular Exchanger Manufacturers' Association (TEMA). This standard is intended to supplement the ASME as well as other boiler and pressure vessel codes. TEMA provides a standard designation system, six examples of the shell-and-tube heat exchanger arrangements are shown in Figure 2.9.

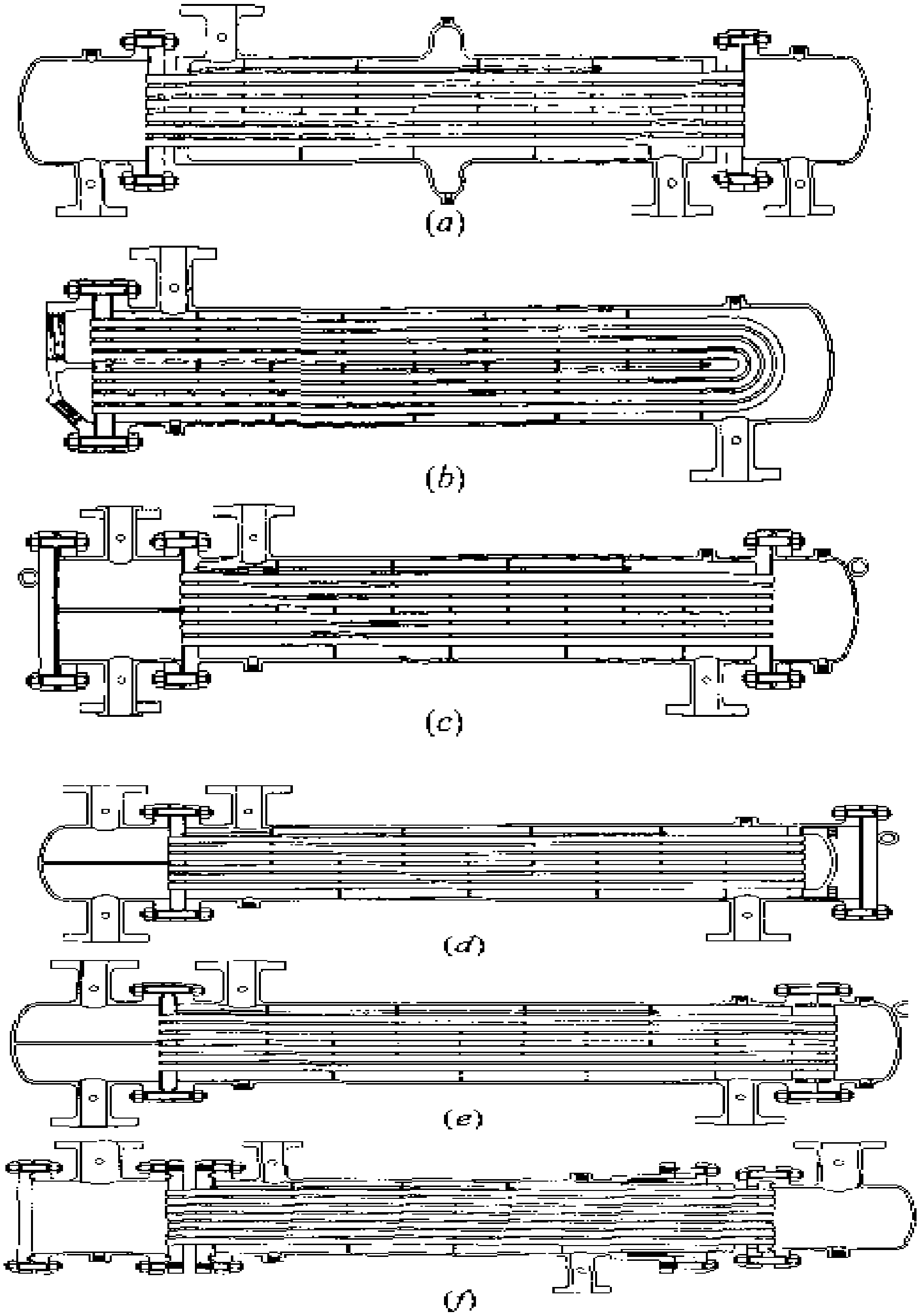


Figure 2.9: *Shell and tube heat exchanger arrangements (Adrian B and Allan K, 2003)*
Illustrations for the above heat exchanger diagrams include:

a) Single-tube-pass baffled single-pass-shell shell-and-tube heat exchanger designed to give essentially counter-flow conditions. The toroidal expansion joint in the center of the shell accommodates differential thermal expansion between the tubes and the shell.
(b) U-tube single-pass-shell shell-and-tube heat exchanger.

(c) Two-pass baffled single-pass shell shell-and-tube heat exchanger.
(d) Heat exchanger similar to that of (c) except for the floating head used to accommodate differential thermal expansion between the tubes and the shell.

(e) Heat exchanger that is similar to the heat exchanger in (d) but with a different type of floating head. Here, leakage from one fluid stream into the other through the packed joints of the floating head goes directly to the exterior of the shell, where it can be detected readily and without contamination of the other stream. This is the heat exchanger type presently used at the crude distillation unit of the Port Harcourt, and it forms the network which is the basis of this study.

(f) Single-tube-pass baffled single-pass-shell shell-and-tube heat exchanger with a packed joint floating head and double header sheets to assure that no fluid leaks from one fluid circuit into the other.

FOULING IN HEAT EXCHANGERS

As contained in (Adrian B. and Allan K., 2003), fouling mechanism in heat exchangers can be categorized into six.

1. *Particulate fouling:* The accumulation of solid particles is suspended in the process stream on the heat transfer surfaces. Typical examples include dust deposition, particles carried in condenser cooling water, and unburned fuel, or fly-ash. If the solid deposition is due to gravity, the process is referred to as sedimentation fouling.
2. *Precipitation fouling:* Dissolved substances carried in the process stream are precipitated on the heat transfer surfaces. Examples include sulfates and carbonates. *Scaling* occurs when precipitation occurs on heated rather than cooled surfaces.
3. *Chemical reaction fouling:* In certain cases, deposits on the heat transfer surfaces which are not, in themselves, reactants are formed by chemical reactions. In this type of fouling, cracking and coking of hydrocarbons and polymerization are typical examples.
4. *Corrosion fouling:* In this type of fouling, the heat transfer surface reacts, at certain pH levels, to produce products that adhere to the heat transfer surfaces, and in turn, this may promote the attachment of additional fouling materials. Sulfur in fuel oil and sulfur products in the flue gas, such as sulfur dioxide, can lead to sulfuric acid. This has caused, for example, significant damage to heat exchange surfaces in air heaters in the power industry.
5. *Biological fouling:* Materials such as algae, bacteria, molds, seaweed, and barnacles carried in the process stream cause biological fouling of the heat transfer surfaces. A prime example of biological fouling is in marine power plant condensers.
6. *Freezing fouling:* In this type of fouling, a liquid, or some of its higher-melting point components will deposit on a sub-cooled heat transfer surface.

SOFTWARE USE AND EVALUATION

An achievement in pinch technology crucially comes from the advancement in computer software. One essential element is process simulation software, the outputs from which can be used to check sensor-based data such as flow rates, pressures, temperatures, and concentrations. This research work will use Aspen Engineering Suite (AES). Aspen-tech was found in 1981 to commercialize technology developed by the Advanced System for Process Engineering (ASPEN) project at the Massachusetts institute of technology. Aspen tech went to public in October 1994 and has acquired

19 industries-leading companies as part of its mission to offer a complete integrated solution to the process industries. Aspen pinch is a process synthesis and design tool for energy integration. Aspen pinch is a unique powerful tool for designing minimum-cost processes for chemical plants and refineries. With aspen pinch, you can achieve cost savings by reducing energy and equipments requirements while still meeting process objectives.

Aspen pinch is used to retrofit existing plants as well as to develop new designs. Aspen pinch can retrieve the results from an aspen plus simulation model for consistent handling of stream data, physical properties and unit operation models. For retrofits, aspen pinch uses the targets to determine energy saving or increased, throughout (de-bottlenecks) possible for a given capital investments or payback requirements. For new designs, aspen pinch optimizes the energy and capital target to determine minimum total cost designers.

RESEARCH METHODOLOGY

OVERVIEW OF MATERIALS USED

An overview of the materials used for this project work, including their specific applications here, are discussed below:

I. Process Flow Diagram (PFD) of the Crude Distillation Unit (Area 1) of the New Port Harcourt refinery situated at Alesa-Eleme, Nigeria.

II. Aspen Pinch 11.1 process tool was used to carry out a detailed and sufficiently accurate pinch analysis of the three heat exchanger networks. To do this, the thermal data obtained after data extraction were fed as input to the software to construct the composite curves and grid diagram of all networks. Analyses of the representation were actually manual.

STEPS OF PINCH ANALYSIS

In order to retrofit the heat exchanger networks in the Crude Distillation Column of the new Port Harcourt refinery, the pinch design method and its rules must be followed carefully and duly obeyed. The steps followed are shown in figure 3.1.

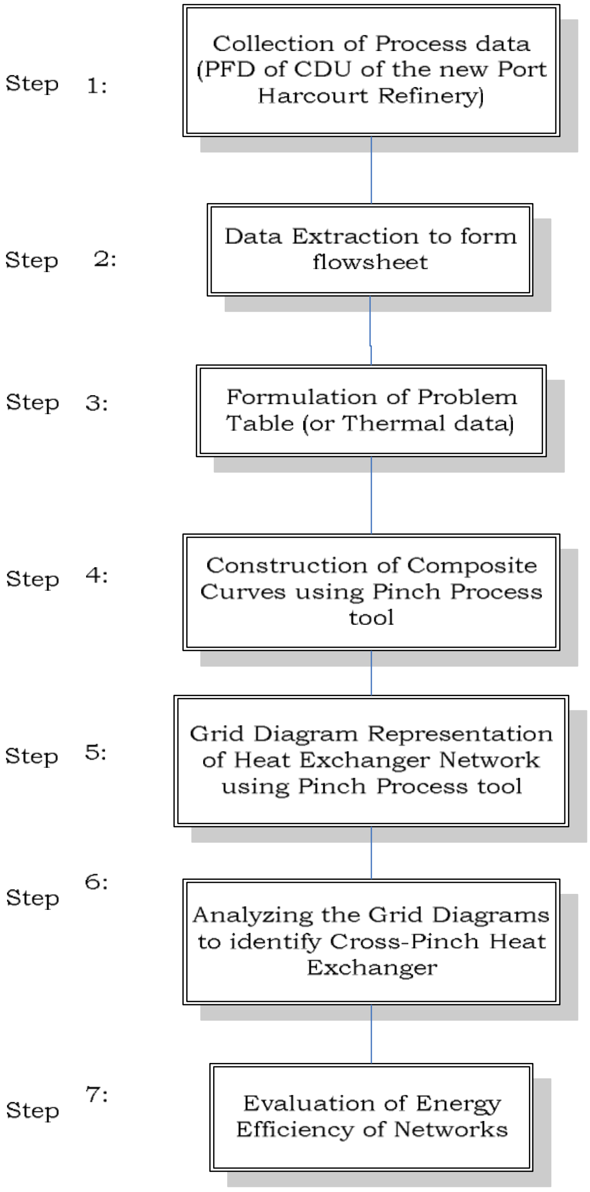


Figure 3.1: *Flowchart for the Pinch Analysis*

DATA EXTRACTION

Data extraction relates to the extraction of information required for Pinch Analysis from a given process heat and material balance. Pinch Analysis principles will be applied to identify the energy saving potential (or target) for the process and subsequently to aid the retrofitting of the heat exchanger network to achieve that targeted saving.1 In order to start the Pinch Analysis the necessary thermal data must be extracted from the process. This involves the identification of process heating and cooling duties. This is called the data extraction flow-sheet representation. The assumption in the data extraction flow- sheet is that any process cooling duty is available to match against any heating duty in the process.

The required data involves process stream heating and cooling information, utility system information, and certain background information regarding the process (crude preheating and distillation) and the site (crude distillation unit). The thermal data, which involves the stream heating and cooling information and utilities information, is the most critical data required for pinch analysis. There are several possibilities for extracting the thermal data from a given heat and material balance. This was done carefully, as poor data extraction can easily lead to missed opportunities for improved process design, the following rules were strictly followed.

Rule 1: Do not mix streams at different temperatures
Rule 2: Extract thermal data only at effective temperatures
Rule 3: Do not extract true utility streams
Rule 4: Carefully identify soft data

OPERATING DATA OF THE HEAT EXCHANGER NETWORKS UNDER STUDY

Following a principled data extraction, a flow sheet was obtained from the process flow diagram. This flow-sheet form the basis of all our analysis (both pinch and transient), and it contains a summarized 23 heat exchangers with 79 nodes, shared amongst three networks, as outlined below:

1. 7 heat exchangers in the HEN – 1, with 25 nodes
2. 12 heat exchangers in the HEN – 2, with 36 nodes
3. 4 heat exchangers in the HEN – 3, with 18 nodes

The specifications and parameters of all the heat exchangers are contained in table 3.1 to table 3.3 below.

Table 3.1: *Details of Heat Exchangers for HEN - 1*

Heat Exchanger Block Label	Heat Duty (MMkCal/hr)	Heat Duty (KW)	Heat Exchanger Name	Total Weight Empty (kg)	Surface Area (m^2)
10 E 01 A-C	14.30	16630.61	Top PA/Crude X	17600	380.6
10 E 01 D-F	14.30	16630.61	Top PA/Crude X	17600	416.5
10 E 02	3.56	4140.21	Cold Kerosene/Crude X	18100	416.5
10 E 03 AB	10.09	11734.47	Cold LDO/Crude X	18200	416.5
10 E 04	4.06	4721.70	HDO/Crude X	17900	416.5
10 E 05 A	0.93	1081.57	Cold Residue/Crude X	17700	416.5
10 E 05 B	1.17	1360.69	Cold Residue/Crude X	17700	416.5

Table 3.2: *Details of Heat Exchangers for HEN - 2*

Heat Exchanger Block Label	Heat Duty (MMkCal/hr)	Heat Duty (KW)	Heat Exchanger Name	Total Weight Empty (kg)	Surface Area (m^2)
10 E 06 A	2.97	3454.05	Warm R/Crude X	17700	416.5
10 E 06 B	2.97	3454.05	Warm R/Crude X	17700	416.5
10 E 07AB	4.10	4768.22	Cold Kerosene PA/Crude X	17600	380.6
10 E 07 CD	4.10	4768.22	Cold Kerosene PA/Crude X	17600	416.5
10 E 08 A	2.42	2814.41	Hot Kerosene/Crude X	17600	416.5
10 E 08 B	2.42	2814.41	Hot Kerosene/Crude X	17600	416.5
10 E 09 AB	5.30	6163.80	Hot Kerosene PA/Crude X	17600	380.6
10 E 09 CD	5.30	6163.80	Hot Kerosene PA/Crude X	17600	380.6
10 E 10 A	3.34	3884.35	Hot LDO/Crude X	17800	416.5
10 E 10 A	3.34	3884.35	Hot LDO/Crude X	17800	416.5
10 E 11 AB	2.11	2453.89	Mild R/Crude X	17900	416.5
10 E 11 CD	2.11	2453.89	Mild R/Crude X	17900	416.5

Table 3.3: *Details of Heat Exchangers for HEN - 3*

Heat Exchanger Block Label	Heat Duty (MMkCal/hr)	Heat Duty (KW)	Heat Exchanger Name	Total Weight Empty (kg)	Surface Area (m^2)
10 E 13 A	2.50	2907.45	HVGO/Crude X	14500	337.4
10 E 13 B	2.50	2907.45	HVGO/Crude X	14500	337.4
10 E 12 AB	6.00	6977.88	LDO PA/Crude X	14500	337.4
10 E 12 CD	6.00	6977.88	LDO PA/Crude X	14500	337.4
10 H 01	80.00	93038.40	Crude Charge Heater	14500	337.4

Meanwhile, the operative data is a process flow diagram (PFD) obtained from the new Port Harcourt Refinery. It was designed by JCC Corporation approved by the Nigerian National Petroleum Corporation (N.N.P.C.) in 1985 for the construction of 150,000 BPD production- capacity Crude Distillation Unit (C.D.U.) in the Port Harcourt Refinery project. The services (or equipment) contained in the PFD include: columns (crude column, stripper), drums (desalter, receivers), exchangers (condensers and heat exchangers), 0heater, pumps and compressor. It also contains the controllers (level, pressure, temperature, and flow rate).

CONFIGURATIONS OF THE HEAT EXCHANGERS AND STREAMS

As part of the steps toward achieving an optimal heat exchanger network via pinch technology, the entire PFD was sectioned or splitted into HEN-1, HEN-2 and HEN-3. The figurative orientations and configurations of the three networks are individually shown below. Each diagram contains the hot stream, cold stream, and the temperatures at which they enter and leave the heat exchangers; and also the heat exchangers and heat duties. The heat exchangers configurations for the **Heat Exchanger Network- 1** are shown below.

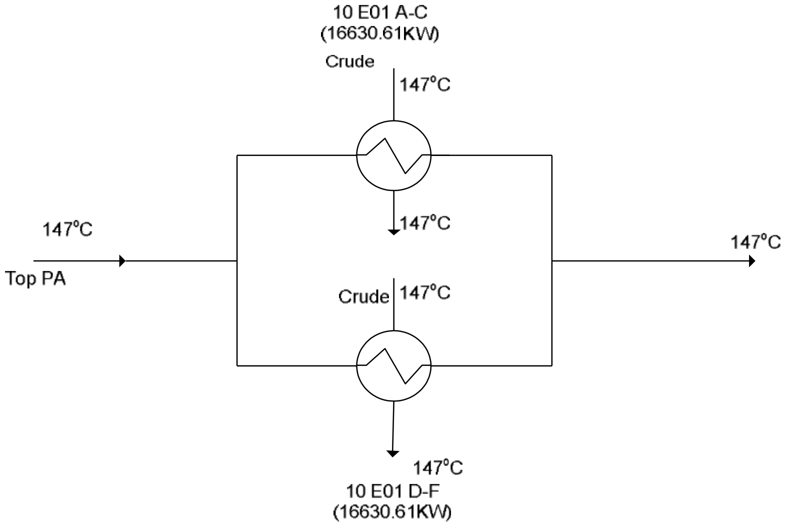


Figure 3.2: *Heat exchanger configuration for Top PA/Crude streams*

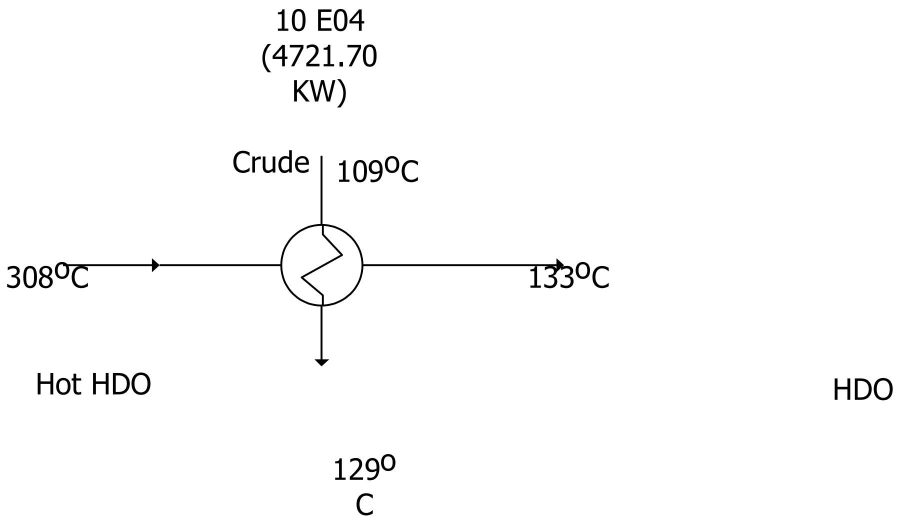


Figure 3.3: *Heat exchanger configuration for Hot HDO/Crude streams*

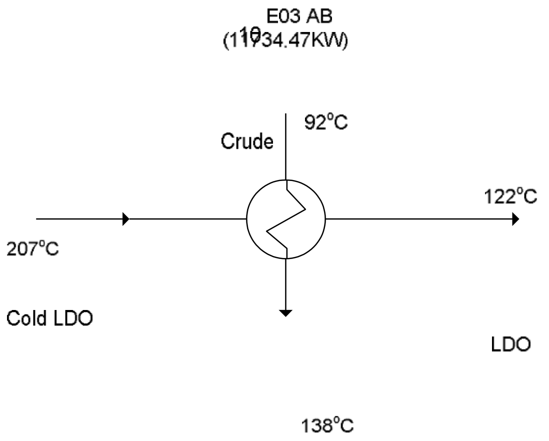


Figure 3.4: *Heat exchanger configuration for Cold LDO/Crude streams*

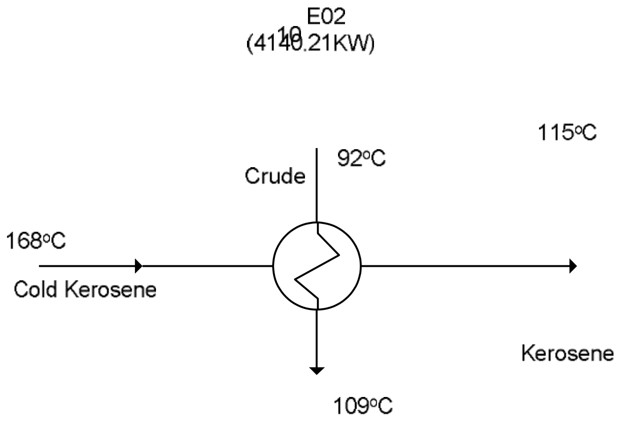


Figure 3.5: *Heat exchanger configuration for Cold Kerosene/Crude streams*

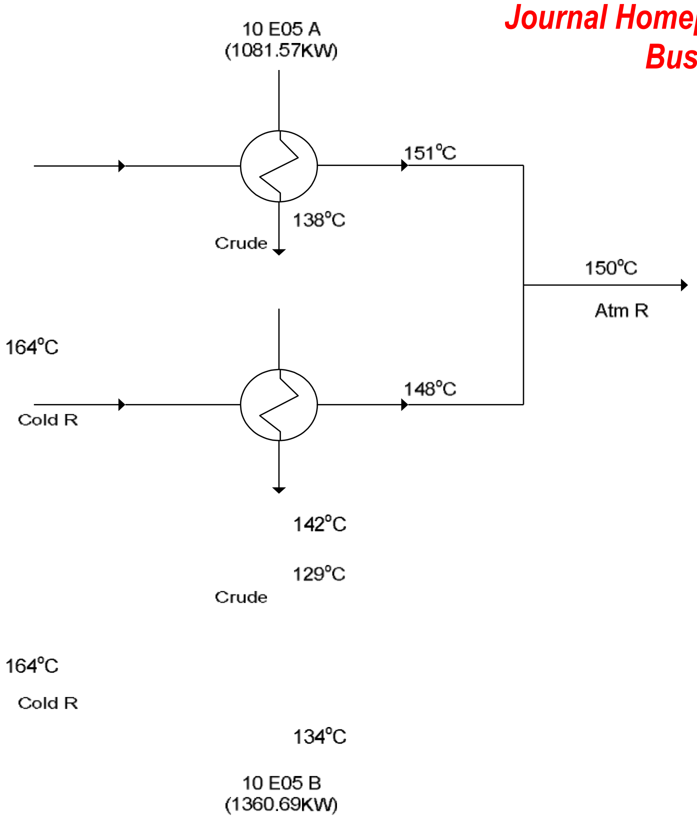


Figure 3.6: *Heat exchanger configuration for Cold R/Crude streams*

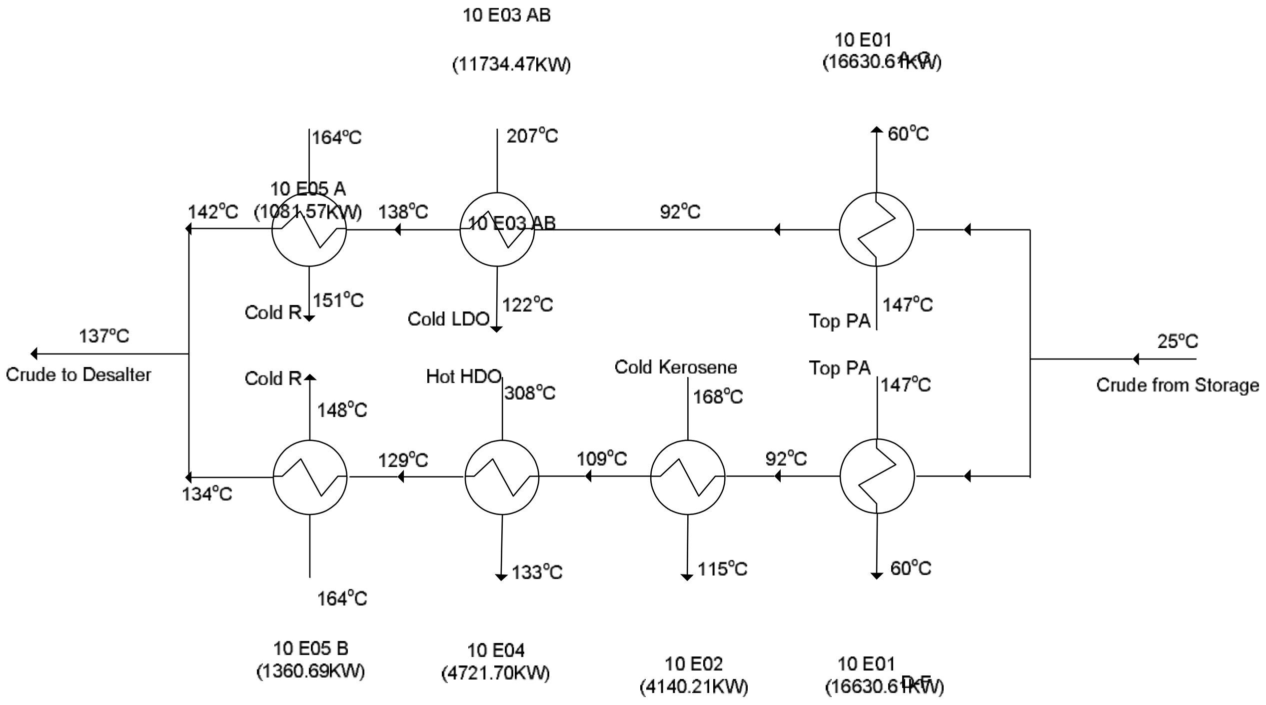


Figure 3.7: *Heat exchangers configuration showing all streams in HEN-1*

The second sets of representations are the heat exchangers configurations for the **Heat Exchanger Network- 2**, they are as illustrated below.

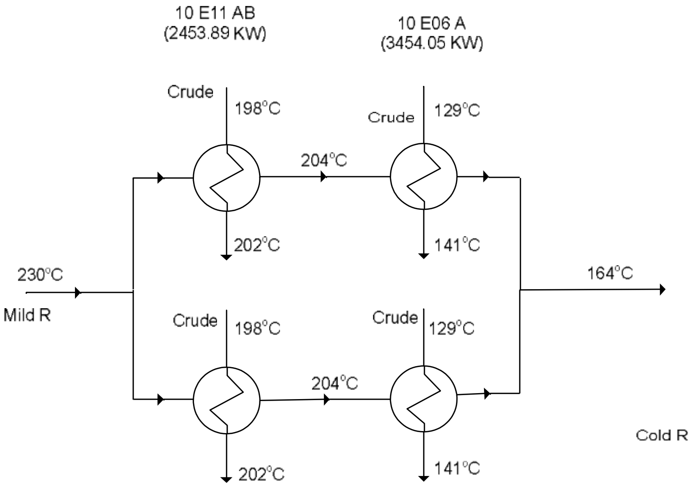


Figure 3.8: *Heat exchangers configuration for Mild R/Crude streams*

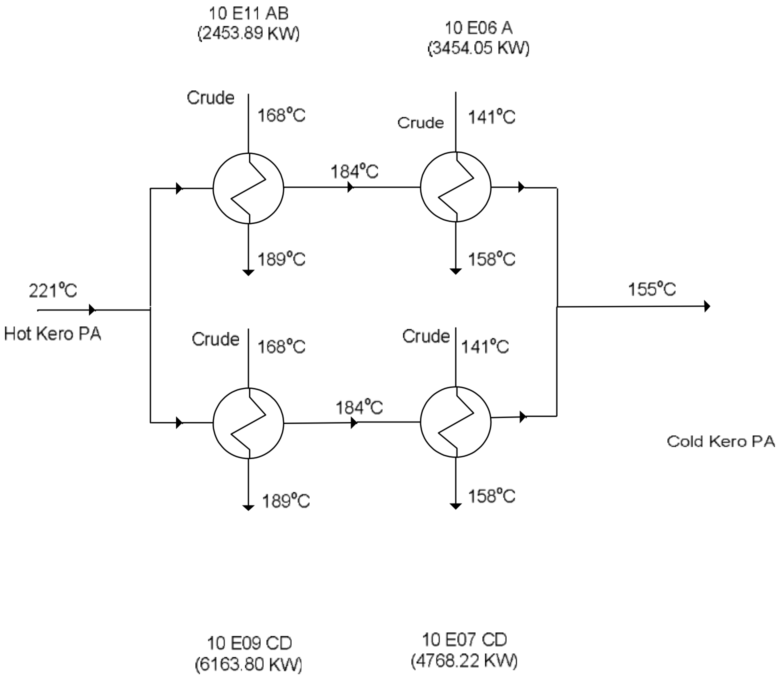


Figure 3.9: *Heat exchangers configuration for Hot Kero PA/Crude streams*

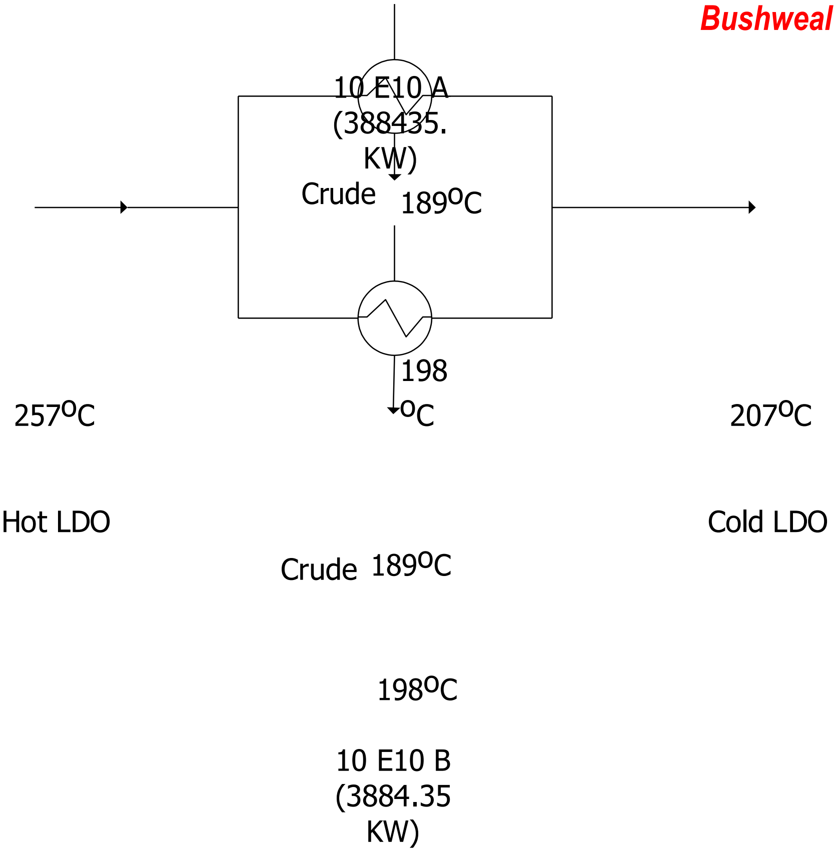


Figure 3.10: *Heat exchangers configuration for Hot LDO/Crude streams*

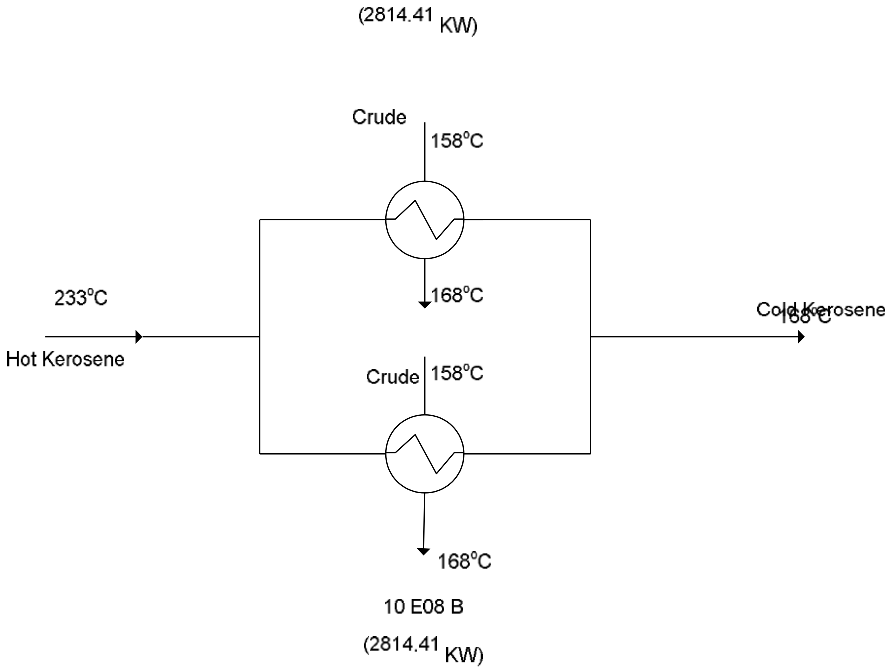


Figure 3.11: *Heat exchangers configuration for Hot Kerosene/Crude streams*

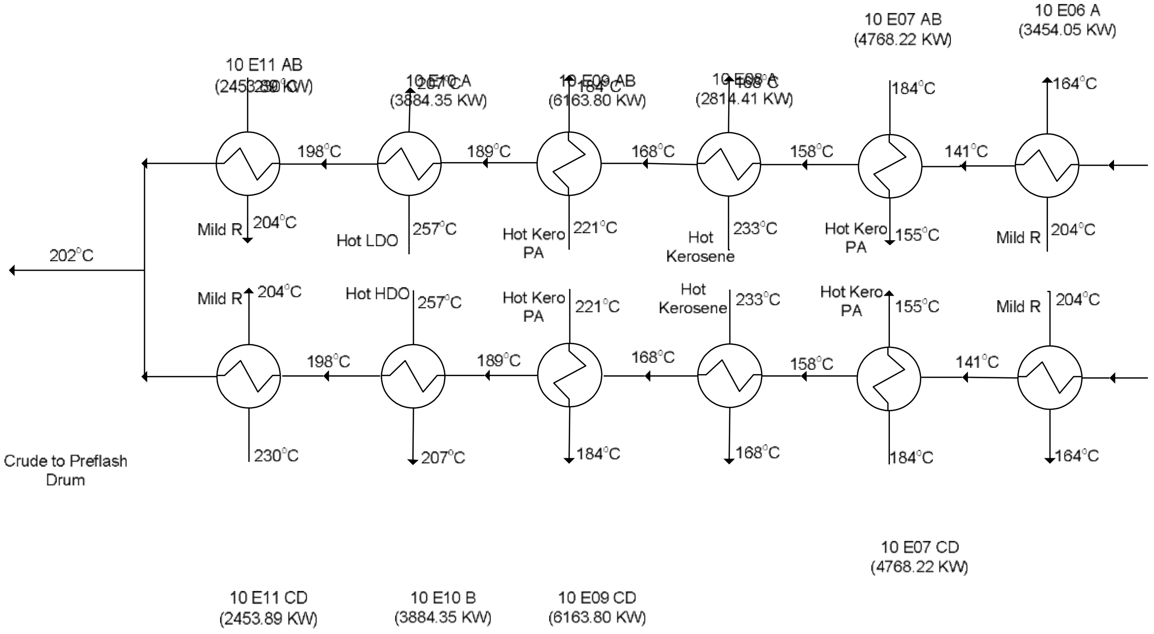
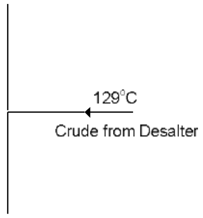


Figure 3.12: *Heat exchangers configuration showing all streams in HEN-2*

The third sets of representations are the heat exchangers configurations for the **Heat**



Exchanger Network- 3, they are as illustrated below.

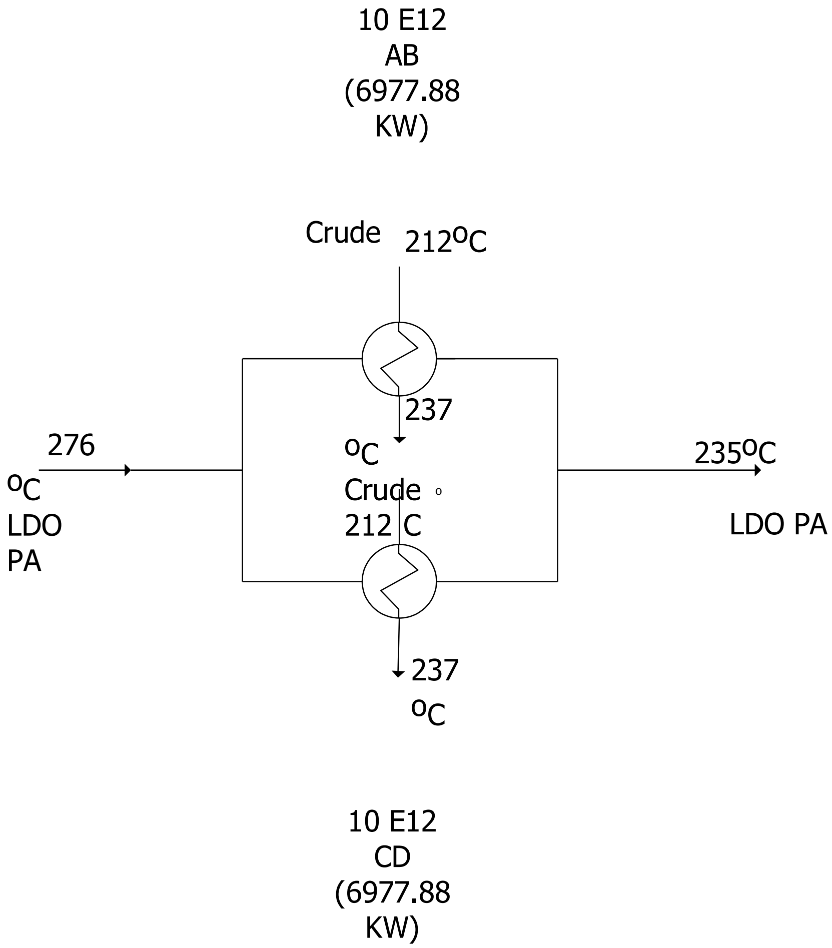


Figure 3.13: *Heat exchangers configuration for LDO PA/Crude streams*

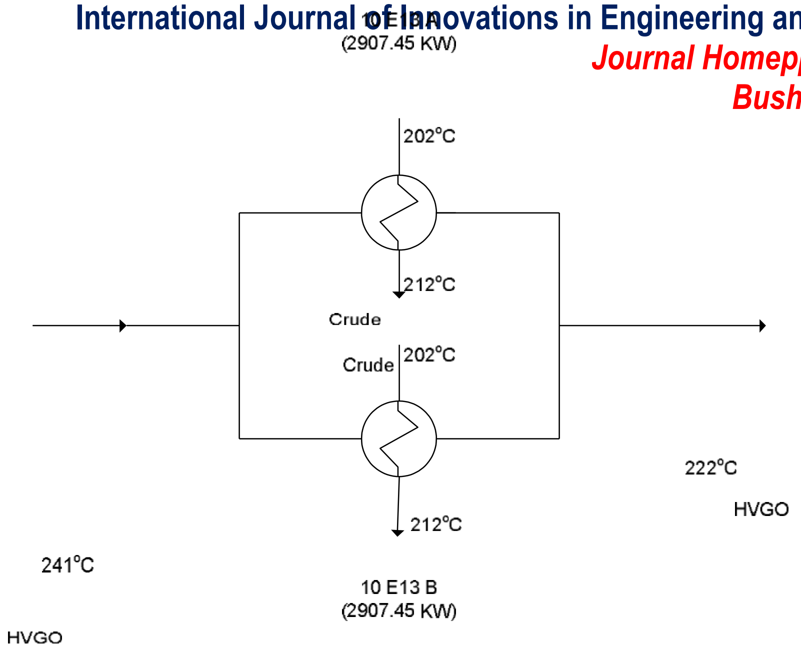


Figure 3.14: *Heat exchangers configuration for HVGO/Crude streams*

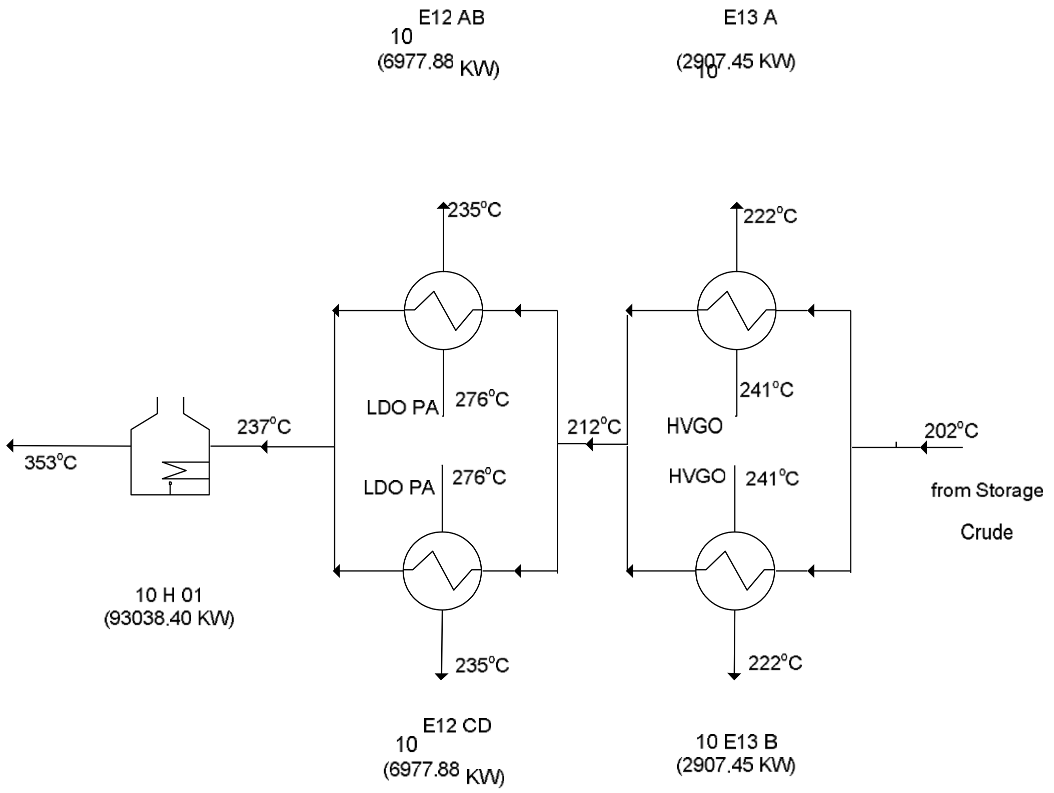


Figure 3.15: *Heat exchangers configuration showing all streams in HEN-3*

FORMULATION OF THE PROBLEM TABLE (THERMAL DATA)

The assembly of the process stream and equipment (heat exchangers and utilities) parameters from the data extraction flow-sheet produces the problem table (PT), otherwise known as thermal data. The data required to form this problem table include:

- Stream supply
- Target temperature
- Heat capacity flow rate (CPF)
- Minimum temperature of approach (▪T_{min}) or optimum ▪T_{min} value
- Heat exchanger duties or heat loss.

Below is an illustration of the problem table formulation using one of the networks as an instance.

Table 3.4: *Problem table for HEN – 1(Crude from Storage through heat exchangers to Desalter)*

Streams	Start (or supply) temperature	Target temperature	Mass flow rate (kg/s)	Specific heat capacity (kJ/kg^{O}C)	Heat capacity flow rate (kW/^{O}C)	Heat duty (kW)
Top Pump Around (PA)	147	60	157.7365	2.7683	436.6619	33261.22
Hot HDO	308	133	10.8972	3.0375	33.1002	4721.70
Cold LDO	207	122	56.0000	2.7637	154.7672	11734.47
Cold kerosene	168	115	32.2333	2.7206	87.6939	4140.21
Cold Residue	164	150	72.4416	2.3722	171.8459	2442.26
Crude from Storage	25	137	232.2889	2.1022	488.3177	56299.86

The stream supply is the initial temperature with which the stream enters a heat exchanger or utility. The target temperature is the final temperature of the stream as it leaves the heat exchanger or utility. Both the stream supply and target temperatures are obtained from the process flow diagram of the crude distillation unit of the new Port Harcourt Refinery. The minimum temperature of approach (▪T_{min}) will be obtained from either the rigorous method or simple method. Heat capacity flow rate is defined as specific heat capacity times mass flow rate. The heat load or heat duty of the heat exchanger can be obtained as follows:

$$\mathbf{Q = (Cp \times F) \times \cdot T = (CPF) \times \cdot T} \quad - \quad - \quad - \quad - \quad 3.1$$

Where CPF = heat capacity flow rate given as **Cp x F** (kW/^{O}C) Cp = specific heat capacity of the stream (kJ/kg. ^{O}C)

F = mass flow rate of the stream (kg/s)

▪T = temperature difference (^{O}C) Q = Heat exchanger duty (KW)

The data using here is based on the assumption that the heat capacity flow rate is constant. In practice, this assumption is valid because every streams with or without phase change can easily be described in terms of linearized temperature-enthalpy data (i.e. CPF is constant).

DETERMINATION OF OPTIMAL $\cdot T_{min}$

The optimum value of $\cdot T_{min}$ could be obtained by either the rigorous method or the simple method. The rigorous method uses plots of capital cost, energy cost and total cost versus $\cdot T_{min}$ to locate optimal $\cdot T_{min}$. The Simple method uses the experience value of $\cdot T_{min}$, estimated from the plot of heat exchanger area versus $\cdot T_{min}$ to locate optimal $\cdot T_{min}$. Literatures also showcase various experienced $\cdot T_{min}$ values. A table of typical $\cdot T_{min}$ values for several types of processes is presented below.

Table 3.5*: Typical $\cdot T_{min}$ values for various types of processes (Linnhoff March, 1998)*

No.	Industrial Sector	Experience $\cdot T_{min}$ values
1	Oil Refining	20 to 40^{O}C
2	Petrochemical	10 to 20^{O}C
3	Chemical	10 to 20^{O}C
4	Low temperature processes	3 to 5^{O}C

Following a choice of 20 to 40^{O}C as experience $\cdot T_{min}$ value, a setback on the unit (specifically the refining unit) would be "fouling of heat exchangers. It is therefore vital to put into consideration the evaluation and manipulation of fouling in the heat exchangers. More so, different refining units (or processes) require different $\cdot T_{min}$ values for retrofitting. Example, the Vacuum Distillation Unit (VDU) and Fluid Catalytic Cracking Unit (FCCU) require 20 to 30^{O}C and 30 to 40^{O}C respectively as $\cdot T_{min}$. For this project work, the experienced $\cdot T_{min}$ values and simple method are useful.

HEAT EXCHANGER NETWORK ANALYSIS

PINCH ANALYSIS OF HEAT EXCHANGER NETWORKS

In this aspect of the analysis, the following pinch rules were employed in order to achieve the minimum energy targets for the crude preheating process.

- Heat must not be transferred across the pinch
- There must be no external cooling above the pinch
- There must be no external heating below the pinch

Violating any of these rules will lead to cross-pinch heat transfer resulting in an increase in the energy requirement beyond the target. The design procedure for heat exchanger networks should therefore ensure that there is no cross pinch heat transfer. The pinch design method states that there must be no heat transfer across the pinch, heaters must be placed above the pinch and coolers, below the pinch. Any heat transfer across the pinch is excess heat which is wasted, and expressed as pinch penalty.

CONSTRUCTION OF COMPOSITE CURVES

Energy targets are calculated using a tool known as the "composite curves". The curves, as shown in figure 4.1, consist of temperature-enthalpy (T-H) profiles of heat availability in the process (the hot composite curve) and heat demands in the process (the cold composite curve) together in a graphical representation.
The requirements for construction of the composite curves include:

- Start temperature or Stream supply
- Target temperature
- Heat capacity flow rate (CPF)

CP = Cp x F - - - - 4.1

Where CP = heat capacity flow rate (kW/^{O}C)

Cp = specific heat capacity of the stream (kJ/ kg ^{O}C) F = mass flow rate of the stream (kg/s)

- Enthalpy change (▪H or Q)

▪H = CP x ▪T - - - - - - 4,2

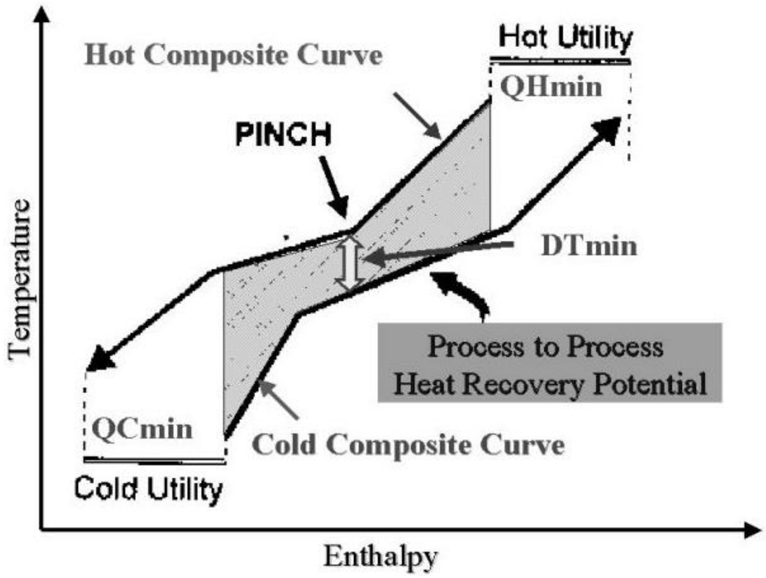


Fig 4.1: *The complete Composite curve (hot and cold)*

The steps involved in construction of the composite curves as follows:

1. Formulation of Problem Table (Thermal data)
2. Computation of enthalpy change (▪H or Q)

3. Construction of Hot Composite Curve, which involves:
   a. T-H profile construction
   b. Composite curve construction
4. Construction of Cold Composite Curve, which involves:
   a. T-H profile construction
   b. Composite curve construction
5. Overlapping the Hot and Cold composite curves above, thereby forming a single composite curve.

At the end of these tasks, we will obtain a diagram of the form of figure 4.1 above.

REPRESENTATING THE HEAT EXCHANGER NETWORK ON A GRID DIAGRAM

The figure below shows the Grid Diagram representation of a heat exchanger network.

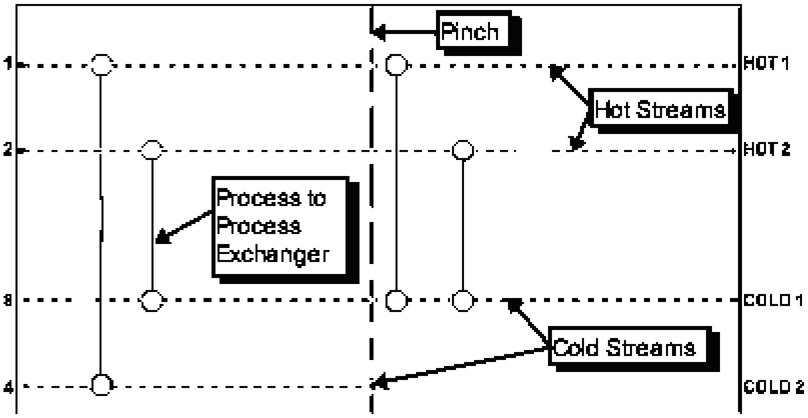


Figure 4.2: *The Grid diagram for representation of the heat exchanger network*

As illustrated in figure 4.2, cold streams run across the bottom, from right to left. The hot streams are shown at the top of the figure, running from left to right. A heat exchanger transferring heat between the process streams is shown by a vertical line joining circles on the two matched streams. The pinch principle, discussed above, explains how the process must be separated into two regions, above and below the pinch, for network design in order to achieve the energy targets. The understanding of the pinch location is therefore very important for network design. In the grid diagram the process pinch location is shown by a dashed vertical line cutting the process into two parts. The pinch hot and cold temperatures as determined from the composite curves are shown on the grid diagram.

The difference between the hot and cold pinch temperatures equals ΔT_{min} as seen on the composite curves. The process below the pinch (heat source) is shown on the right whilst the process above the pinch (heat sink) is shown on the left. From this it can be seen that the horizontal axis implies a temperature decrease from left to right. However, it is important to note that this is not a gradual scale. Instead, the grid diagram just shows significant temperature locations, such as whether a stream starts above or below a pinch. Applying the three rules of the pinch principle therefore means that there must be no heater on the right hand section of the grid diagram, no cooler on the left hand section and no process heat exchangers between the hot streams on the left hand section and the cold streams on the right hand section. This will ensure that the network will always achieve the energy target.

EVALUATION OF ENERGY EFFICIENCY

The energy efficiency is evaluated using the following equation:

$$\text{Energy Efficiency} \;\cdot\; \frac{\text{Minimum Energy required network, } (QH, \min)}{\text{Energy consumed by network, } (QH, op)} \cdot 100\% \qquad - \qquad - \qquad 4.3$$

The minimum energy requirement by network is estimated from the composite curve of the overall HEN as the minimum hot utility. The energy consumed by the network could vary depending on circumstances. It could be any of the following.

(i) The operating heat load obtained from plant measurements. (ii)
Simulated heat load obtained from plant simulation
(iii) Process design heat load obtained from original process design specifications
(iv) Retrofit heat load obtained from plant retrofitting.

DATA REPRESENTATION, CALCULATION AND DISCUSSION OF RESULTS

RESULTS OF PINCH ANALYSIS

Aspen Pinch 11.1 process tool was used to carry out a detailed and sufficiently accurate pinch analysis of the three heat exchanger networks. To do this, the thermal data obtained after data extraction were fed as input to the software to construct the composite curves and grid diagrams of all the networks. Thereafter, the analyses and further discussion of the obtained representations were done manually, and are shown below. The analysis took a total of 141,039 CPU seconds on 3.2GHz, 1024MB RAM Intel ® Core ™ 2 CPU T5200 laptop.

Since a choice of 20 to 40^{O}C as experience ▪T_{min} value for the oil refining industrial sector has been established, the analysis is done at varying ▪T_{min} values.

REPRESENTATION OF RESULTS OF DATA EXTRACTION

Following a careful data extraction based on principles, a flow sheet was obtained from the process flow diagram. This flow-sheet forms the basis of all our analysis (both pinch and transient), and it contains a summarized 23 heat exchangers shared amongst three networks, as outlined below:

4. 7 heat exchangers in the HEN – 1 with 25 nodes (Appendix A- figure A.1)
5. 12 heat exchangers in the HEN – 2 with 36 nodes (Appendix A, figure A.2)
6. 4 heat exchangers in the HEN – 3 with 18 nodes (Appendix A, figure A.3)

The specifications and parameters of all the heat exchangers are contained in table 5.1 to table 5.3 below.

Table 5.1: *Data Extraction Result for HEN - 1*

Heat Exchanger Block Label	Heat Exchanger Name	Heat Duty (MMkCal/hr)	Heat Duty (KW)
10 E 01 A-C	Top PA/Crude X	14.30	16630.61
10 E 01 D-F	Top PA/Crude X	14.30	16630.61
10 E 02	Cold Kerosene/Crude X	3.56	4140.21
10 E 03 AB	Cold LDO/Crude X	10.09	11734.47
10 E 04	HDO/Crude X	4.06	4721.70
10 E 05 A	Cold Residue/Crude X	0.93	1081.57
10 E 05 B	Cold Residue/Crude X	1.17	1360.69

Heat Exchanger Block Label	Heat Exchanger Name	Heat Duty (MMkCal/hr)	Heat Duty (KW)
10 E 06 A	Warm R/Crude X	2.97	3454.05
10 E 06 B	Warm R/Crude X	2.97	3454.05
10 E 07AB	Cold Kerosene PA/Crude X	4.10	4768.22
10 E 07 CD	Cold Kerosene PA/Crude X	4.10	4768.22
10 E 08 A	Hot Kerosene/Crude X	2.42	2814.41
10 E 08 B	Hot Kerosene/Crude X	2.42	2814.41
10 E 09 AB	Hot Kerosene PA/Crude X	5.30	6163.80
10 E 09 CD	Hot Kerosene PA/Crude X	5.30	6163.80
10 E 10 A	Hot LDO/Crude X	3.34	3884.35
10 E 10 A	Hot LDO/Crude X	3.34	3884.35
10 E 11 AB	Mild R/Crude X	2.11	2453.89
10 E 11 CD	Mild R/Crude X	2.11	2453.89

Table 5.3: *Data Extraction Result for HEN - 3*

Heat Exchanger Block Label	Heat Exchanger Name	Heat Duty (MMkCal/hr)	Heat Duty (KW)
10 E 13 A	HVGO/Crude X	2.50	2907.45
10 E 13 B	HVGO/Crude X	2.50	2907.45

10 E 12 AB	LDO PA/Crude X	6.00	6977.88
10 E 12 CD	LDO PA/Crude X	6.00	6977.88
10 H 01	Crude Charge Heater	80.00	93038.40

Meanwhile, the results for the data extraction containing the streams are represented as the problem table analysis results.

PROBLEM TABLE ANALYSIS RESULTS

The results for the Problem Table analysis are shown below. Table
5.4: *Problem Table for HEN – 1*

Streams	Start (or supply) temperature	Target temperature	Mass flow rate (kg/s)	Specific heat capacity (kJ/kg^{o}C)	Heat capacity flow rate (kW/^{o}C)	Heat duty (kW)
Top PumpAround (PA)	147	60	157.7365	2.7683	436.6619	33261.22
Hot HDO	308	133	10.8972	3.0375	33.1002	4721.70
Cold LDO	207	122	56.0000	2.7637	154.7672	11734.47
Cold kerosene	168	115	32.2333	2.7206	87.6939	4140.21
Cold Residue	164	150	72.4416	2.3722	171.8459	2442.26
Crude from Storage	25	137	232.2889	2.1022	488.3177	56299.86

Table 5.5: *Problem Table for HEN – 2*

Streams	Start (or supply) temperature	Target temperature	Mass flow rate (kg/s)	Specific heat capacity (kJ/kg^{o}C)	Heat capacity flow rate (kW/^{o}C)	Heat duty (kW)
Mild Residue	230	164	72.4416	2.5158	182.2486	11815.88
Hot Kero PA	221	155	186.9444	2.9203	545.9337	21864.04
Hot LDO	257	207	56.0000	2.8449	159.3114	7768.7

Hot kerosene	233	168	32.2333	2.9869	96.2776	5628.82
Crude from Desalter	129	202	116.1444	2.5215	292.8581	47077.44

Table 5.6: *Problem Table for HEN – 3*

Streams	Start (or supply) temperature	Target temperature	Mass flow rate (kg/s)	Specific heat capacity (kJ/kg^{o}C)	Heat capacity flow rate (kW/^{o}C)	Heat duty (kW)
LDO PA	276	253	120.8333	3.0529	368.8919	13955.76
HVGO	241	222	122.7000	2.6971	330.9342	5814.9
Crude from Pre-flash drum	202	353	212.9277	2.8158	599.5618	112809.06
(Fuel Oil)	353	350	108.6240	3.2362	351.5389	93038.40

Table 5.7: *Problem Table for Overall HEN*

Streams	Start (or supply) temperature	Target temperature	Mass flow rate (kg/s)	Specific heat capacity (kJ/kg^{o}C)	Heat capacity flow rate (kW/^{o}C)	Heat duty (kW)
Top PA	147	60	157.7365	2.7683	436.6620	33261.22
LDO	257	122	56.0000	2.8449	159.3144	19503.17
Atmospheric Residue	230	150	72.4416	2.6092	189.0146	14258.14
Kerosene	233	115	32.2333	2.9869	96.2776	9769.03
HDO	308	133	10.8972	3.0375	33.1002	4721.70
Kero PA	221	155	186.9444	2.9203	545.9337	21864.04
LDO PA	276	235	120.8333	3.0529	368.8920	13955.76
HVGO	241	222	122.7000	2.6971	330.9342	5814.9
(Fuel Oil)	353	350	108.6240	3.2362	351.5389	93038.40

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Crude from	25	137	232.2889	2.1022	488.3177	56299.86
Storage						
Crude from Deslater	129	202	116.1444	2.5215	292.8581	47077.44
Crude from Pre-flash	202	353	212.9277	2.8158	599.5618	112809.06

ANALYSIS OF HEAT EXCHANGER NETWORK-1

Consider the pinch analysis carried out on the network of 7 heat exchangers supplying crude from the storage to the desalter, the composite curves and grid representations are presented below. *Note that the red lines in the composite curves represent the hot composite curves, while the blue lines represent the cold composite curves.*

Note also, that the red lines in the grid diagrams represent the hot streams requiring cooling, while the blue lines represent the cold streams requiring heating.

1. Composite and Grand Composite Curves: The composite curves are analyzed at different ·T_{min} values (Appendix C)

(i) At ·T_{min} = 20^{O}C: It can be seen from the composite curve in figure 5.1 (Appendix C - figure C.1) that no hot utility exists since the minimum heating requirement is zero. Observe that the pinch location exactly cuts across the end points of the hot and cold composite curves. In practice, the HEN-1 of the CDU of Port Harcourt refinery does not require any external heating unit operation like heater. Of interest is the large area enclosed within both curves, indicating a large process-to-process heat recovery potential. Likewise, there is a heat imbalance in this network, meaning that the exchangers are not properly arranged to yield optimal process-to-process heat exchange amongst the streams.

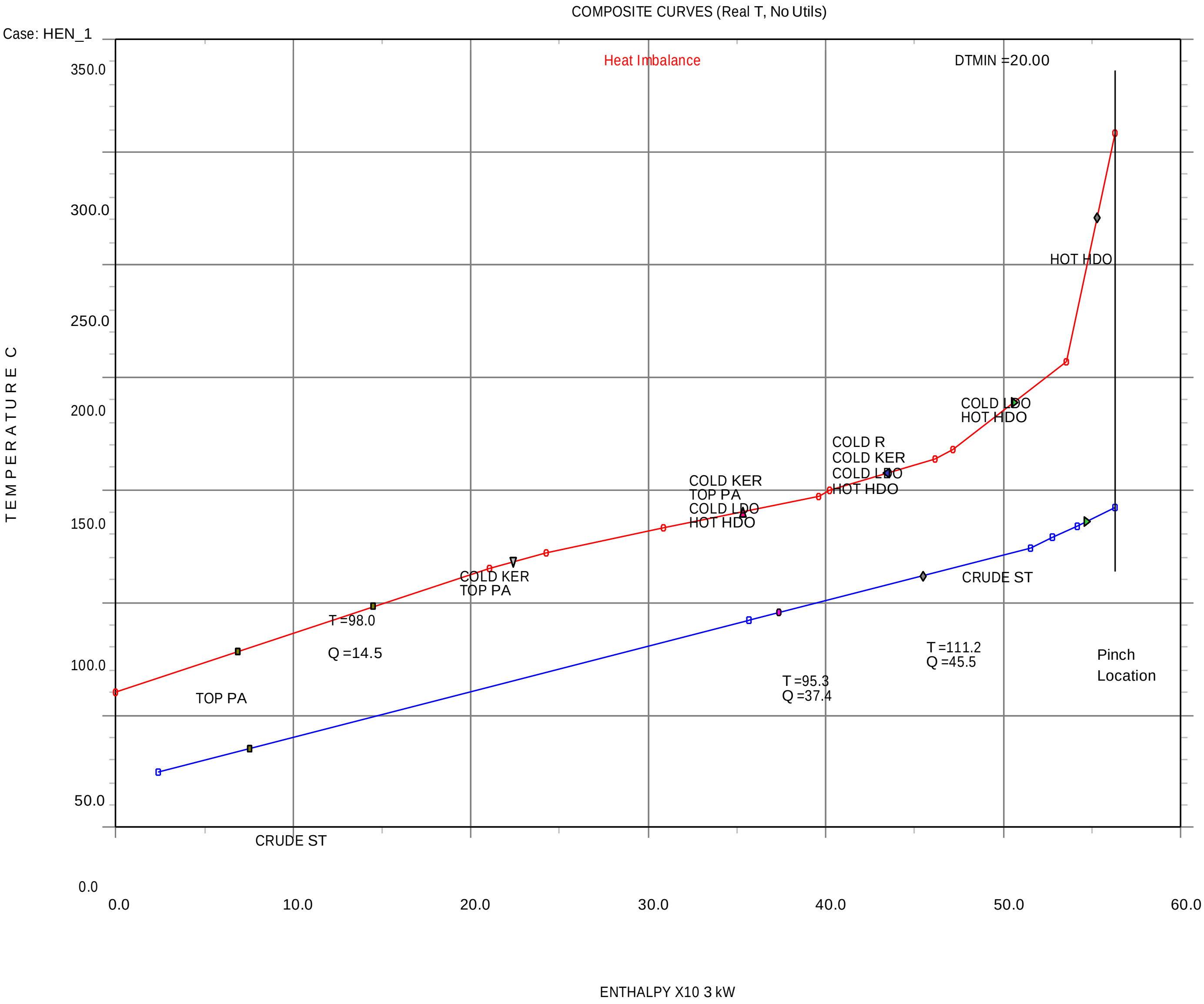


Figure 5.1: *Composite Curve of HEN-1 for $\Delta T_{min} = 20^oC$*

(ii) At ΔT_{min} = 30^oC: Varying the ΔT_{min} by 10^oC does not improve the HEN-1 performance, since there is still heat imbalance, large process-to-process heat recovery potential and no hot utility requirement. (Appendix C – figure C.2)

(iii) At ΔT_{min} = 40^{O}C: Further increasing the ΔT_{min} by another 10^{O}C does not help as the composite curve still shows heat imbalance. (Appendix C – figure C.3)
The Grand Composite Curve shown in figure 5.2 (Appendix C – figure C.4) plotted at ΔT_{min} = 20^{O}C clearly shows the high potential for process-to-process heat exchange in the HEN-1.

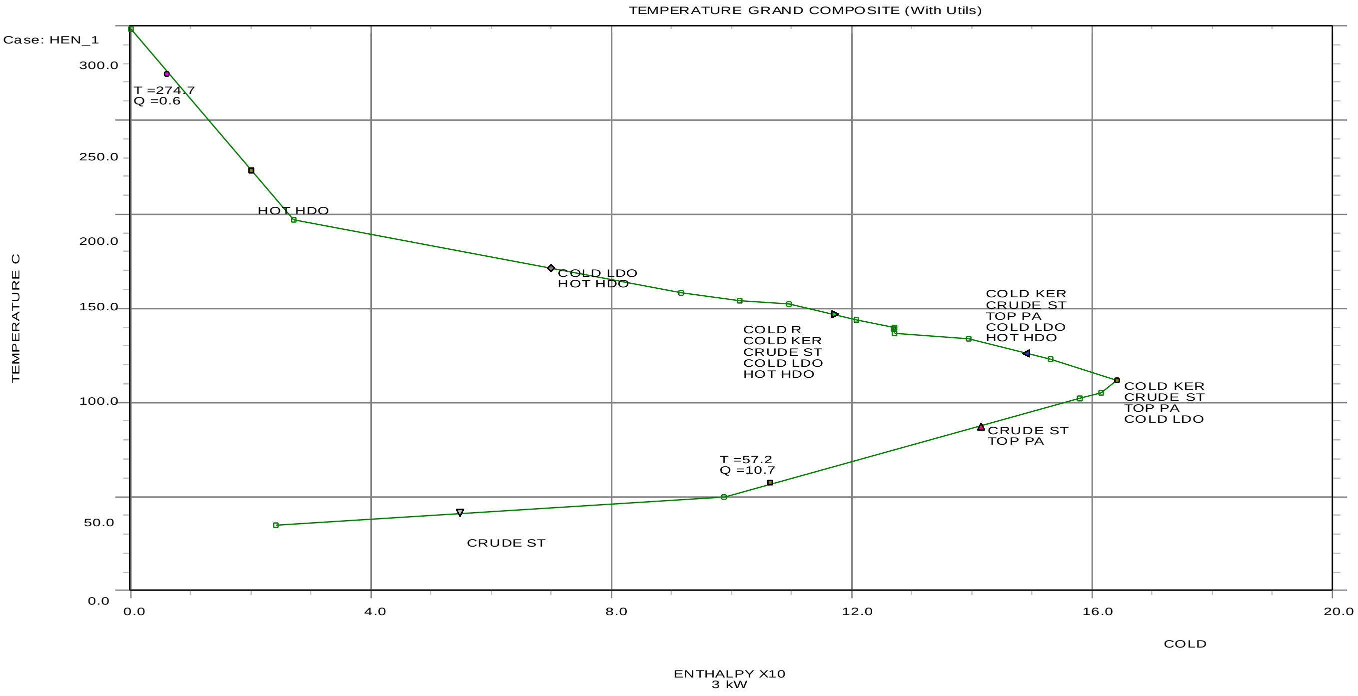


Figure 5.2: *Grand Composite Curve for HEN-1 for ΔT_{min} = 20^{o}C*

2. Grid Representation: The grid diagrams are also analyzed at different ΔT_{min} values (Appendices C)

(i) At ΔT_{min} = 20^{O}C: Since there is heat imbalance in this network, the pinch location is positioned at one far end of the grid diagram indicating the deficiency in stream matching. In practice, the HEN-1 of the CDU of Port Harcourt refinery is not properly placed on network grid diagram for design analysis. Nonetheless, we can say there is no cross pinch, as shown in figure 5.3 (Appendix C – figure C5)

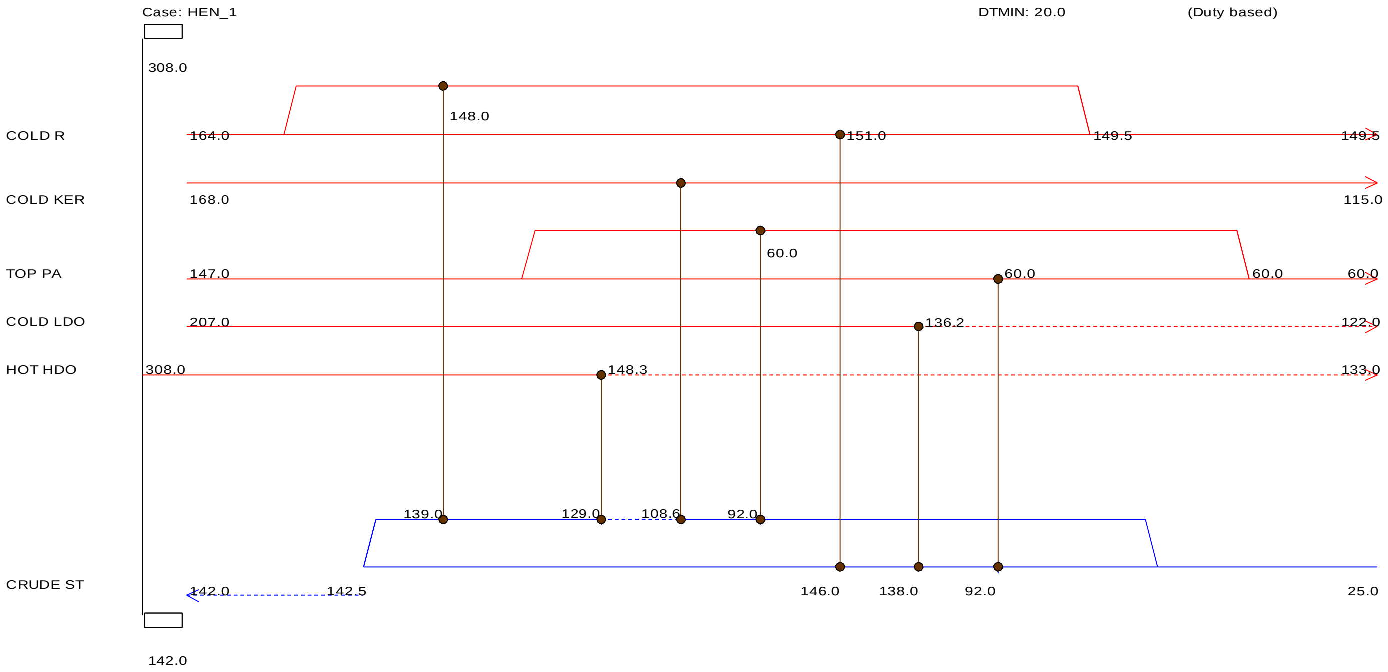


Figure 5.3: *Grid Representation of HEN-1 for* $\Delta T_{min} = 20^oC$

(ii) At ·T_{min} = 40^{O}C: Increasing the ·T_{min} by 10^{O}C does not improve the poor representation of the HEN-1 on the grid diagram. There is a poor stream matching and nocross pinch. (Appendix – figure C.6). In addition to these graphical illustrations, a targeting report of the HEN-1 pinch analysis is also presented on Appendix C – Table C.1. This shows that HEN-1 requires a minimum cold utility of 2421.0kW and minimum hot utility of 0kW.

ANALYSIS OF HEAT EXCHANGER NETWORK-2

Analysis of the 12 heat exchangers lying between the desalter and preflash column are as follows.

1. **Composite and Grand Composite Curves:** The composite curves are analyzed at different ·T_{min} values (Appendix D).

(i) At ·T_{min} = 20^{O}C: There is heat balance between the streams and utilities, the composite curve in figure 5.4 (Appendix D – figure D.1) shows a zero minimum requirement for heating and cooling. This implies that the HEN-2 does not need any external heating and cooling. Nonetheless, there is still room for process-to-process heat recovery.

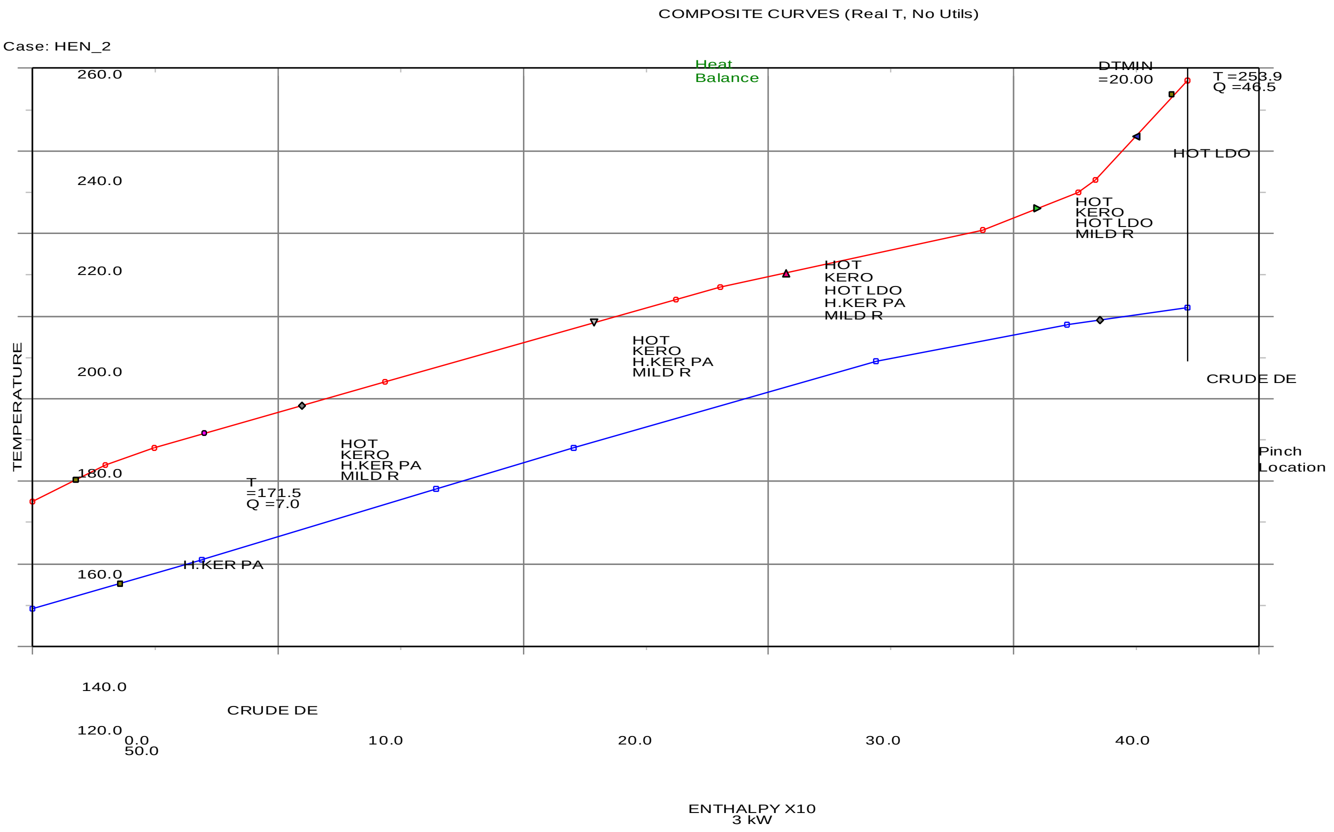


Figure 5.4: *Composite Curve of HEN-2 for* $\Delta T_{min} = 20^{o}C$

(ii) At ΔT_{min} = 30^{O}C: As the ΔT_{min} is increased by 10^{O}C, there becomes a heat imbalance. Observe that the pinch location moves to the left and the two composite curves slightly move away from each other. This is illustrated in Appendix D - figure D.2.

(iii) At ΔT_{min} = 40^{O}C: A Further increase in ΔT_{min} even worsens the situation. The heat is still imbalance, and the hot and cold composite curves moves further away from each other. This is illustrated in Appendix D – figure D.3

The Grand Composite Curve shown in figure 5.5 (Appendix D – figure D.4) plotted at ·T_{min} = $20^{O}C$ shows an irregular curve. There is significantly high potential for process-to-process heat recovery. The grand composite curve for ·T_{min} = $40^{O}C$ shows a small process-to- process heat recovery potential (Appendix D – figure D.5).

2. Grid Representation: Analysis on grid diagrams at different ·T_{min} values are given below.

(i) At ·T_{min} = $20^{O}C$: The network grid diagram on figure 5.6 (Appendix D – figure D.6) shows that there is almost a perfect matching of hot streams (hot kero, hot LDO, mild R, etc) with the cold stream (crude). This is evident since there is no need for external hot and cold utilities.

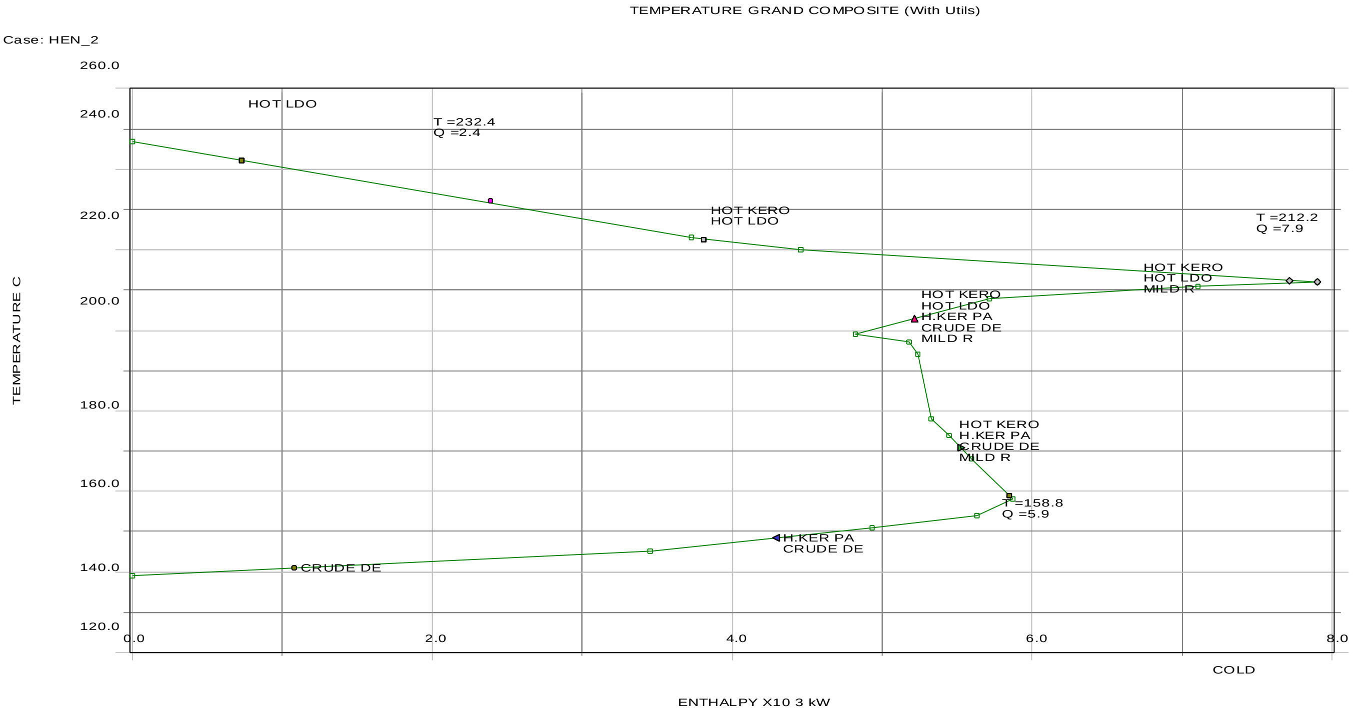


Figure 5.5: *Grand Composite Curve of HEN-2 for T_{min} = $20^{o}C$*

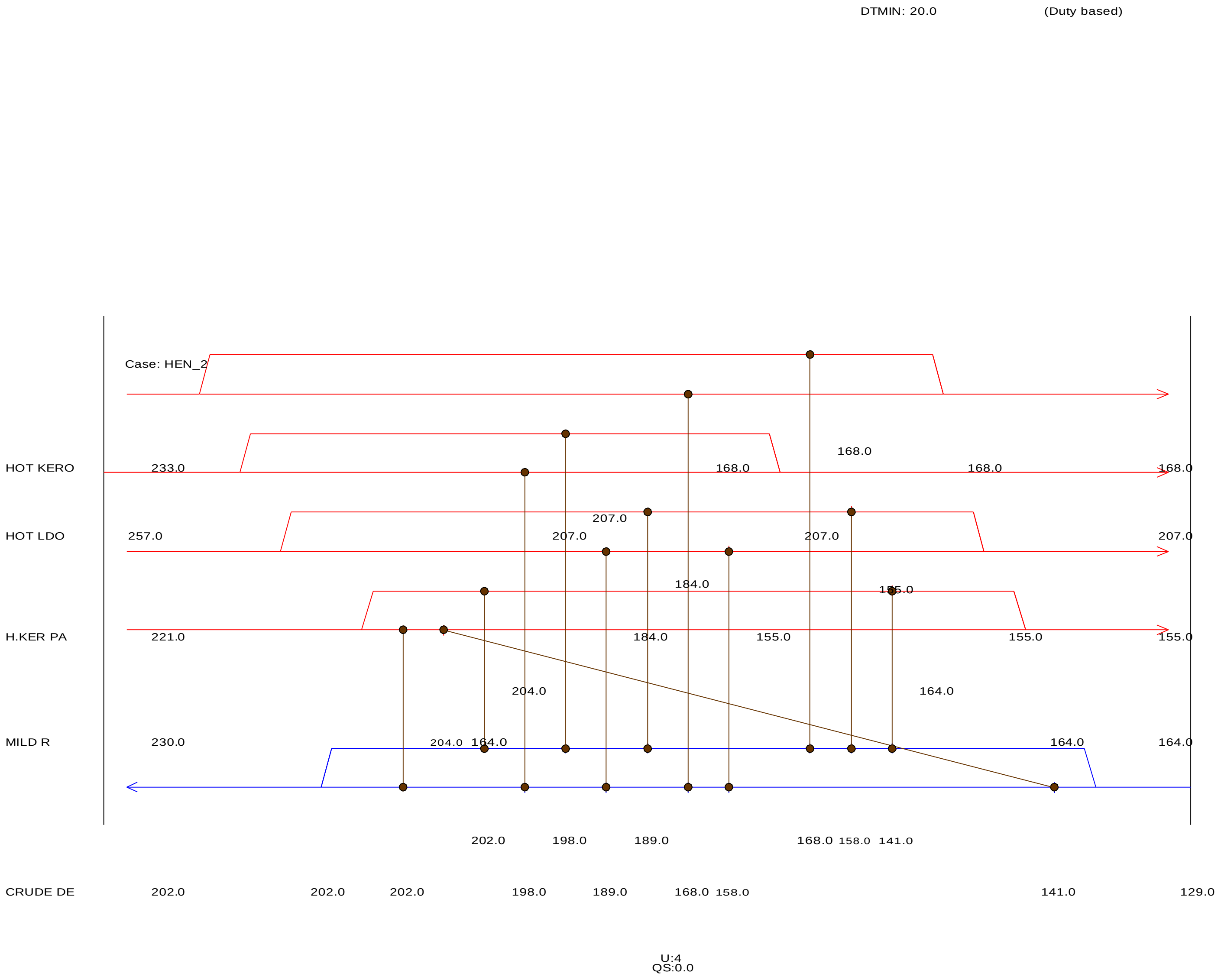


Figure 5.6: *Grid Representation of HEN-2 for ·T_{min} = $20^{O}C$*

(ii) At ·T_{min} = $40^{O}C$: Due to the increase in ·T_{min}, there is heat imbalance in the network. The grid diagram (Appendix D – figure D.7) reveals the pinch locations and cross pinch heat transfer. 8 heat exchangers are crossing the pinch, out of a total of 12 heat exchangers.

In addition, the targeting report (Appendix D – Table D.1) reveals that there is a minimum hot utility of 9041.2kW and minimum cold utility of 9041.2kW. It also reveals a cross pinch heat transfer penalty of -9041.2kW, and 8 heat exchangers violating the pinch rule.

ANALYSIS OF HEAT EXCHANGER NETWORK-3

Analysis of the 4 heat exchangers lying between the pre-flash column and heater plus distillation column, are as follows.

1. **Composite and Grand Composite Curves:** The composite curves are analyzed at different $\cdot T_{min}$ values (Appendices E)

(i) At $\cdot T_{min}$ = $20^{O}C$: There is heat balance between the streams and utilities, this is evident as the composite curve in figure 5.7 (Appendix E – figure E.1) shows a large minimum heating requirement and zero cooling requirement. In contrast, there is little potential for process-to-process heat recovery.

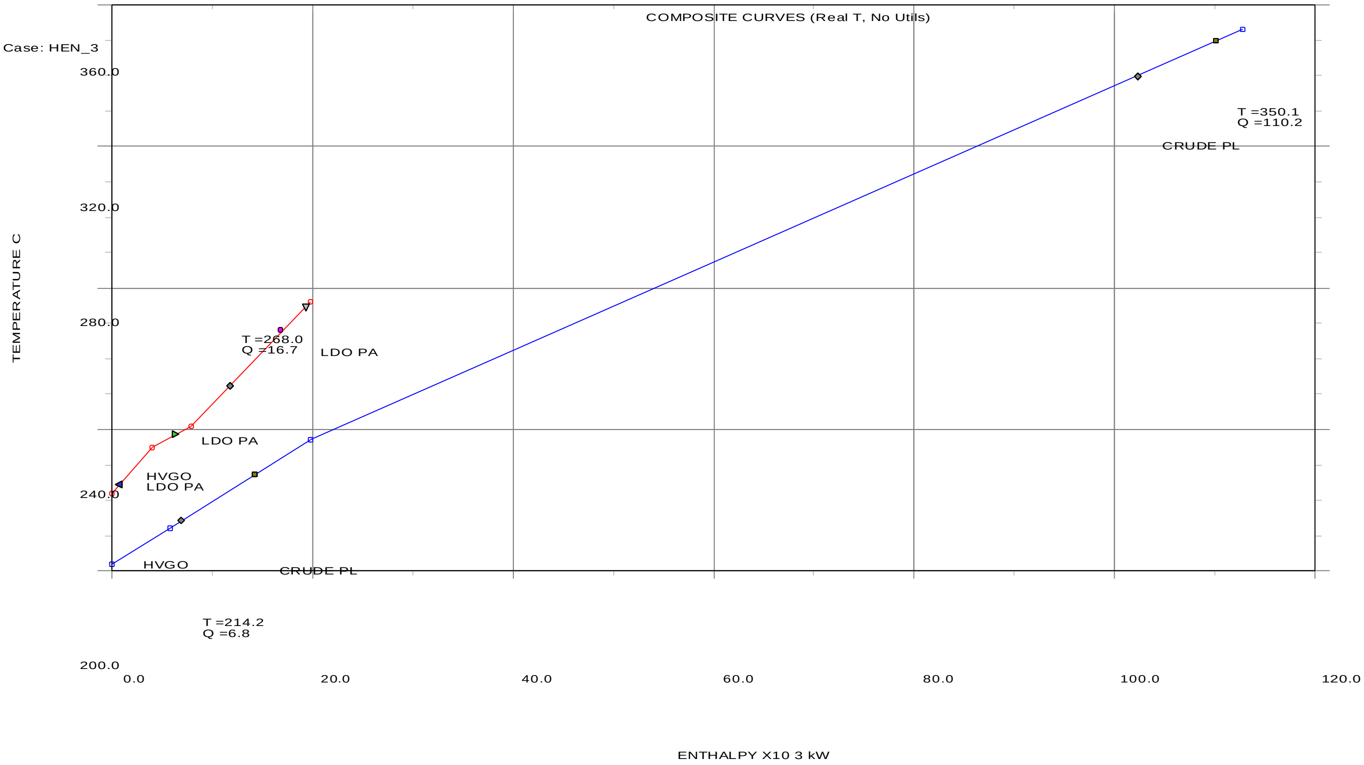


Figure 5.7: *Composite Curves of HEN-3 for* $\cdot T_{min} = 20^{O}C$

(ii) At $\cdot T_{min}$ = $30^{O}C$: At this $\cdot T_{min}$ value, there is also a heat imbalance. The pinch location moves slightly to the right to reveal a small minimum cooling requirement, this in turn reduces the process-to-process heat recovery, as illustrated in Appendix E – figure E.2.

(iii) At $\cdot T_{min}$ = $40^{O}C$: Here, the minimum heating requirement is growing even larger in response to the shift in pinch location and increase in minimum cooling requirement. Appendix E – figure E3 also reveals a smaller process-to-process heat recovery.

2. **Grid Representation:** Analysis on grid diagrams at different $\cdot T_{min}$ values are given below.

(i) At ·T_{min} = 20^{O}C: From appendix E – figure E.5, due to the heat imbalance in this network, the pinch location is positioned at the far end of the grid diagram, indicating that there is deficiency in stream matching. Consequently, there is poor interpretation and no cross pinch.

(ii) At ·T_{min} = 30^{O}C: At this value, the pinch location drifts to the left indicating a better stream matching between process streams and utility. 2 of the 4 heat exchangers are found to be crossing the pinch, as illustrated in appendix E – figure E.6. Observe the heat exchanger between the crude and HVGO violate the pinch rule.

(iii) At ·T_{min} = 40^{O}C: Figure 5.8 (appendix E – figure E.7) shows that at this value of ·T_{min}, the pinch location drifts even further to the left, exposing a wider section of the grid diagram to violation. Consequently, all four heat exchangers in the HEN-3 are guilty of the pinch rule violation, as they cross the pinch to incur a penalty of -8197.58kW.

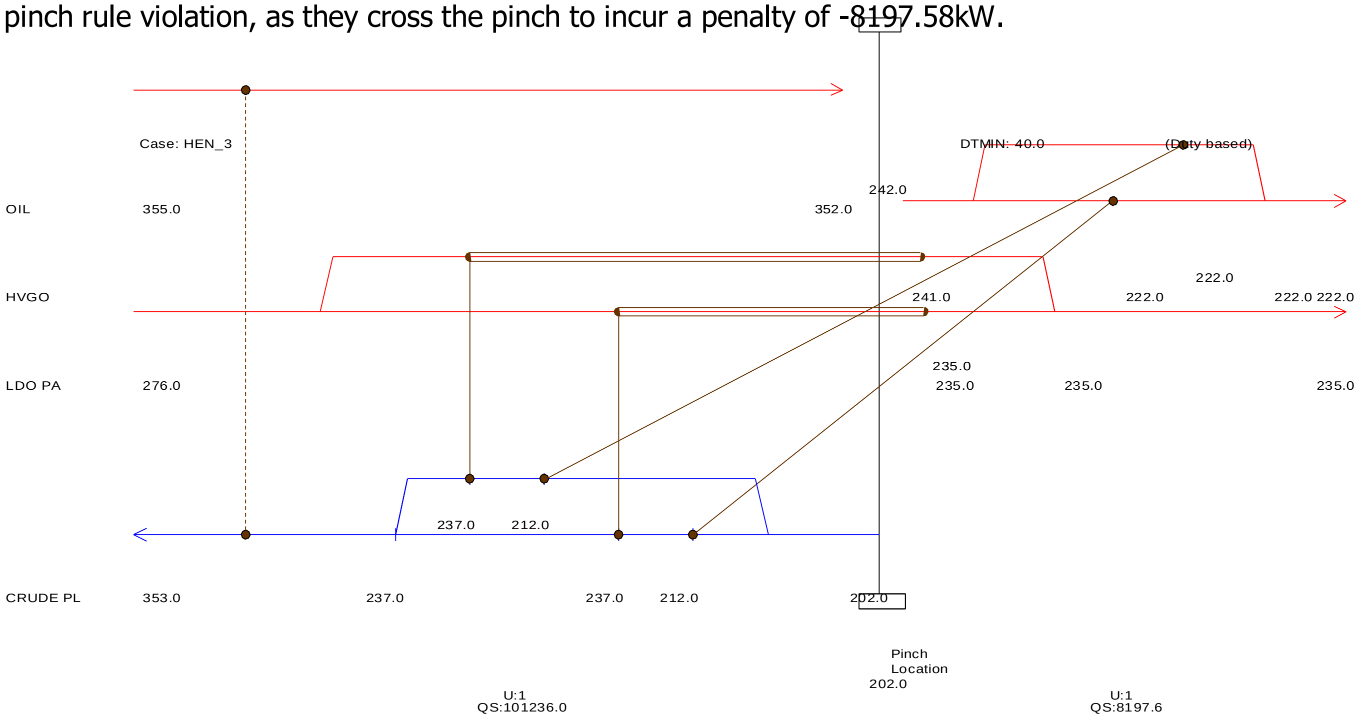


Figure 5.8: *Grid Representation of HEN-3 for ·T_{min} = 40^{O}C*

In addition, the targeting report (Appendix E – Table E.1) further shows a minimum hot utility of 101236.0kW and minimum cold utility of 8197.6kW, and details of heat exchangers crossing the pinch, all at ·T_{min} = 40^{O}C

ANALYSIS OF OVERALL HEAT EXCHANGER NETWORK

Analysis of the all 23 heat exchangers lying between the crude storage and heater plus distillation column, are as follows.

1. Composite and Grand Composite Curves: The composite curves are analyzed at different ·T_{min} values (Appendix F)

(i) At ·T_{min} = 20^{O}C: Figure 5.9 (appendix F – figure F.1) reveals that there is a heat balance between the process streams and utilities. This imbalance results to a large minimum heating requirement and zero cooling requirements. However, there is poor pinch and network representation.

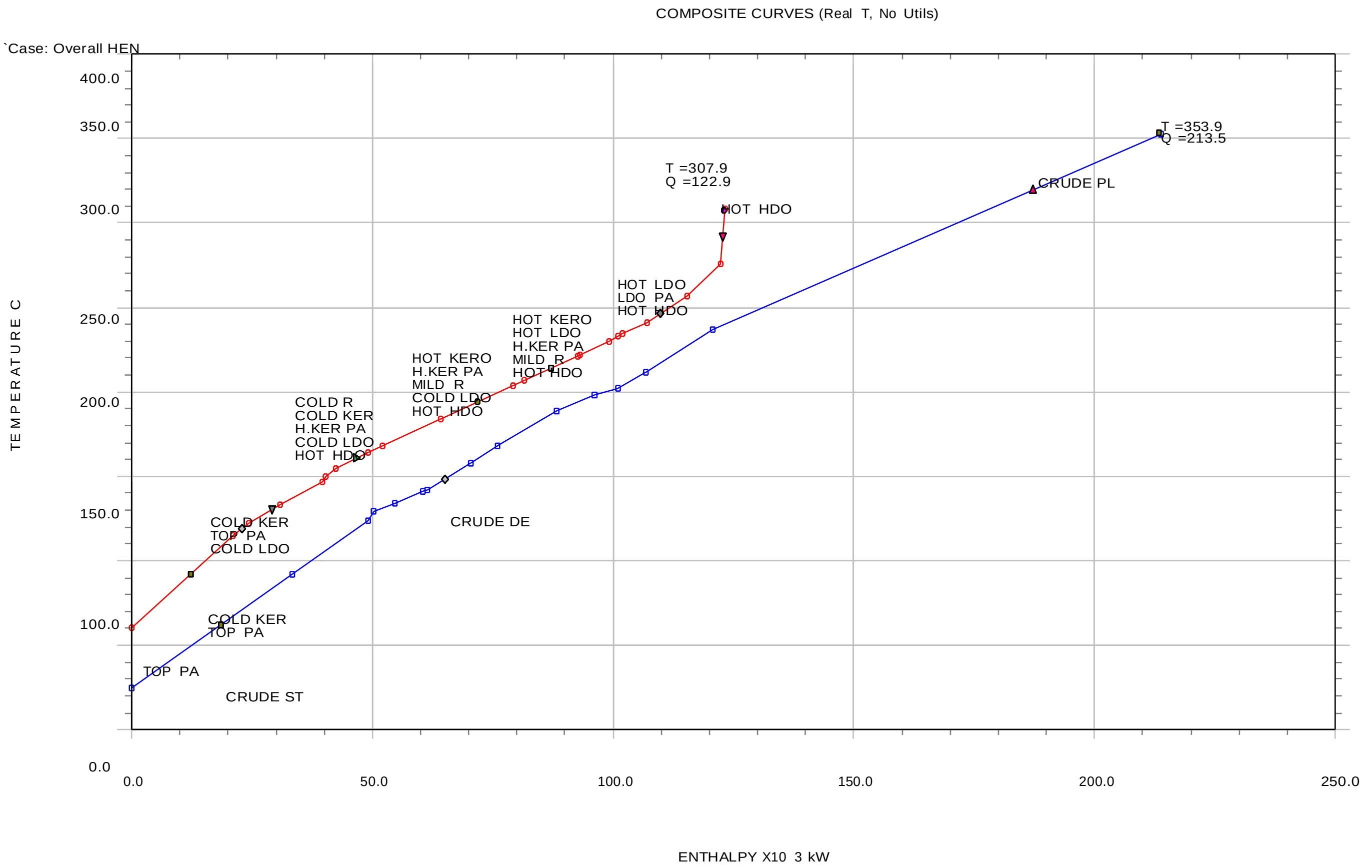


Figure 5.9: *Composite Curves of Overall HEN for* ·T_{min} = 20^{O}C

(ii) At ·T_{min} = 30^{O}C: Appendix F – figure F.2 shows that increasing the ·T_{min} reveals the pinch location, there is also an additional minimum cooling requirement. There is still heat imbalance.

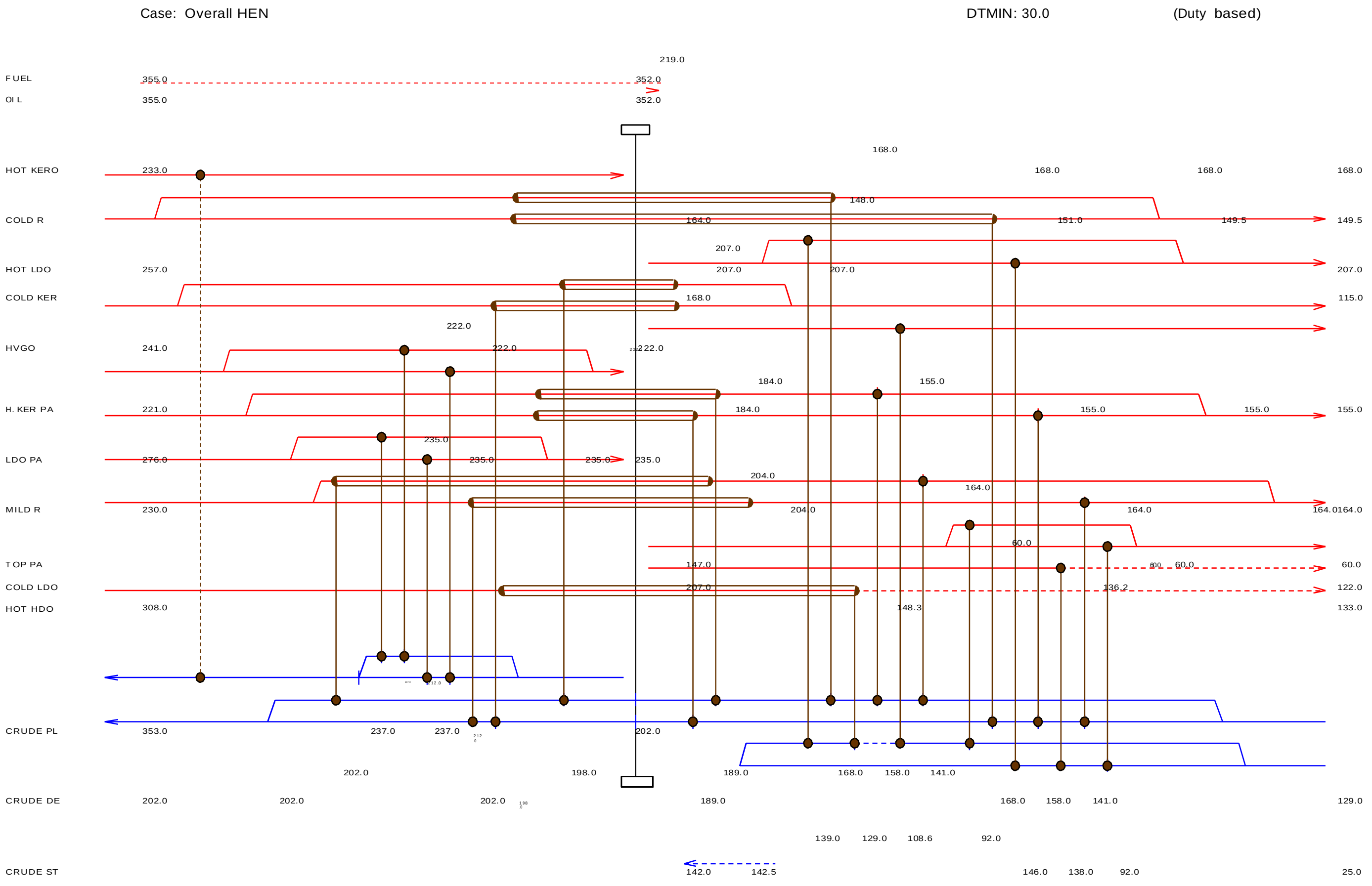
(iii) At ·T_{min} = 40^{O}C: The hot and cold composite curves are pulling apart to further broaden the minimum heating and cooling requirements, the pinch location makes a drift to the right (Appendix F – figure F.3)

The Grand composite curve at ·T_{min} = 20^{O}C contains patches where little process-to-process heat recovery can be achieved

2. Grid Representation: Analysis on grid diagrams at different ·T_{min} values are given below.

(i) At ·T_{min} = 20^{O}C: From appendix F – figure F.5, there is poor representation due the pinch location positioned at one end of the grid diagram. Hence, we can not carry out a proper stream matching.

(ii) At ·T_{min} = 30^{O}C: As shown in figure 5.10 (appendix F – figure F.6), there is proper positioning of pinch location. The heat exchangers crossing the pinch can be clearly identified, 9 heat exchangers are violating the pinch rule.



189.0

U:8

U:10

QS:93454.3

QS:2836.9

Figure 5.10: *Grid Representation of Overall HEN for $T_{min} = 30^{o}C$*

(iii) At ·T_{min} = 40^{O}C: (Appendix F – figure F.7) although the number of heat exchangers crossing the pinch are similar to that at ·T_{min} = 30^{O}, the pinch location has drifted further to the left, justifying an increase in the minimum heating and cooling requirements. As earlier interpreted, 9 heat exchangers are violating the pinch rule.

(iii) At ·T_{min} = 50^{O}C: (Appendix F – figure F.8) Even an increase in the ·T_{min} value, above the stipulated range for oil refinery worsens the condition. The pinch location drifts a little more to the left, implying more minimum heating and cooling requirement for the network, and even more cross pinch penalty.

The targeting report (Appendix F – Table F.1) further shows that ·T_{min} = 20^{O}C, a minimum hot and cold utility are 90617.4kW and 0kW respectively, and zero cross pinch heat transfer. But at ·T_{min} = 40^{O}C, there is a minimum hot and cold utility are 100840.1kW and 10222.7kW respectively, and a total of -7801.68kW cross pinch penalty incurred by the 9 *culprit* heat exchangers.

In summary, the results of the analysis are in agreement with the historical facts that are available from refinery operation measurements, process design specifications and plant simulation. All the results and trends of the composite curves and grid diagrams obtained from pinch analysis of HEN-1, HEN-2, HEN-3 and overall HEN, are summarized in table 5.8 below. This is to enhance a better representation, comparison and appreciation of all features of the different networks; and to carefully draw a conclusion and proffer suggestions and recommendations on an efficient retrofitting approach. The table is given below.

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Table 5.8: *Summary of Pinch Analysis on all HEN*

Features of HEN	HEN -			HEN-			HEN-			Overall HEN		
	ΔTmin= [illegible]	ΔTmin= [illegible]	ΔTmin= 40°C	ΔTmin= [illegible]	ΔTmin= [illegible]	ΔTmin= 40°C	ΔTmin= [illegible]	ΔTmin= [illegible]	ΔTmin= 40°C	ΔTmin= [illegible]	ΔTmin= [illegible]	ΔTmin= 40°C
Clarity of Pinch location	Poor	Poor	Poor	Poor	Good	Good	Poor	Good	Good	Poor	Good	Good
$Q_{H,min}$ (kW) (Required external heating)	0.00	0.00	0.00	0.00	2817.20	9041.20	93038.4	96098.90	101236.0	90617.4	93454.30	100840.10
$Q_{C,min}$ (kW) (Required external cooling)	2421.00	2421.00	2421.00	0.00	2817.20	9041.20	0.00	3060.50	8197.60	0.00	2836.90	10222.70
Process-to-process heat recovery	High	High	High	High	Medium	Medium	Low	Fairly low	Very low	High	Fairly high	Medium
Heat balance	No	No	No	Yes	No	No	No	No	No	No	No	No
Hot and cold	Poor	Poor	Poor	Excellent	Fair	Good	Poor	Fair	Poor	Poor	Fair	Fair
Cross pinch	Nil	Nil	Nil	Nil	Yes	Yes	Nil	Yes	Yes	Nil	Yes	Yes
Representation on Grid diagram	Poor	Poor	Poor	Fair	Good	Good	Poor	Good	Good	Poor	Good	Good
Number of heat exchanger violating	Nil	Nil	Nil	Nil	8	8	Nil	2	4	Nil	9	9
Pinch penalty (kW)	Nil	Nil	Nil	Nil	-2817.20	-9041.23	Nil	-3060.47	-8197.58	Nil	-415.86	-7801.68

5.1.7 ENERGY EFFICIENCY

The energy efficiency for the overall HEN was calculated as follows:

$$\text{Energy Efficiency} = \frac{Q_{H,\min}\,(kW)}{Q_{H,op}\,(kW)}$$

Where, $Q_{H,op}$ is the energy consumed by the network. This was gotten from the process design heat load obtained from the original process design specification, as equal to 98.94MW. More so, $Q_{H,min}$ is the minimum energy required by network. This was obtained from the composite curve and targeting report of our pinch analysis, as equal to 90617.4kW. Therefore,

$$\text{Energy Efficiency} = \frac{90617.4\ (\text{kW})}{98940.0\ (\text{kW})} \times 100\% = 91.5\%$$

From operating energy efficiency of the crude distillation unit of the New Port Harcourt refinery obtained from plant measurement is 90.8% (Anozie and Odejobi, 2007).
Hence, the calculated energy efficiency (91.5%) deviates from the actual operating efficiency by a small amount calculated as follows:

$$\text{Error Estimate} = \frac{\text{Actual value - Calculated value}}{\text{Actual value}}$$

$$= \left(\frac{90.8 - 91.5}{90.8}\right) \times 100\%$$

$$= (-0.0077) \times 100\%$$

$$= -0.77\%$$

CONCLUSION AND RECOMMENDATION

This chapter is created on the analytical results presented in the preceding chapter. These results have given an insight about some of the technical factors militating against the energy efficiency and optimization of the heat exchanger network in the crude distillation unit of the Port Harcourt refinery. Consequently, viable recommendations will also be proffered as suggested solutions to improving the performance of crude distillation unit of Port Harcourt refinery. More so, specific studies related to this research are suggested as future works and areas of particular interest with respect to further study. It has been revealed by pinch analysis that an optimal and best design for an energy efficient heat exchanger network is dependent on the choice of the $\cdot T_{min}$ for the process. By varying the $\cdot T_{min}$ value and analyzing the individual network, it was discovered that no two sets of conditions or features exists for any of the individual network. This is evident also in the analysis of the overall heat exchanger network. Specifically, the HEN-1 presented a relatively poor and unclear representation on the grid diagram, resulting in uncertainties in the cross pinch effect, pinch penalties and proper stream matching, Nonetheless, if this problem is addressed, there is a very high potential of process-to-process heat recovery, which will be beneficial to the entire network and CDU. The HEN-2 presented a relatively better representation on grid diagram, resulting in proper identification of pinch location, cross pinch effect, pinch location even the exact amount of heat exchanger violating the pinch rule. In addition, at $\cdot T_{min} = 20^{O}C$, there is heat balance, perfect stream matching in the network and zero cross pinch effect, it only requires little retrofitting as compared with the other network. For the HEN-3, the three sets of conditions at varying $\cdot T_{min}$, are relatively unsatisfactory, the implication here is that it is the only network in the CDU that needs total retrofitting; worst still, a prospective retrofitting may not even yield an optimal performance as the average potential for process-to-process recovery is low. Summing up the different conditions of all three networks, it was discovered that the overall HEN needs a total retrofitting. There is heat imbalance, poor stream matching and average cross pinch effect on the entire network. It has been shown that the heat exchanger network in the crude distillation unit of the Port Harcourt refinery was designed without the application of pinch design methods. It was found that there are heat exchangers operating against the pinch which violates the pinch principle of no heat transfer across the pinch and indicates that there is room for improvement. There is, therefore, urgent need to retrofit the heat exchanger network in the crude distillation unit of the Port Harcourt refinery so as to improve the energy efficiency.

RECOMMENDATIONS

1. So far only replacements of broken down components and the usual turn around maintenance which involves the cleaning of heat exchangers to remove scales depositions due to fouling have been practiced in the refinery. No wonder, the refinery keep breaking down and refusing to operate efficiently because of excessive energy that is used to drive the process and poor process network. I wish to state categorically in this project work that the problems of the Port Harcourt refinery can be solved by proper retrofitting or revamping of the refinery through pinch analysis.
2. Some other issues in pinch technology, like total site improvement, as concerning process integration were not considered within the scope of this work. I recommend that the government should see it as a point of duty to encourage study and researches into fields that would improve the performance of the nation’s refineries.

3. As modern industrial heat integrated plants involve complex networks, it is necessary that similar thermal transient analysis be performed to predict thermal dynamics in the system and adopt control measure accordingly.

FUTURE WORKS

1. Future work will intimately develop and deploy retrofit model of the HEN and optimize the exchanger area by adding the equation of exchanger area not included in this work.
2. Future work on the application of pinch technology to chemical engineering industries should also be encouraged. Of importance to the optimization of our local refineries is distillation targeting and process heat integration techniques between heat exchanger network and distillation column. These are very useful to recover heat in the refining process.
3. A comprehensive study on heat exchanger network (HEN) costs and performance estimation for multi-period operation should be carried out on the crude distillation unit of the Port Harcourt refinery. This modeling method will be useful for suggesting a thermo-economic model for the HEN.

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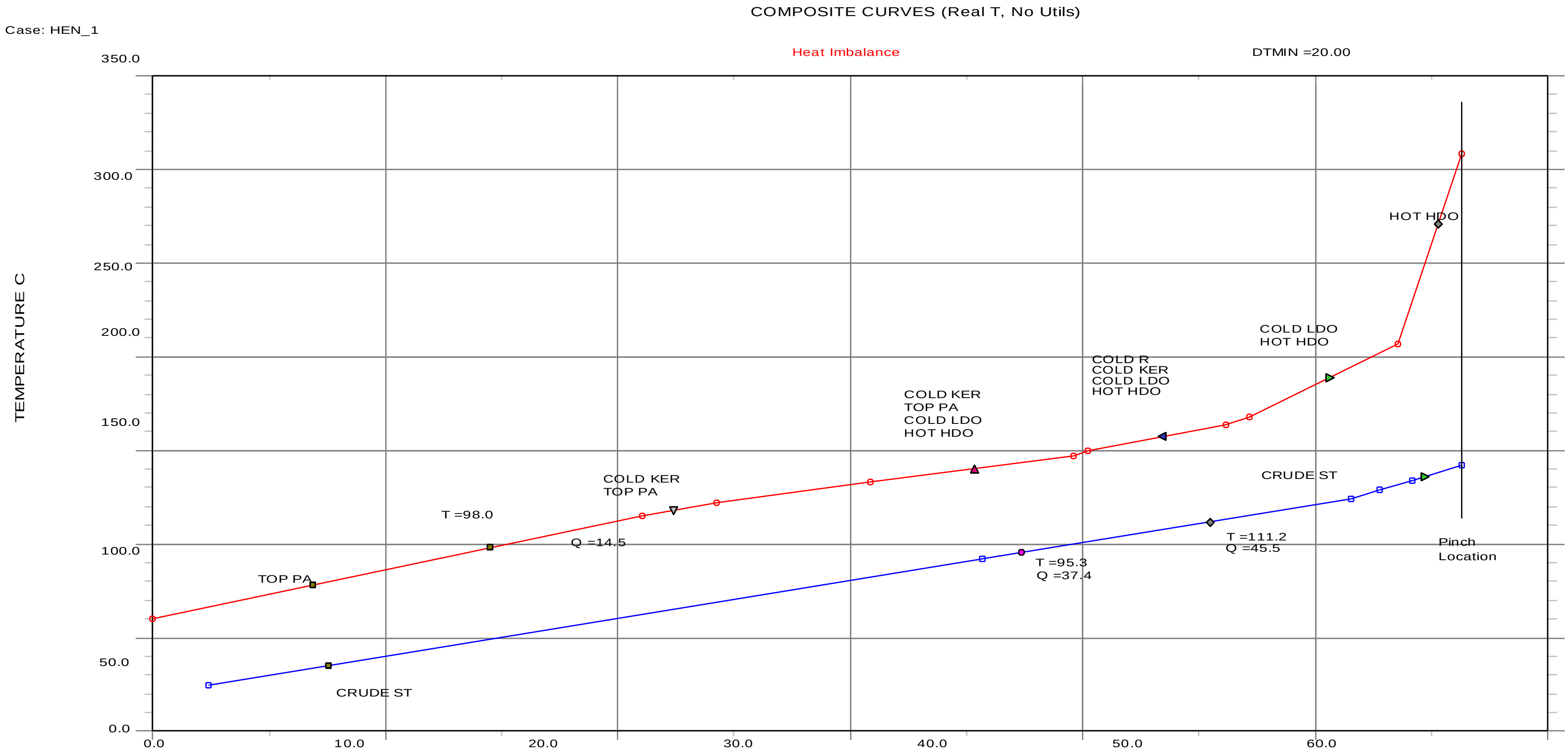
Appendix A: Process Flow Diagrams

AUTOCAD DRAFTING OF "PROCESS FLOW DIAGRAM" STILL ONGOING

AUTOCAD DRAFTING OF "PROCESS FLOW DIAGRAM" STILL ONGOING

AUTOCAD DRAFTING OF "PROCESS FLOW DIAGRAM" STILL ONGOING

Appendix C


COMPOSITE CURVES (Real T, No Utils)
Case: HEN_1
Heat Imbalance
DTMIN =20.00
TEMPERATURE C
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
HOT HDO
COLD LDO
HOT HDO
COLD R
COLD KER
COLD LDO
HOT HDO
COLD KER
TOP PA
COLD LDO
HOT HDO
COLD KER
TOP PA
T =98.0
Q =14.5
TOP PA
CRUDE ST
T =95.3
Q =37.4
T =111.2
Q =45.5
CRUDE ST
Pinch
Location

ENTHALPY X10 3 kW

Figure C.1 : *Composite Curve of HEN-1 for* $T_{min} = 20^{o}C$

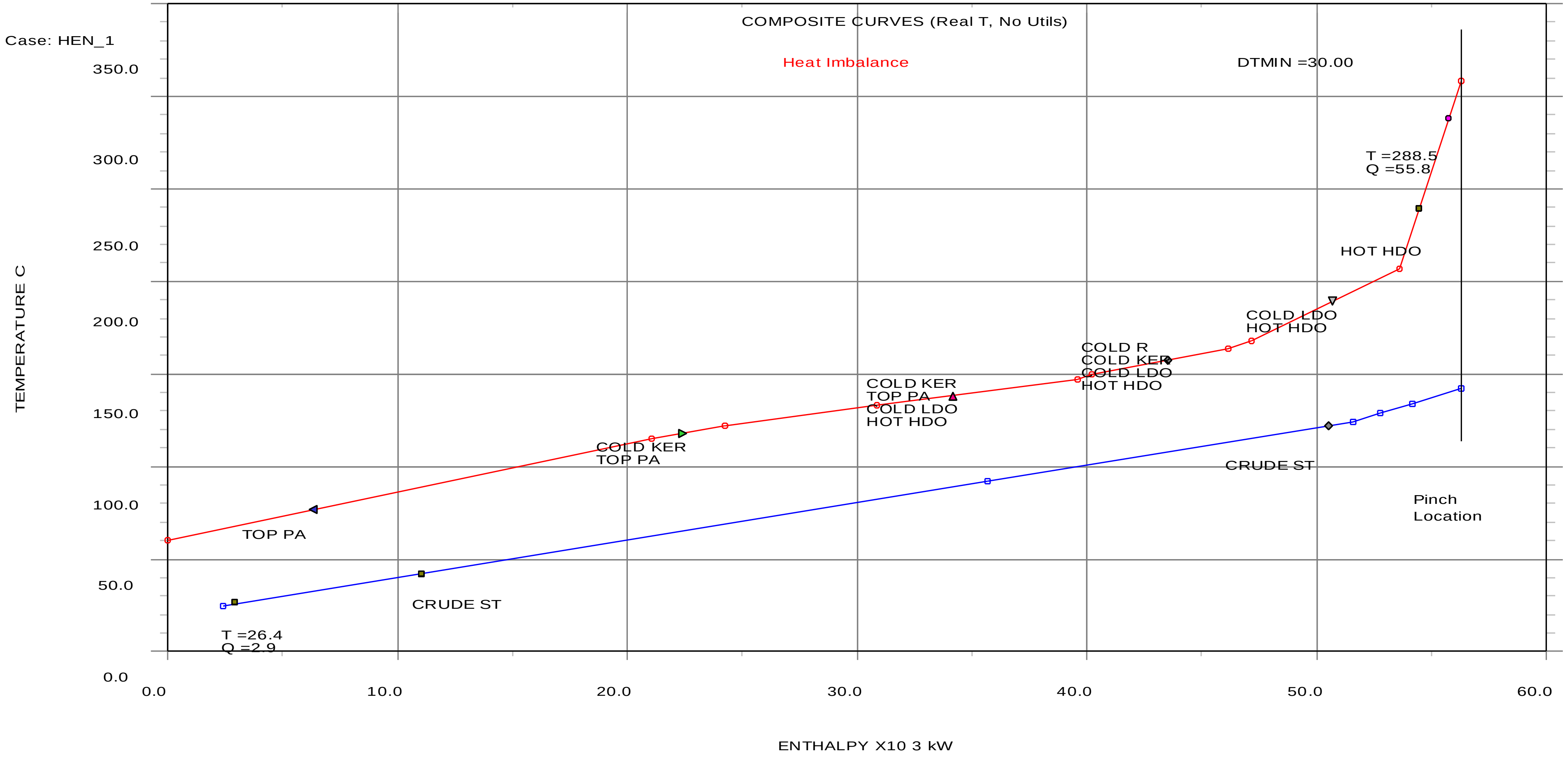

COMPOSITE CURVES (Real T, No Utils)
Case: HEN_1
Heat Imbalance
DTMIN =30.00
T =288.5
Q =55.8
HOT HDO
COLD LDO
HOT HDO
COLD R
COLD KER
COLD LDO
HOT HDO
COLD KER
TOP PA
COLD LDO
HOT HDO
COLD KER
TOP PA
TOP PA
CRUDE ST
CRUDE ST
Pinch
Location
T =26.4
Q =2.9
TEMPERATURE C
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
ENTHALPY X10 3 kW

Figure C.2: *Composite Curve of HEN-1 for* $\Delta T_{min} = 30^{o}C$

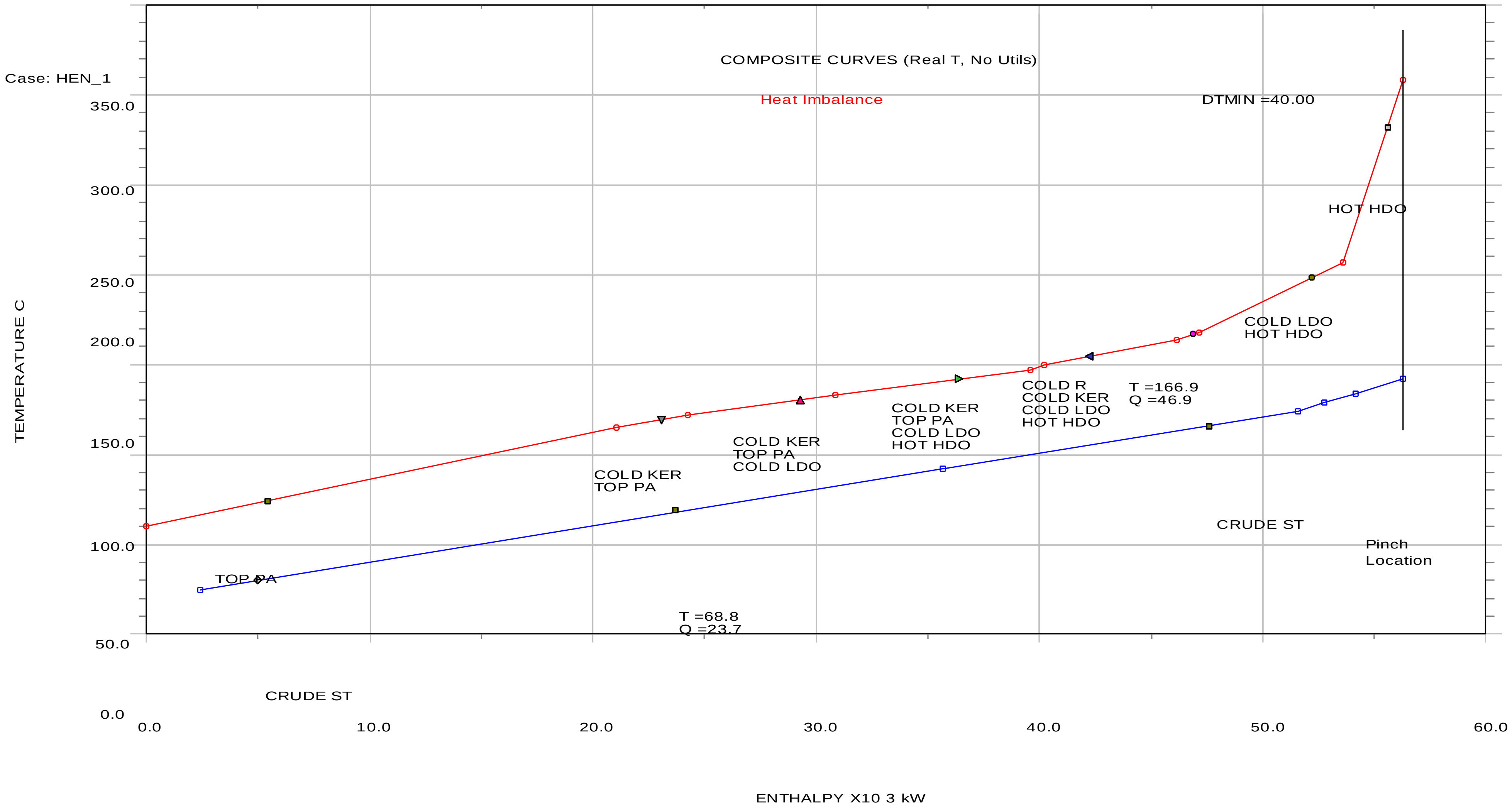

COMPOSITE CURVES (Real T, No Utils)
Case: HEN_1
Heat Imbalance
DTMIN =40.00
HOT HDO
COLD LDO
HOT HDO
COLD R
COLD KER
COLD LDO
HOT HDO
T =166.9
Q =46.9
COLD KER
TOP PA
COLD LDO
HOT HDO
COLD KER
TOP PA
COLD LDO
COLD KER
TOP PA
CRUDE ST
Pinch
Location
TOP PA
T =68.8
Q =23.7
CRUDE ST
TEMPERATURE C
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
ENTHALPY X10 3 kW

Figure C.3: *Composite Curve of HEN-1 for* $\Delta T_{min} = 40^oC$

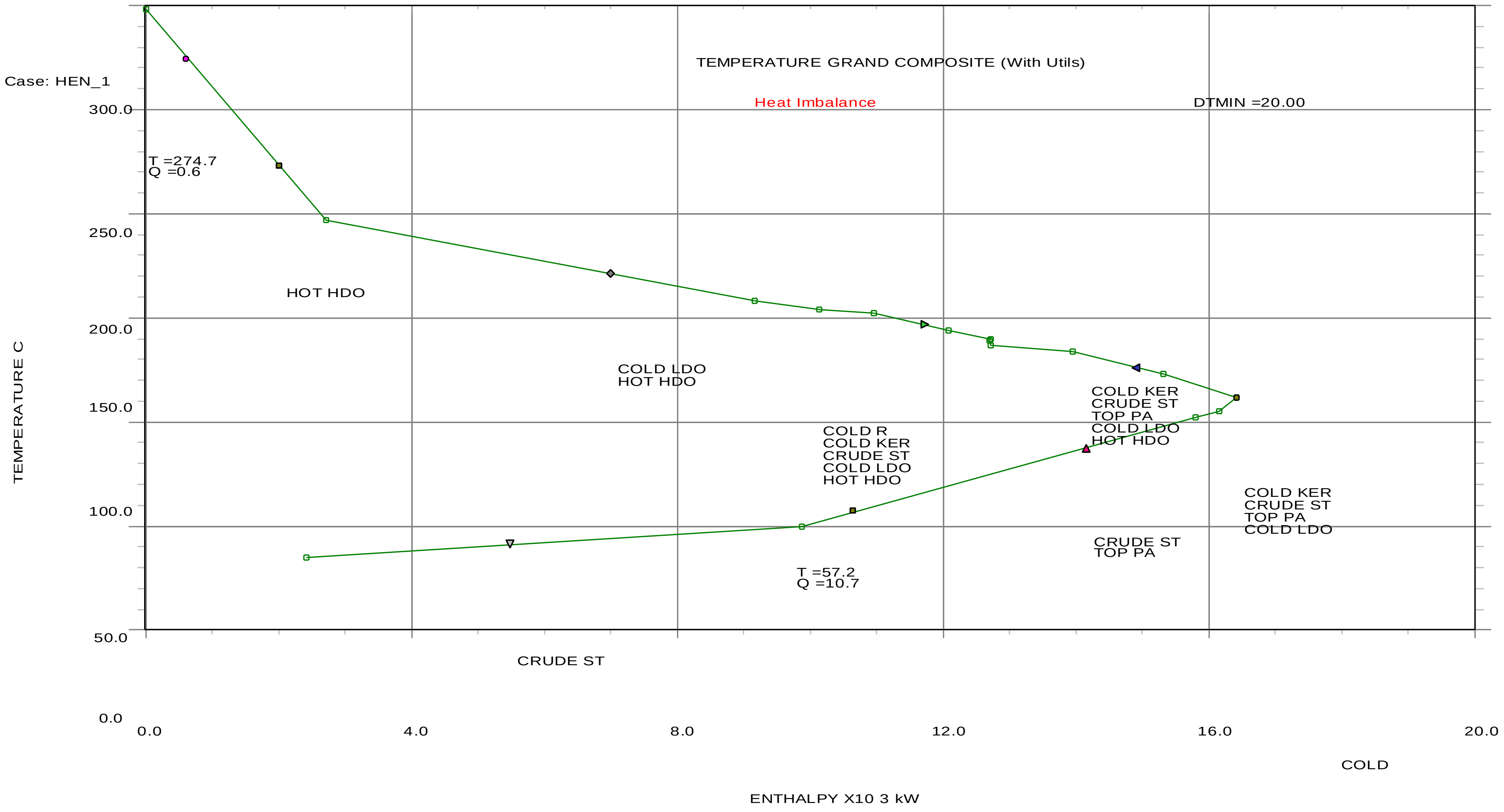

TEMPERATURE GRAND COMPOSITE (With Utils)
Case: HEN_1
Heat Imbalance
DTMIN =20.00
300.0
250.0
200.0
150.0
100.0
50.0
0.0
TEMPERATURE C
T =274.7
Q =0.6
HOT HDO
COLD LDO
HOT HDO
COLD KER
CRUDE ST
TOP PA
COLD LDO
HOT HDO
COLD R
COLD KER
CRUDE ST
COLD LDO
HOT HDO
COLD KER
CRUDE ST
TOP PA
COLD LDO
CRUDE ST
TOP PA
T =57.2
Q =10.7
CRUDE ST
0.0
4.0
8.0
12.0
16.0
20.0
COLD
ENTHALPY X10 3 kW

Figure C.4: *Grand Composite Curve for HEN-1 for* $\Delta T_{min} = 20^{o}C$

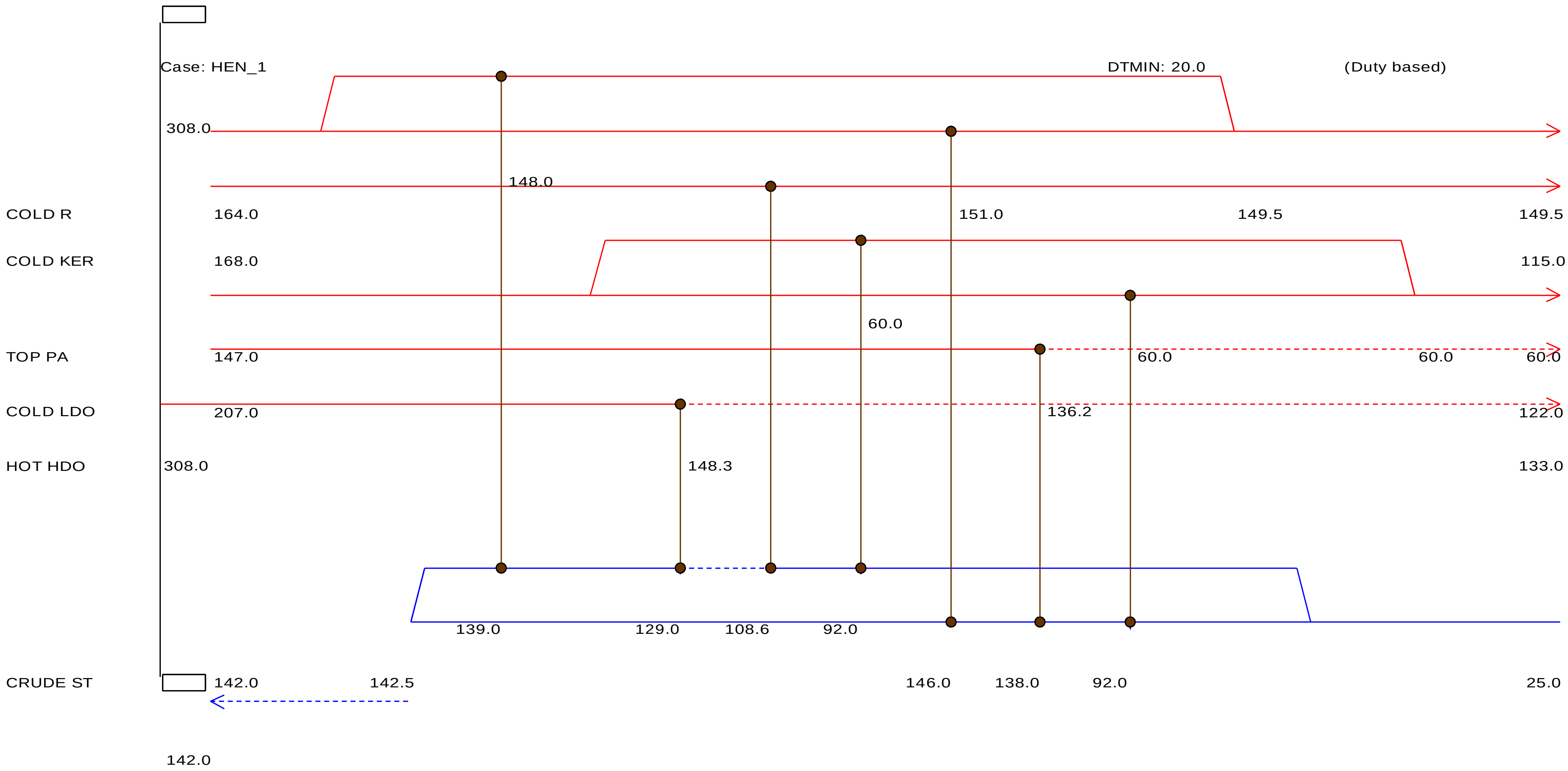

Case: HEN_1
DTMIN: 20.0
(Duty based)
308.0
148.0
COLD R
164.0
151.0
149.5
149.5
COLD KER
168.0
115.0
60.0
TOP PA
147.0
60.0
60.0
60.0
COLD LDO
207.0
136.2
122.0
HOT HDO
308.0
148.3
133.0
139.0
129.0
108.6
92.0
CRUDE ST
142.0
142.5
146.0
138.0
92.0
25.0
142.0

Figure C.5: *Grid Representation of HEN-1 for* $\Delta T_{min} = 20^{o}C$

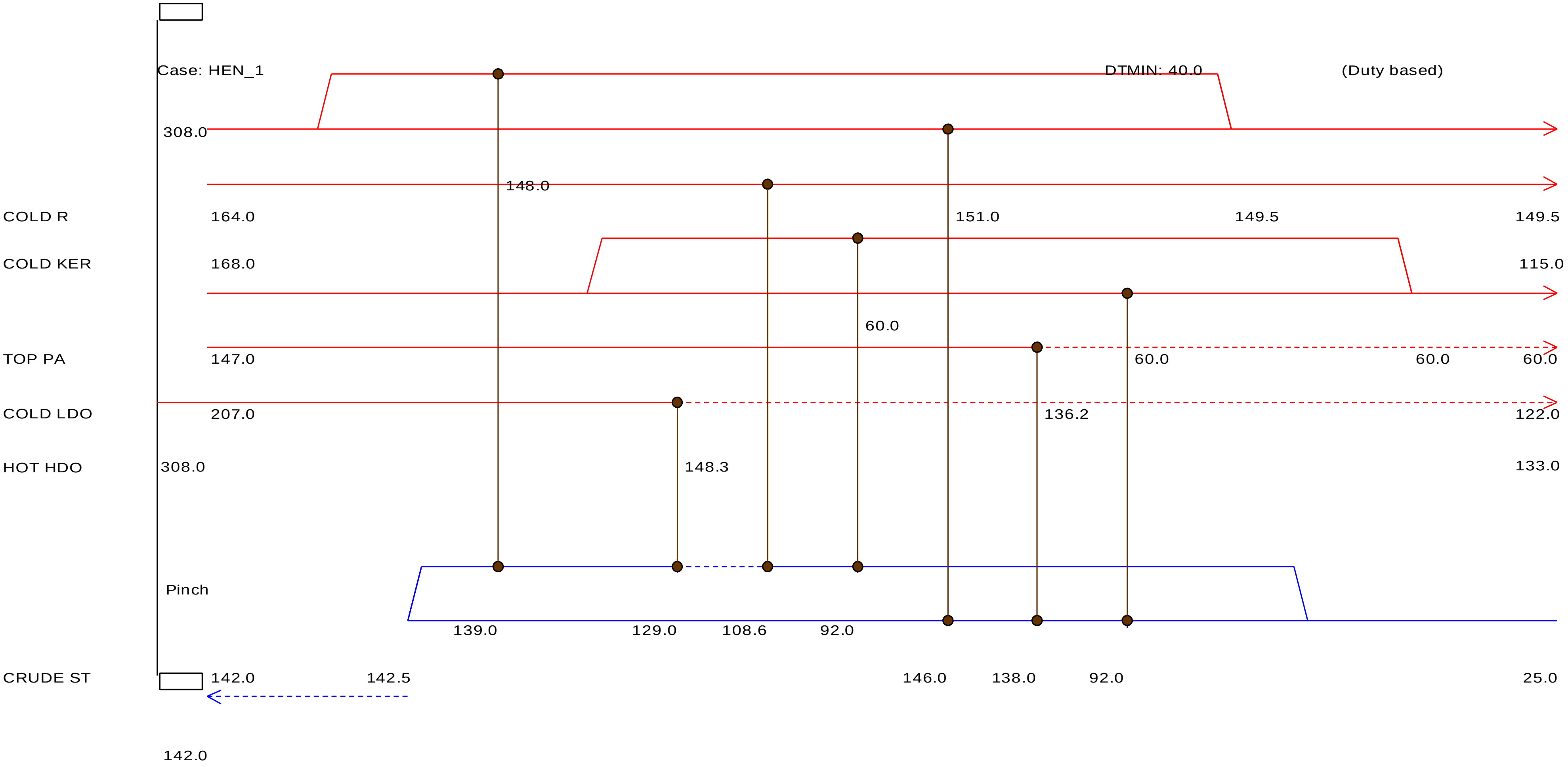

Case: HEN_1
DTMIN: 40.0
(Duty based)
308.0
148.0
COLD R
164.0
151.0
149.5
149.5
COLD KER
168.0
115.0
60.0
TOP PA
147.0
60.0
60.0
60.0
COLD LDO
207.0
136.2
122.0
HOT HDO
308.0
148.3
133.0
Pinch
139.0
129.0
108.6
92.0
CRUDE ST
142.0
142.5
146.0
138.0
92.0
25.0
142.0

Figure C.6: *Grid Representation of HEN-1 for* $\Delta T_{min} = 40^{o}C$

Table C.1: *Targeting Report of HEN-1 for* $\Delta T_{min} = 20^{o}C$ *and 40* ^{o}C

```
A S P E N   P I N C H  (TM)


  Targeting Results, Case:  HEN_1

 *****************************************************
 *           No utilities have been placed           *
 *****************************************************

           Minimum hot  utility               0.0  kW
           Minimum cold utility            2421.0  kW

          Delta Tmin                  20.0          C

                         Pinch T          Delta T  (Real)
Pinch temperature(s):    298.0    C       166.0      C

          Total Hot  utility used     0.0           kW
          Total Cold utility used     0.0           kW
```

```
A S P E N   P I N C H  (TM)


  Targeting Results, Case:  HEN_1

 *****************************************************
 *           No utilities have been placed           *
 *****************************************************

          Minimum hot  utility              0.0  kW
          Minimum cold utility           2421.0  kW

         Delta Tmin                  40.0          C

                         Pinch T          Delta T  (Real)
Pinch temperature(s):    288.0       C    166.0          C

         Total Hot  utility used     0.0            kW
         Total Cold utility used     0.0            kW
```

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```
Cross Pinch Heat Transfer Penalties

                           Penalty units : kW

                         * denotes a near pinch


                     (No cross pinch heat exchange)
```

```
Cross Pinch Heat Transfer Penalties
                           Penalty units : kW

                         * denotes a near pinch


                     (No cross pinch heat exchange)
```

Appendix D

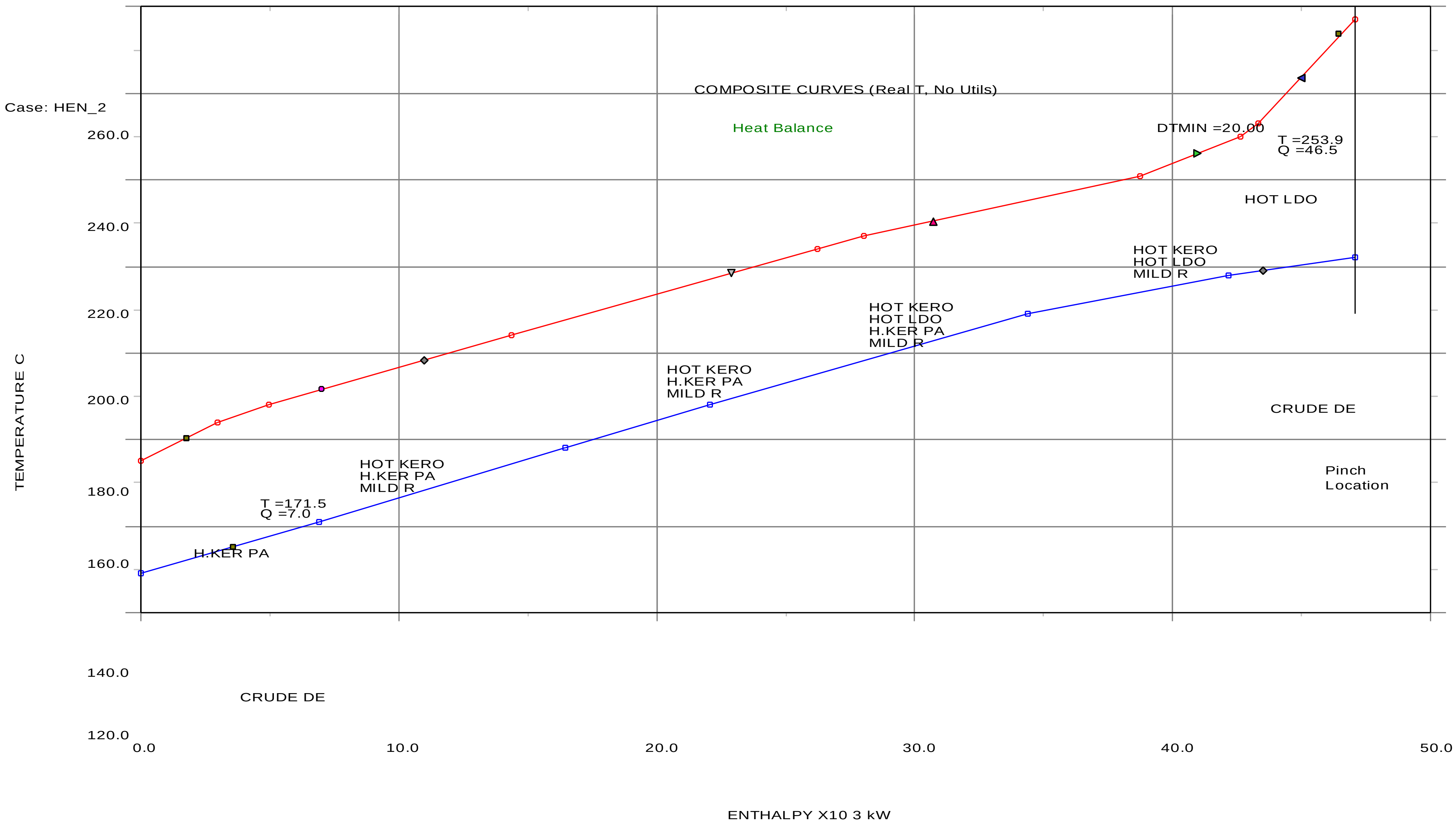

COMPOSITE CURVES (Real T, No Utils)
Case: HEN_2
Heat Balance
DTMIN =20.00
T =253.9
Q =46.5
HOT LDO
HOT KERO
HOT LDO
MILD R
HOT KERO
HOT LDO
H.KER PA
MILD R
HOT KERO
H.KER PA
MILD R
CRUDE DE
Pinch
Location
HOT KERO
H.KER PA
MILD R
T =171.5
Q =7.0
H.KER PA
CRUDE DE
TEMPERATURE C
260.0
240.0
220.0
200.0
180.0
160.0
140.0
120.0
0.0
10.0
20.0
30.0
40.0
50.0
ENTHALPY X10 3 kW

Figure D.1: *Composite Curve of HEN-2 for* $\Delta T_{min} = 20^{o}C$

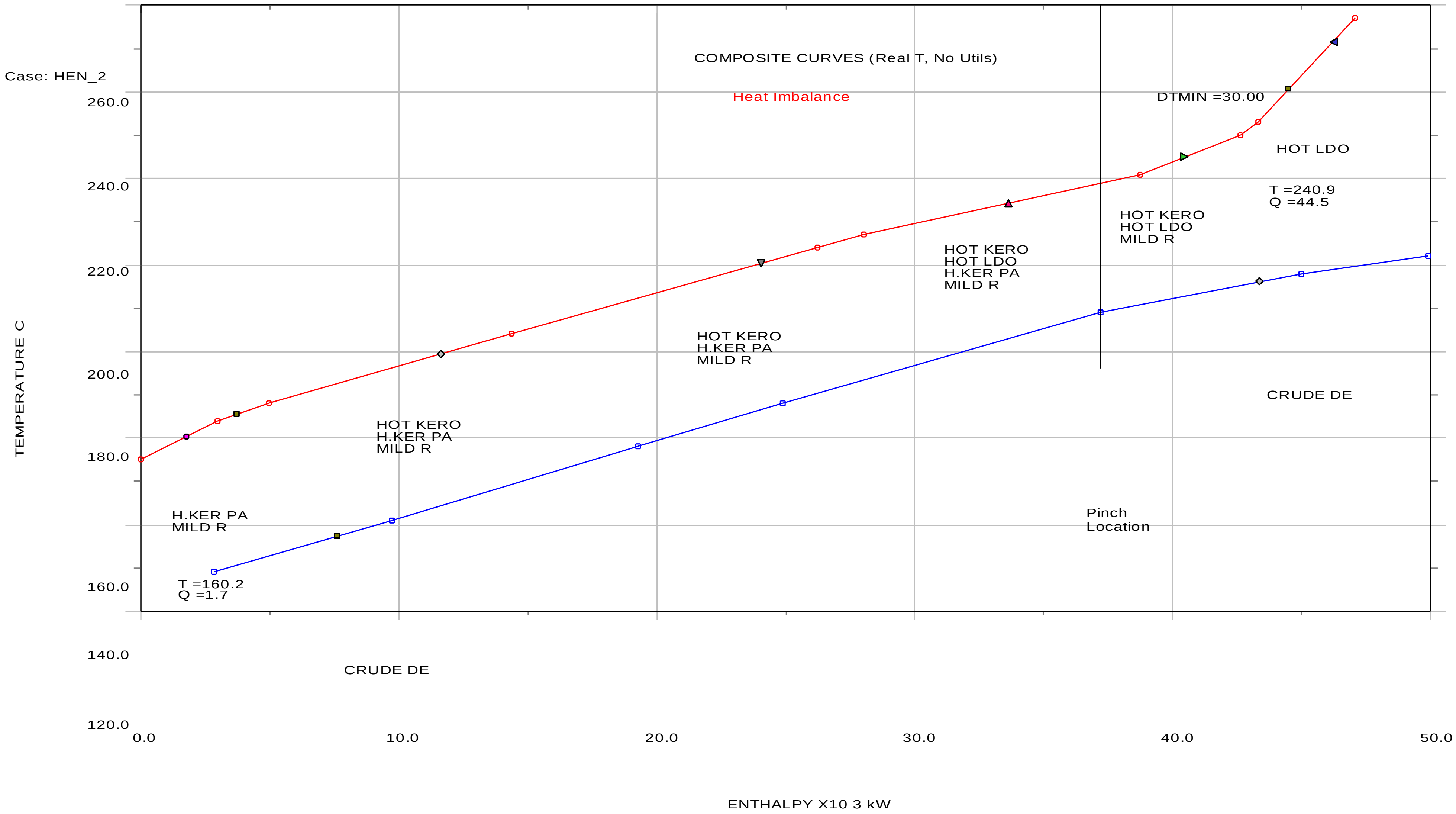


Figure D.2: *Composite Curve of HEN-2 for $\Delta T_{min} = 30^{o}C$*

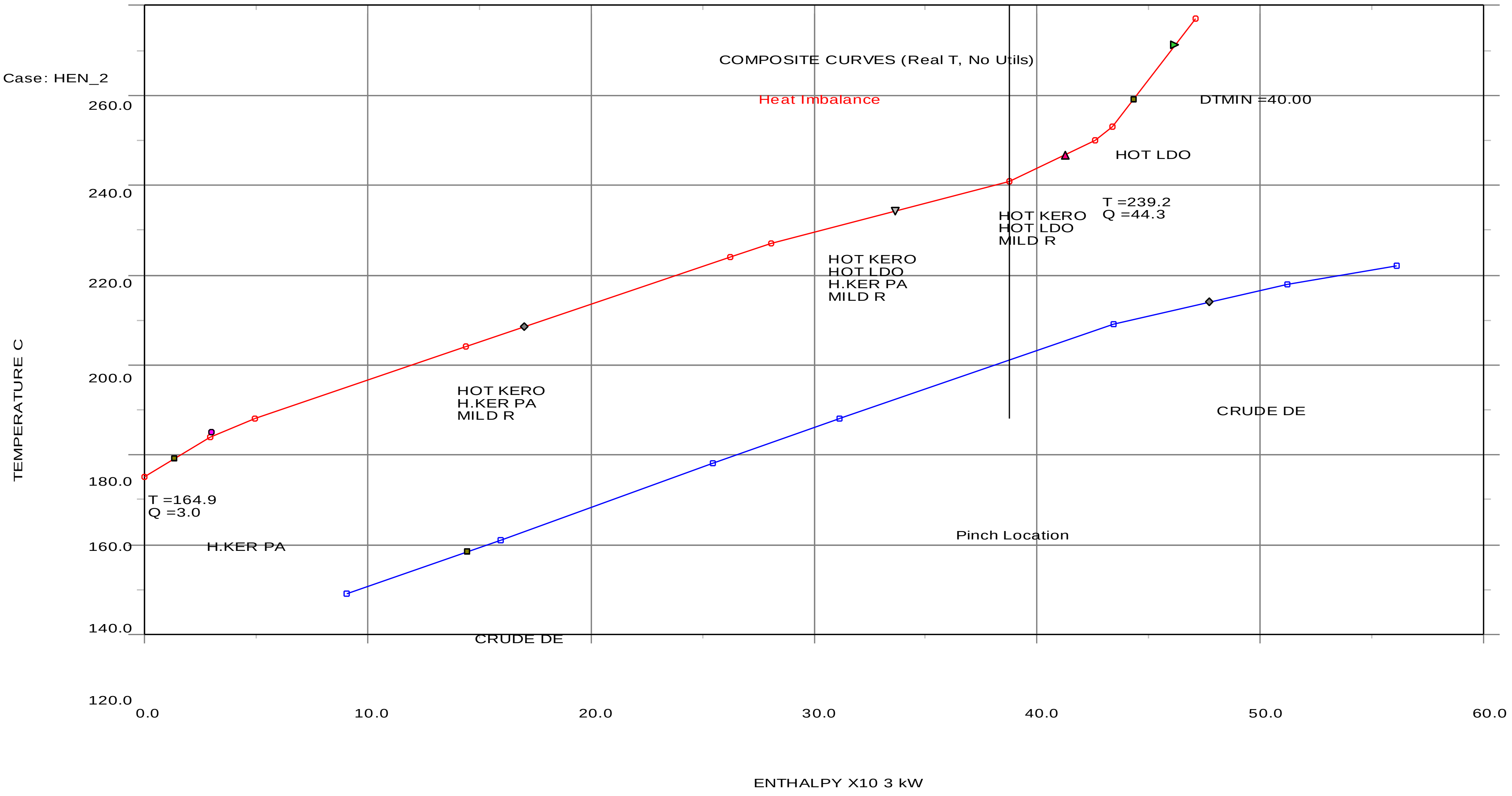


Figure D.3: *Composite Curve of HEN-2 for* $\Delta T_{min} = 40^{o}C$

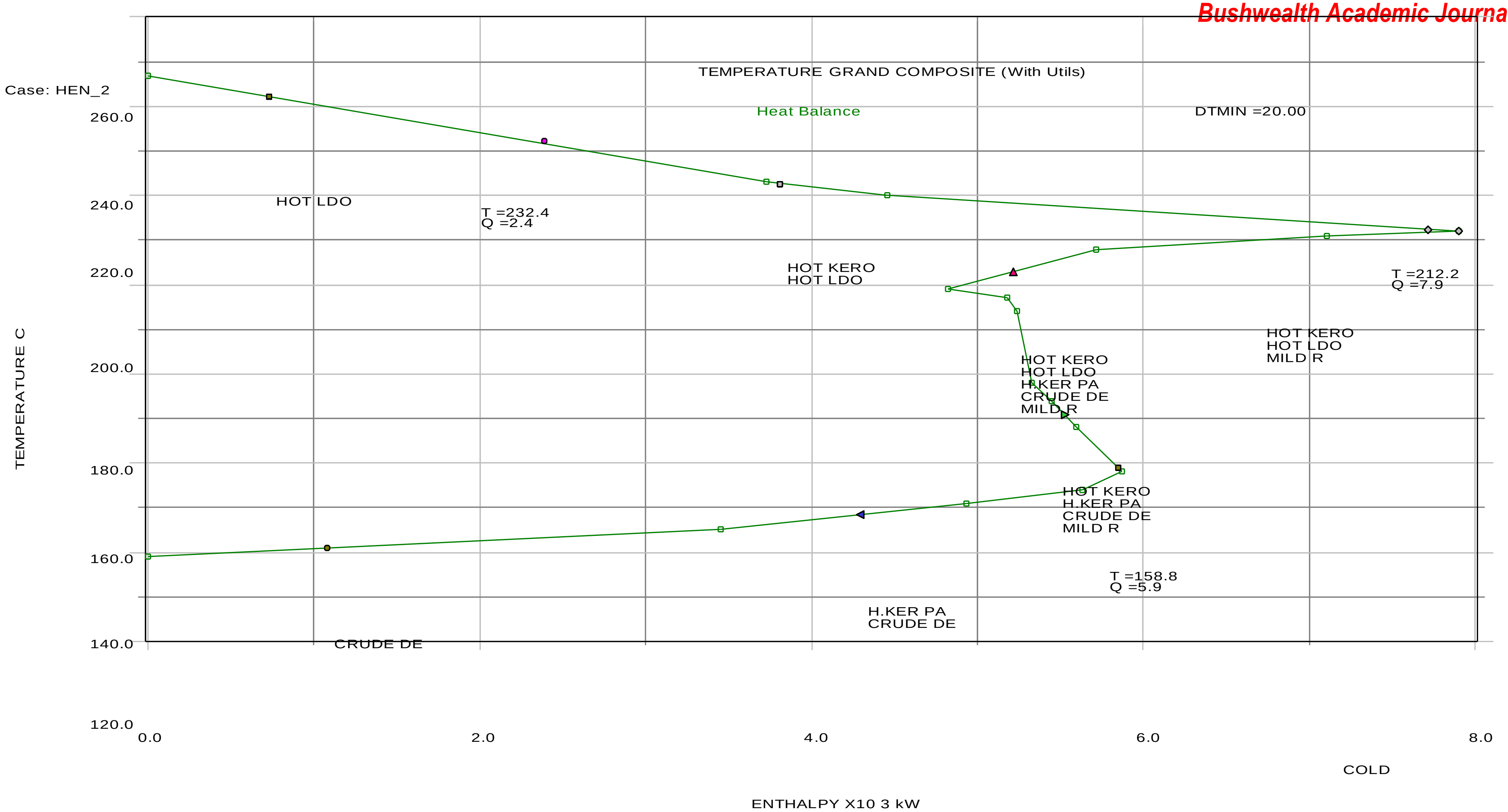


Figure D.4: *Grand Composite Curve of HEN-2 for* $\Delta T_{min} = 20^{o}C$

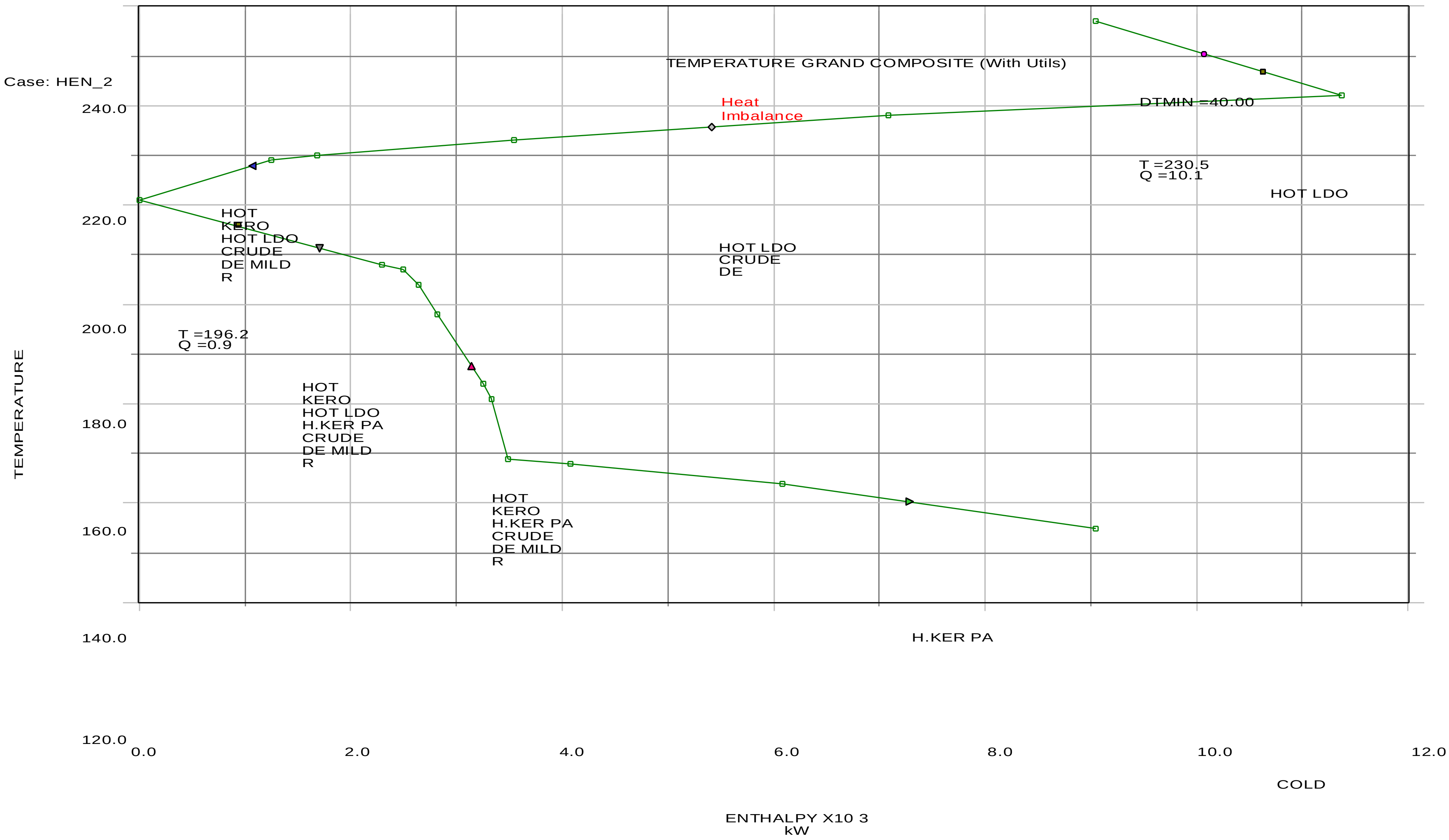

Case: HEN_2
TEMPERATURE GRAND COMPOSITE (With Utils)
Heat
Imbalance
DTMIN =40.00
T =230.5
Q =10.1
HOT LDO
HOT
KERO
HOT LDO
CRUDE
DE MILD
R
HOT LDO
CRUDE
DE
T =196.2
Q =0.9
HOT
KERO
HOT LDO
H.KER PA
CRUDE
DE MILD
R
HOT
KERO
H.KER PA
CRUDE
DE MILD
R
H.KER PA
COLD
TEMPERATURE
240.0
220.0
200.0
180.0
160.0
140.0
120.0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
ENTHALPY X10 3
kW

Figure D.5: *Grand Composite Curve of HEN-2 for* $\Delta T_{min} = 40^oC$

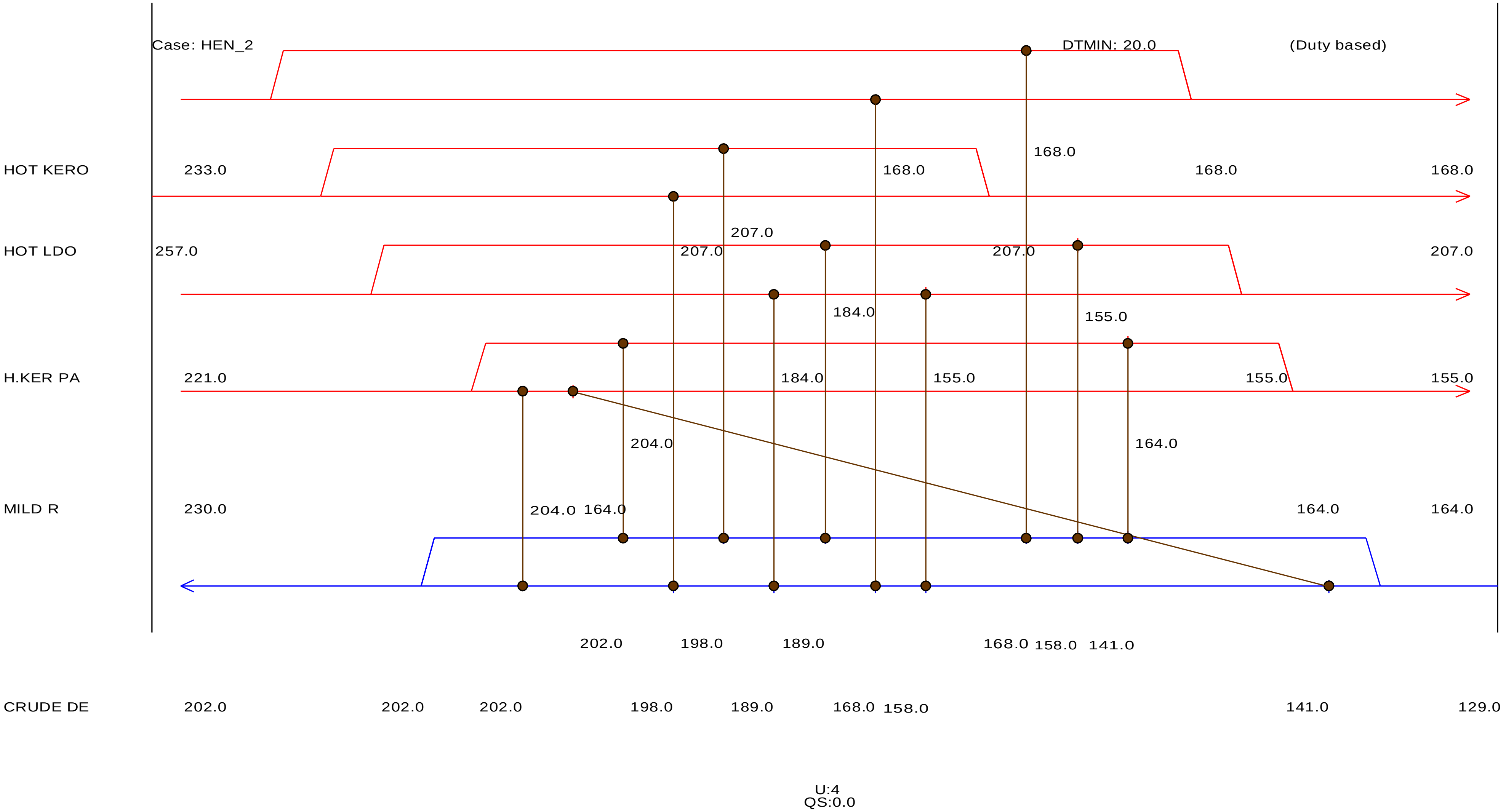

Case: HEN_2
DTMIN: 20.0
(Duty based)
HOT KERO
233.0
168.0
168.0
168.0
168.0
207.0
HOT LDO
257.0
207.0
207.0
207.0
184.0
155.0
H.KER PA
221.0
184.0
155.0
155.0
155.0
204.0
164.0
MILD R
230.0
204.0
164.0
164.0
164.0
202.0
198.0
189.0
168.0
158.0
141.0
CRUDE DE
202.0
202.0
202.0
198.0
189.0
168.0
158.0
141.0
129.0
U:4
QS:0.0

Figure D.6: *Grid Representation of HEN-2 for* $\Delta T_{min} = 20^{o}C$

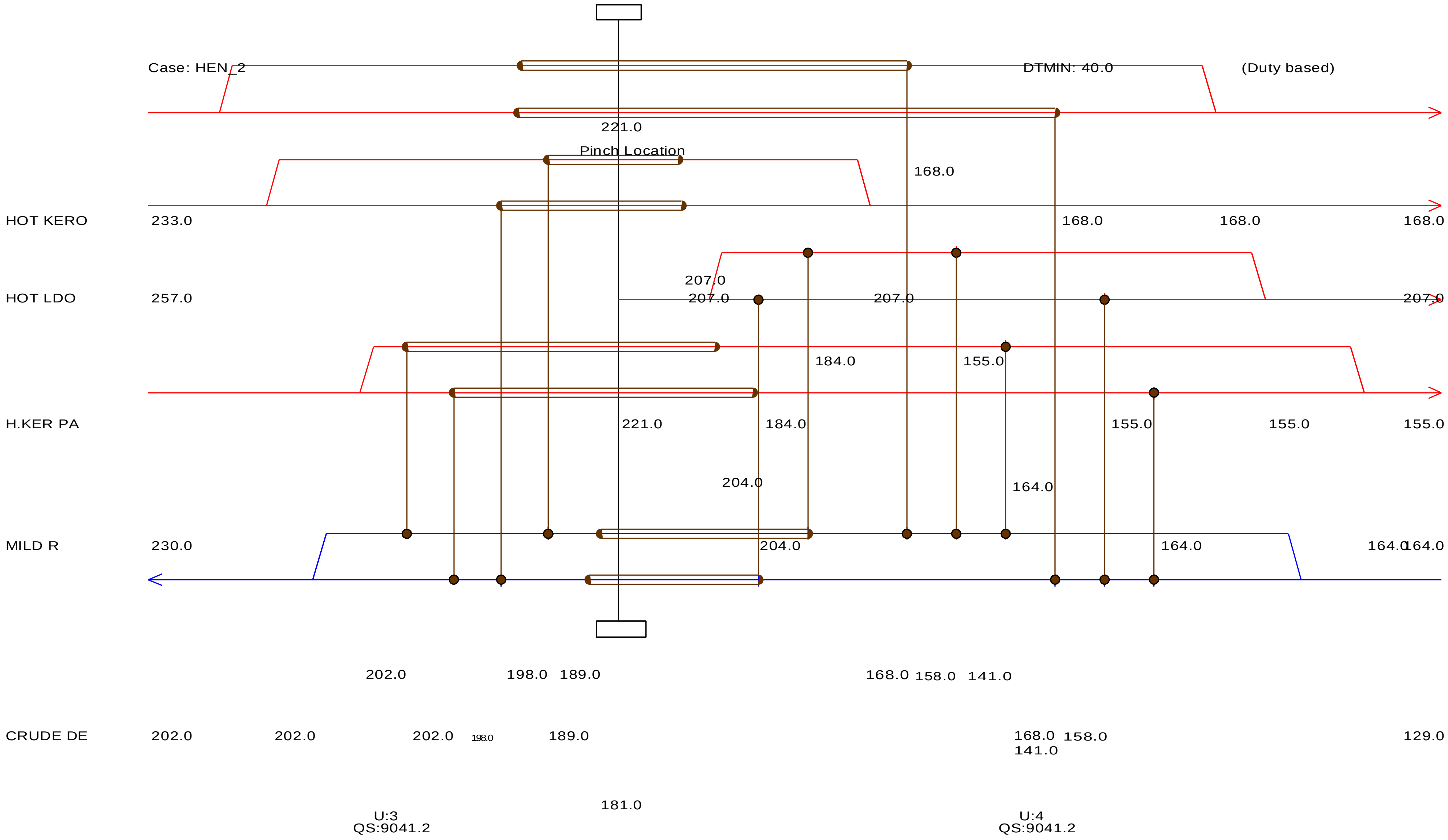

Case: HEN_2
DTMIN: 40.0
(Duty based)
221.0
Pinch Location
168.0
HOT KERO
233.0
168.0
168.0
168.0
207.0
HOT LDO
257.0
207.0
207.0
207.0
184.0
155.0
H.KER PA
221.0
184.0
155.0
155.0
155.0
204.0
164.0
MILD R
230.0
204.0
164.0
164.0
164.0
202.0
198.0
189.0
168.0
158.0
141.0
CRUDE DE
202.0
202.0
202.0
198.0
189.0
168.0
158.0
141.0
129.0
181.0
U:3
QS:9041.2
U:4
QS:9041.2

Figure D.7: *Grid Representation of HEN-2 for* $\Delta T_{min} = 40^oC$

Table D.1: *Targeting Report of HEN-2 for* $\Delta T_{min} = 20^oC$ *and* 40^oC

```
 A S P E N   P I N C H  (TM)


   Targeting Results, Case:  HEN_2


 *****************************************************
 * The streams and utilities are in heat balance     *
 *    (heat balance toler:         0.0  kW         ) *
 *****************************************************


          Delta Tmin                 20.0         C

                          Pinch T          Delta T  (Real)
Pinch temperature(s):    247.0       C     55.0          C
                          139.0       C     26.0          C


          Total Hot  utility used    0.0          kW
          Total Cold utility used    0.0          kW

          Minimum total 1-1 area     1588781.2    m2
              Pros/Pros 1-1 area     1588781.2    m2
          Minimum number of units            4


Cross Pinch Heat Transfer Penalties

                              Penalty units : kW

                            * denotes a near pinch
```

```
 A S P E N   P I N C H  (TM)


   Targeting Results, Case:  HEN_2

 *****************************************************
 *           No utilities have been placed           *
 *****************************************************

             Minimum hot  utility           9041.2   kW
             Minimum cold utility           9041.2   kW

         Delta Tmin                 40.0         C


                           Pinch T          Delta T (Real)
     Pinch temperature(s):   201.0      C     40.0         C


                          (No cross pinch heat exchange)
```

```
Total Hot  utility used    0.0
kW Total Cold utility used    0.0
kW
```

Cross Pinch Heat Transfer Penalties

```
                          Penalty
                        units : kW

                       * denotes a
                        near pinch


              Pinch#   1
 Hxer ID    Ti =  201.00 C
                                                                          --------    --------------
                                                                          10E11AB     -1604.47
                                                                          10E11CD     -1604.47
                                                                          10E10B      -1087.62
                                                                          10E10A      -1087.62
                                                                          10E09AB     -2348.11
                                                                          10E09CD     -2348.11
                                                                          10E08A      519.583
                                                                          10E08B      519.583
                                                                          --------    --------------
                                                                           Sum -->     -9041.23
```

Appendix E

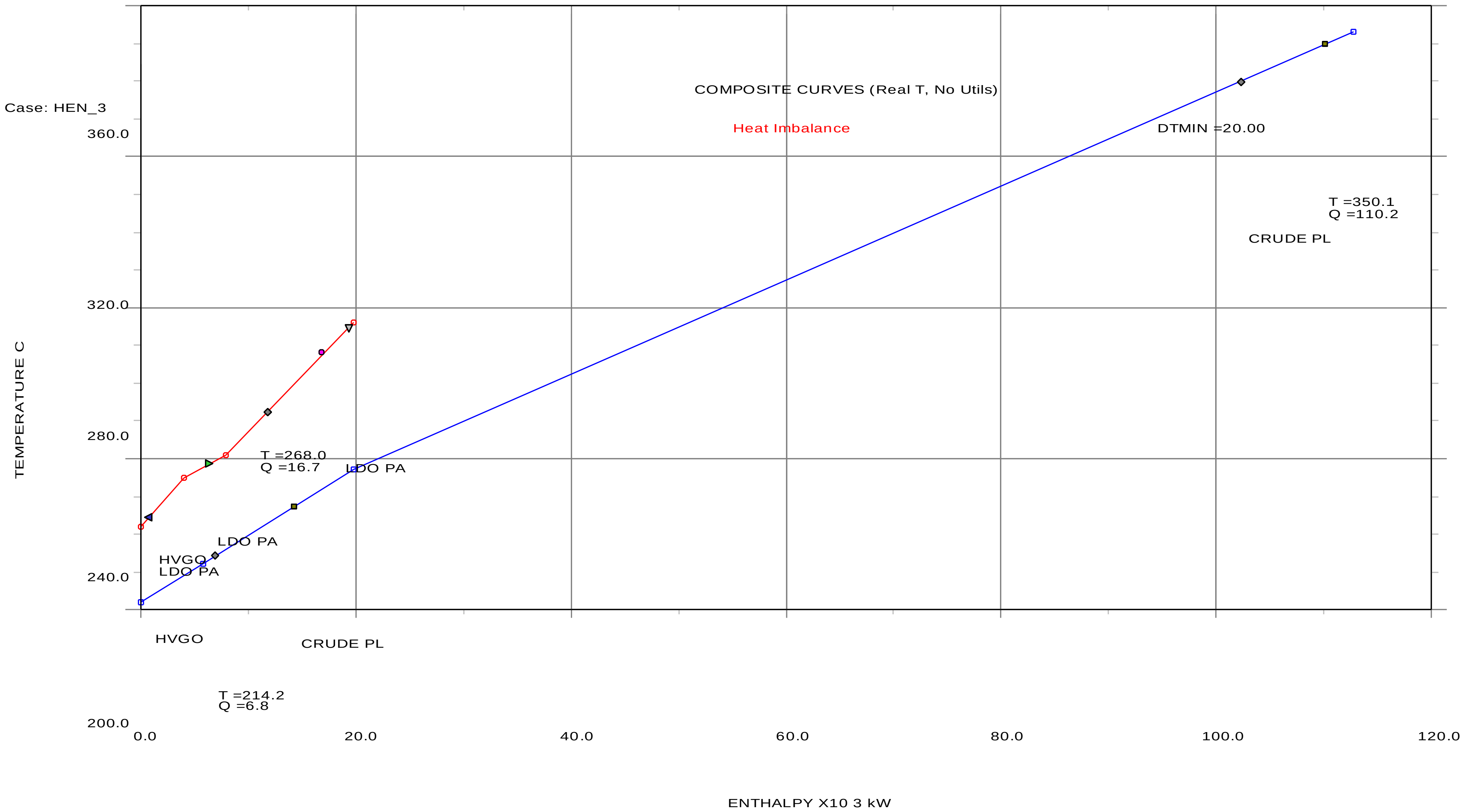

Case: HEN_3
COMPOSITE CURVES (Real T, No Utils)
Heat Imbalance
DTMIN =20.00
T =350.1
Q =110.2
CRUDE PL
T =268.0
Q =16.7
LDO PA
LDO PA
HVGO
LDO PA
HVGO
CRUDE PL
T =214.2
Q =6.8
TEMPERATURE C
360.0
320.0
280.0
240.0
200.0
0.0
20.0
40.0
60.0
80.0
100.0
120.0
ENTHALPY X10 3 kW

Figure E.1: *Composite Curves of HEN-3 for* $\Delta T_{min} = 20^{o}C$

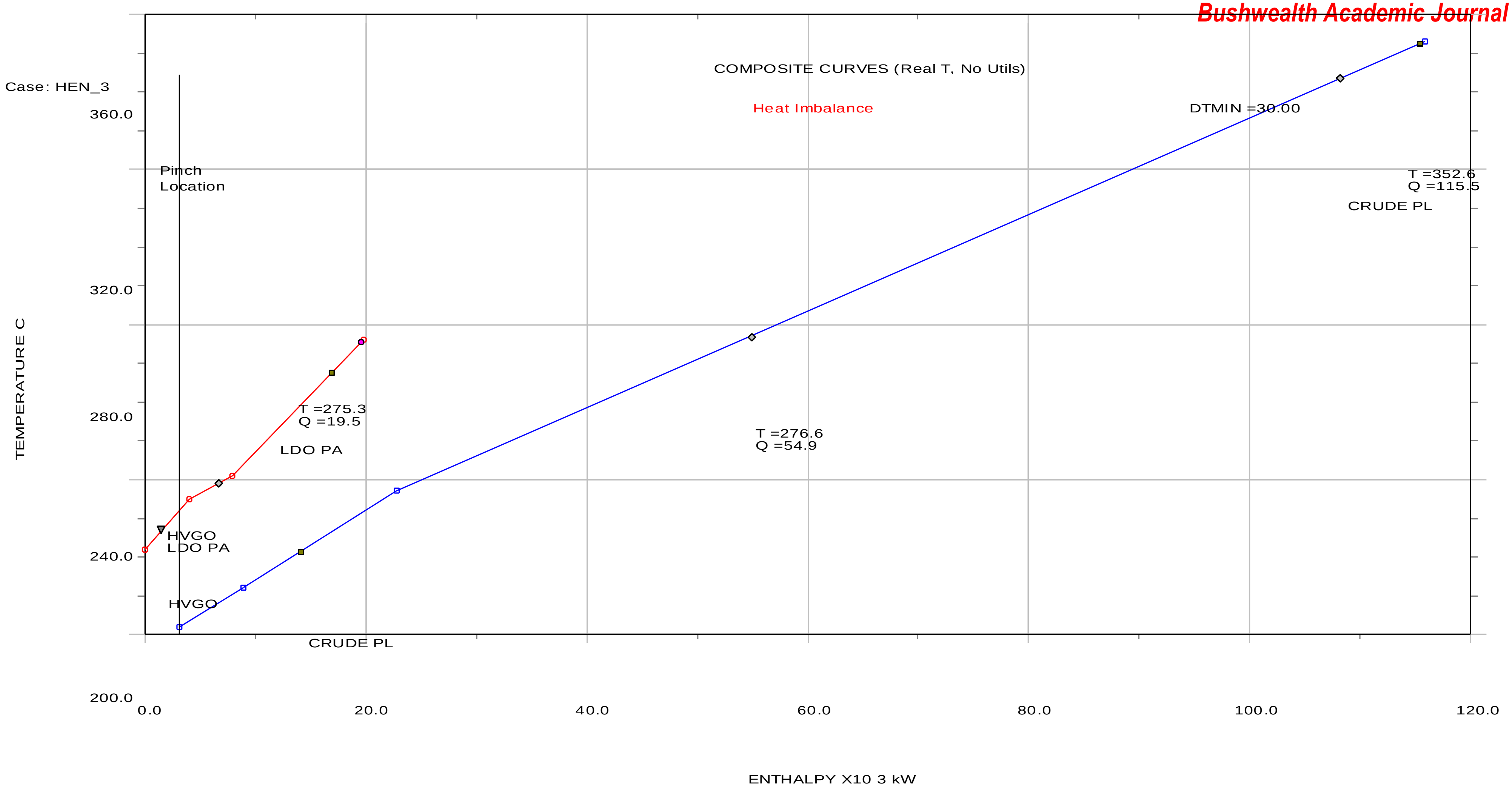


Figure E.2: *Composite Curves of HEN-3 for* $\Delta T_{min} = 30^{o}C$

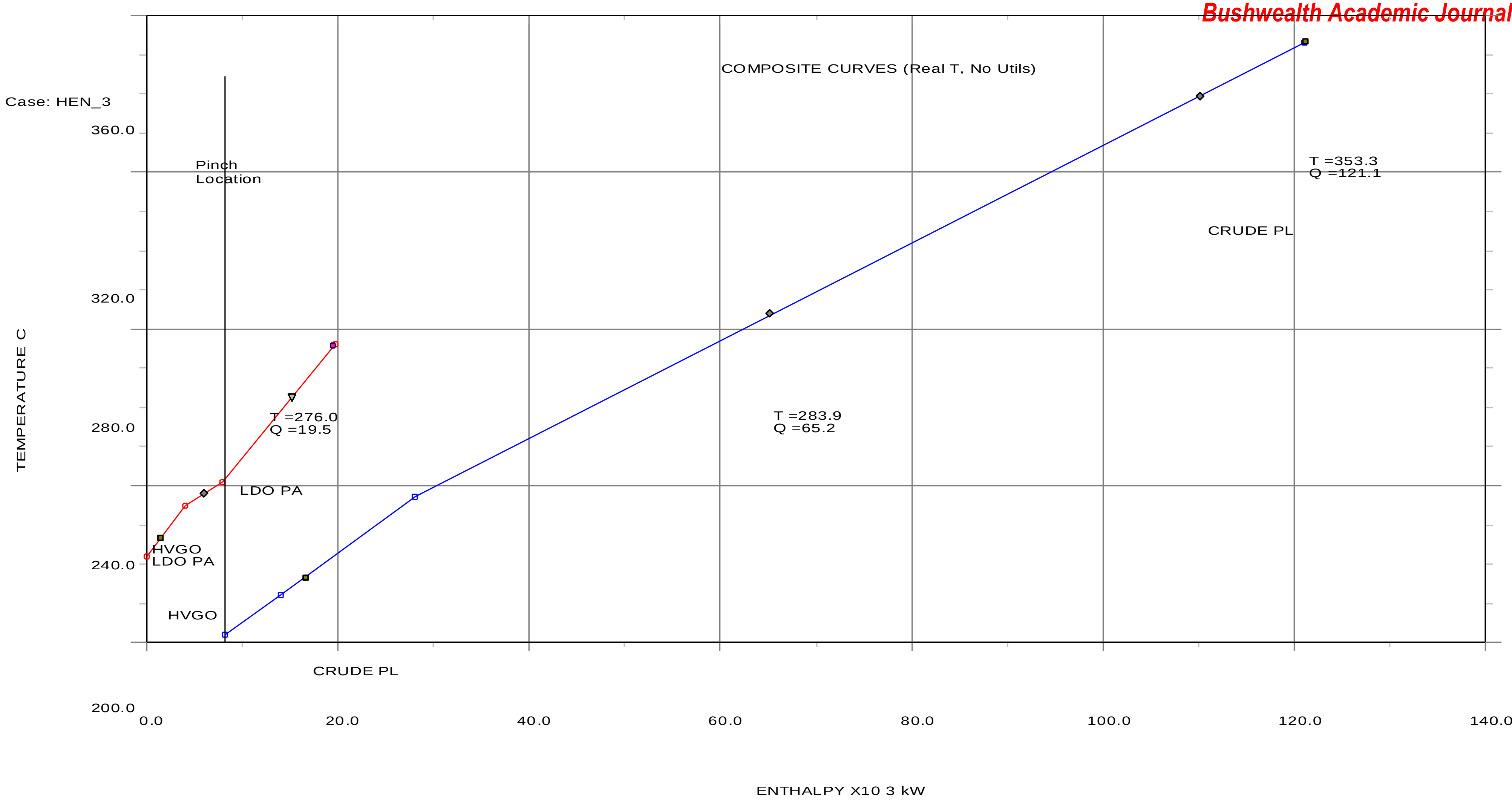


Figure E.3: *Composite Curves of HEN-3 for* $\Delta T_{min} = 40^{o}C$

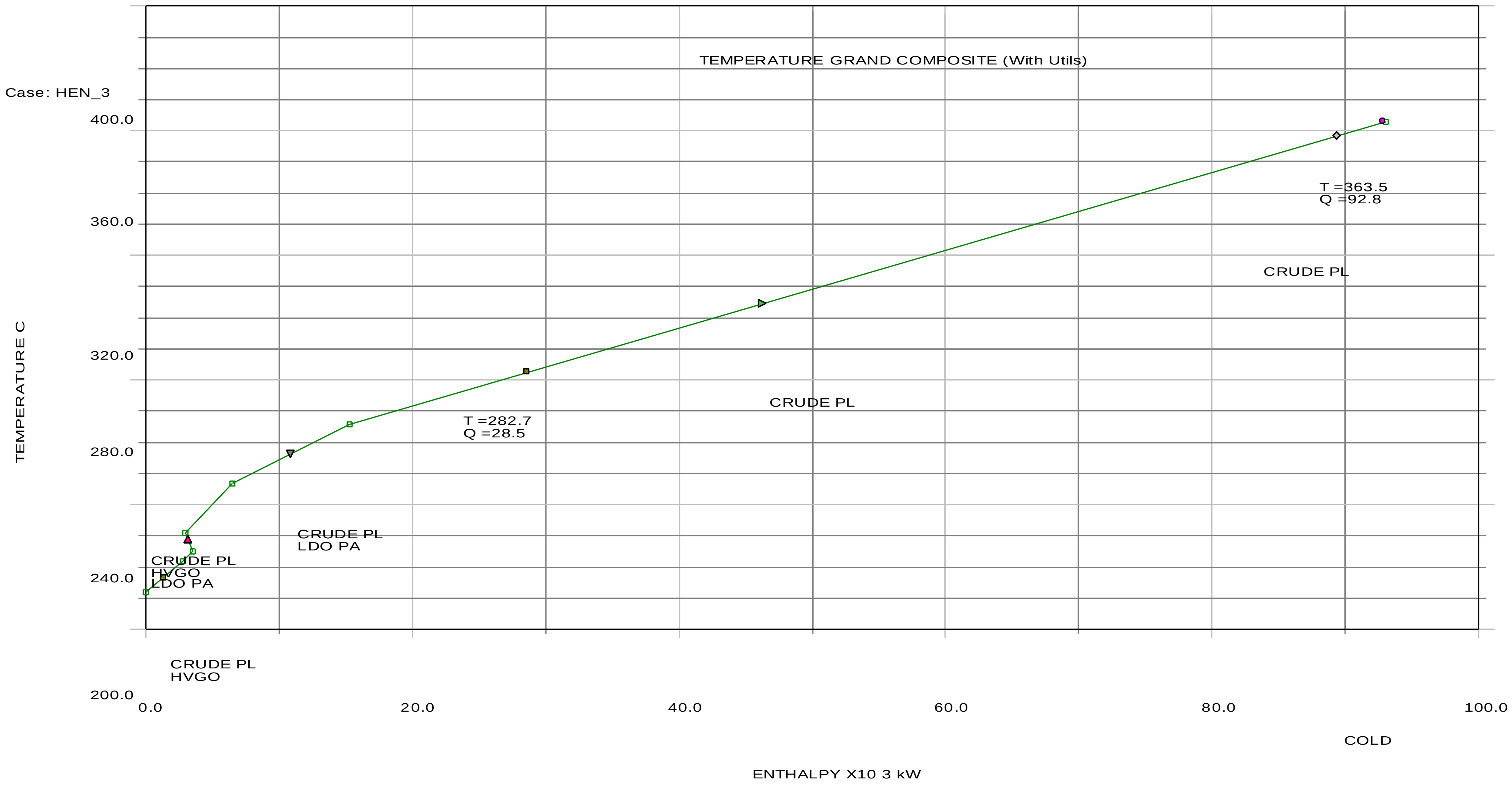


Figure E.4: *Grand Composite Curve for HEN-3 for $\Delta T_{min} = 20^{o}C$*

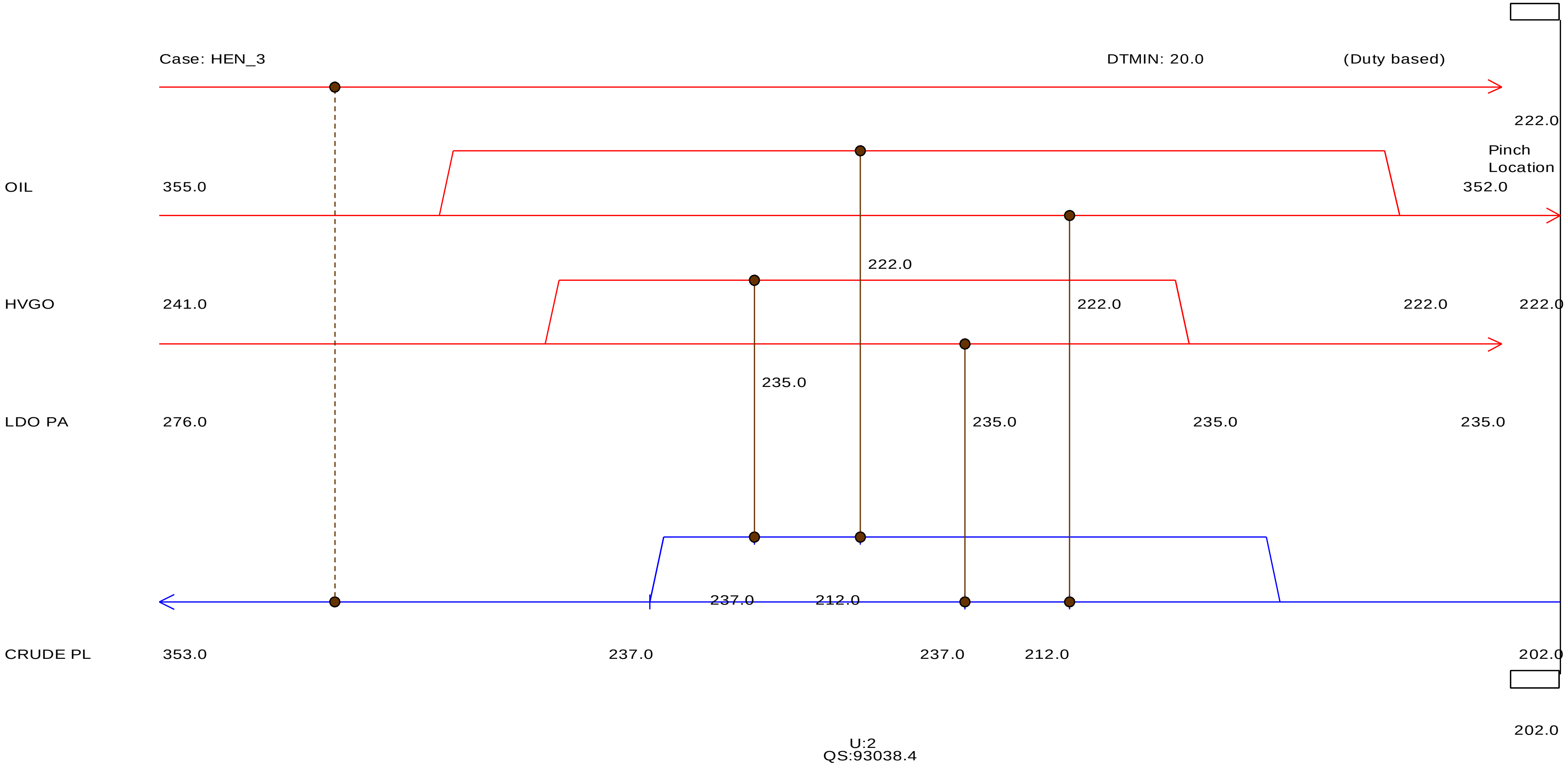


Figure E.5: *Grid Representation of HEN-3 for $\Delta T_{min} = 20^oC$*

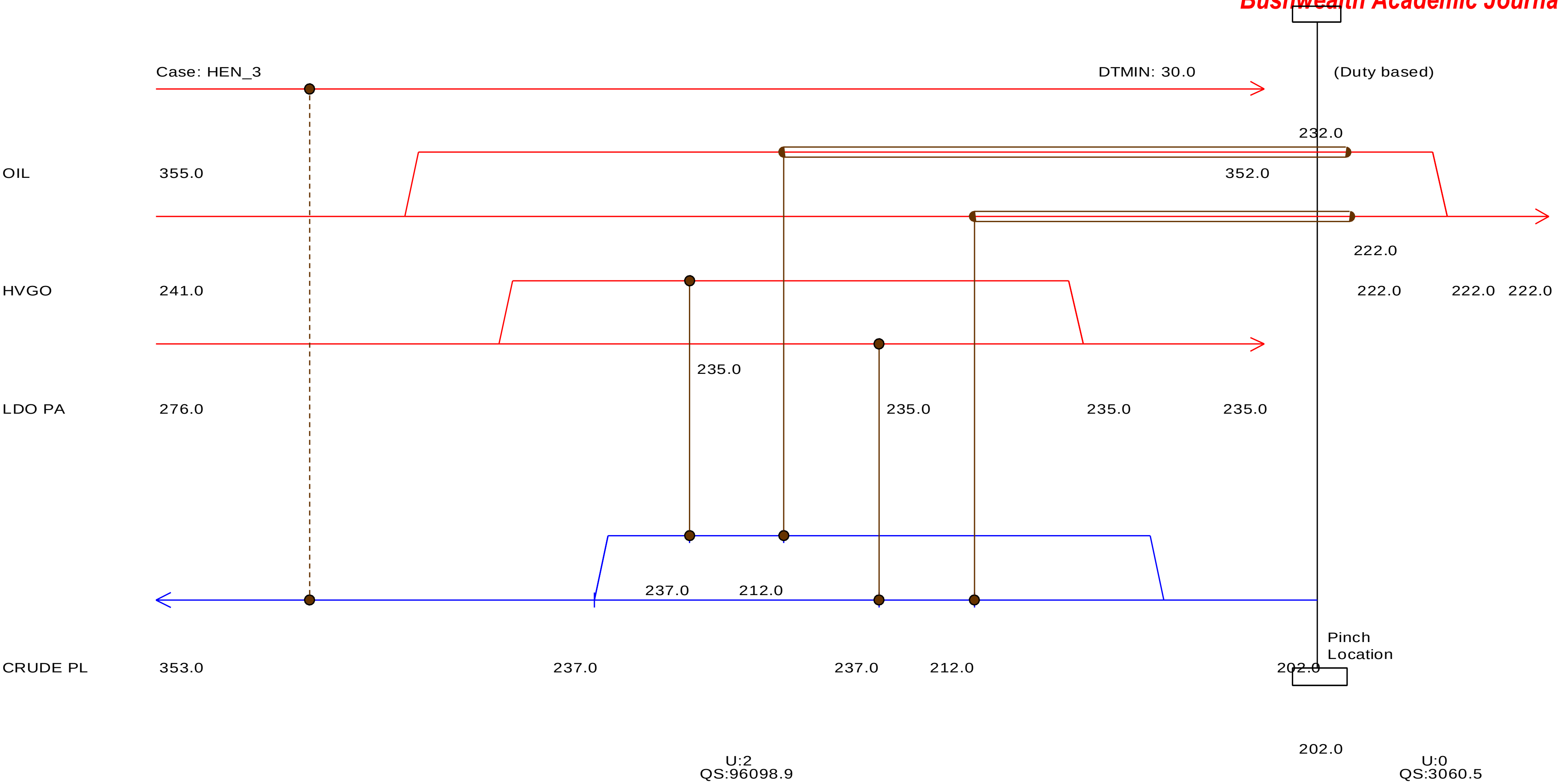


Figure E.6: *Grid Representation of HEN-3 for* $\Delta T_{min} = 30^{o}C$

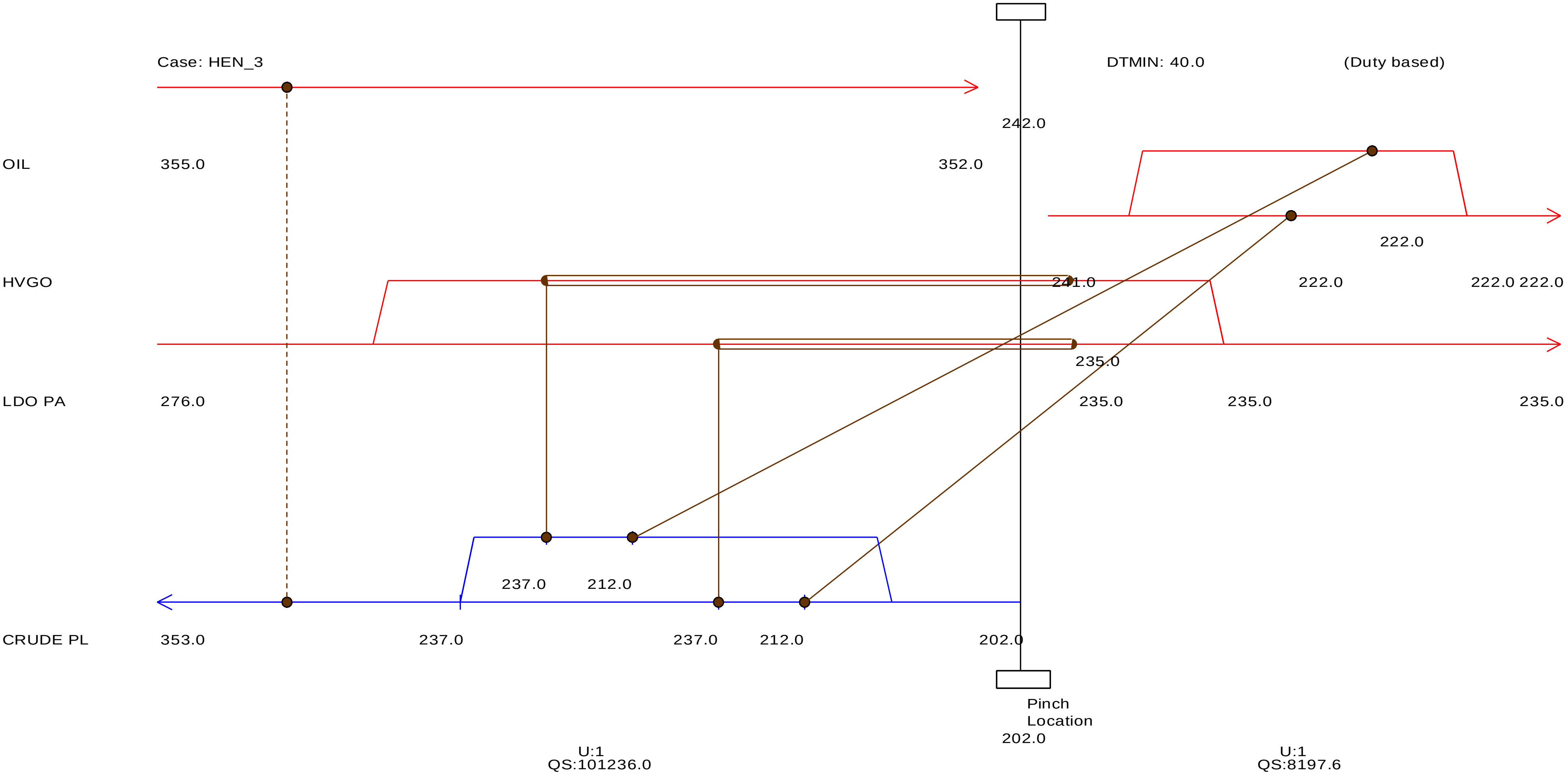


Figure E.7: *Grid Representation of HEN-3 for* $T_{min} = 40^{o}C$

Table E.1: *Targeting Report of HEN-3 for* $\Delta T_{min} = 20^{o}C$ *and* $40\,^{o}C$

```
A S P E N   P I N C H  (TM)


  Targeting Results, Case:  HEN_3


 ****************************************************
 *           No utilities have been placed          *
 ****************************************************

           Minimum hot  utility          93038.4  kW
           Minimum cold utility              0.0  kW

          Delta Tmin                 20.0         C

                                Pinch T         Delta T (Real)
Pinch temperature(s):          212.0       C     20.0         C

          Total Hot  utility used    0.0           kW
          Total Cold utility used    0.0           kW


Cross Pinch Heat Transfer Penalties

                           Penalty units : kW

                         * denotes a near pinch
```

```
A S P E N   P I N C H  (TM)


  Targeting Results, Case:  HEN_3

 ****************************************************
 *           No utilities have been placed          *
 ****************************************************

           Minimum hot  utility          101236.0  kW
           Minimum cold utility            8197.6  kW

          Delta Tmin                 40.0         C

                                Pinch T         Delta T (Real)
  Pinch temperature(s):        222.0       C     40.0         C

          Total Hot  utility used    0.0           kW
          Total Cold utility used    0.0           kW


Cross Pinch Heat Transfer Penalties

                                          (No cross pinch heat
                                                exchange)
```

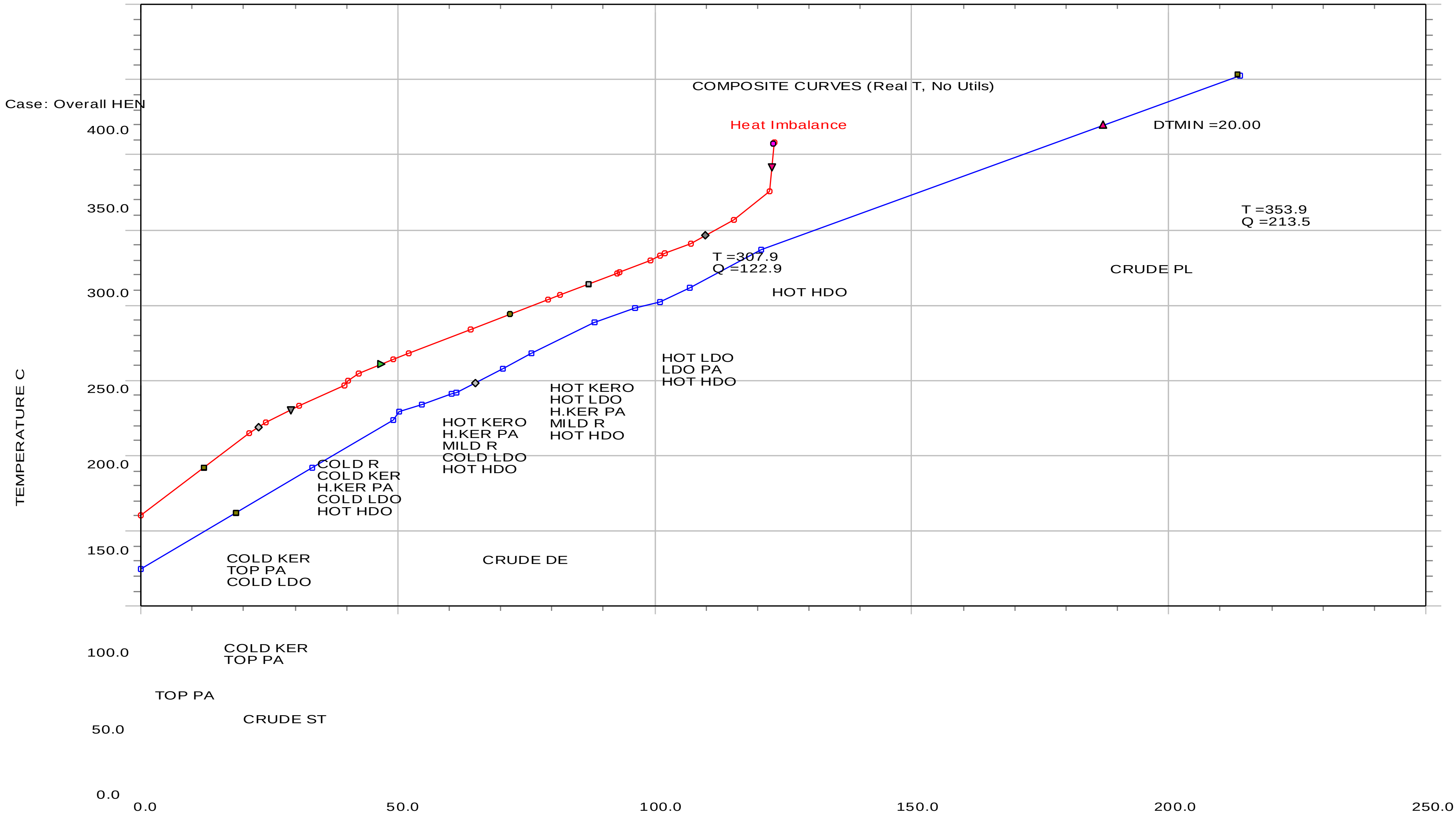
```
            Penalty units : kW

          * denotes a near pinch


Pinch#   1

                                                       Hxer ID     Ti =  222.00 C
                                                       --------    --------------
                                                       10E12CD     -1191.37
                                                       10E13B      -2907.45
                                                       10E12AB     -1191.30
                                                       10E13A      -2907.45
                                                       --------    --------------
                                                        Sum -->     -8197.58
```

Appendix F


COMPOSITE CURVES (Real T, No Utils)
Case: Overall HEN
Heat Imbalance
DTMIN =20.00
T =353.9
Q =213.5
T =307.9
Q =122.9
CRUDE PL
HOT HDO
HOT LDO
LDO PA
HOT HDO
HOT KERO
HOT LDO
H.KER PA
MILD R
HOT HDO
HOT KERO
H.KER PA
MILD R
COLD LDO
HOT HDO
COLD R
COLD KER
H.KER PA
COLD LDO
HOT HDO
COLD KER
TOP PA
COLD LDO
CRUDE DE
COLD KER
TOP PA
TOP PA
CRUDE ST
TEMPERATURE C
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
0.0
50.0
100.0
150.0
200.0
250.0

ENTHALPY X10 3 kW

Figure F.1: *Composite Curves of Overall HEN for* $\Delta T_{min} = 20^{o}C$

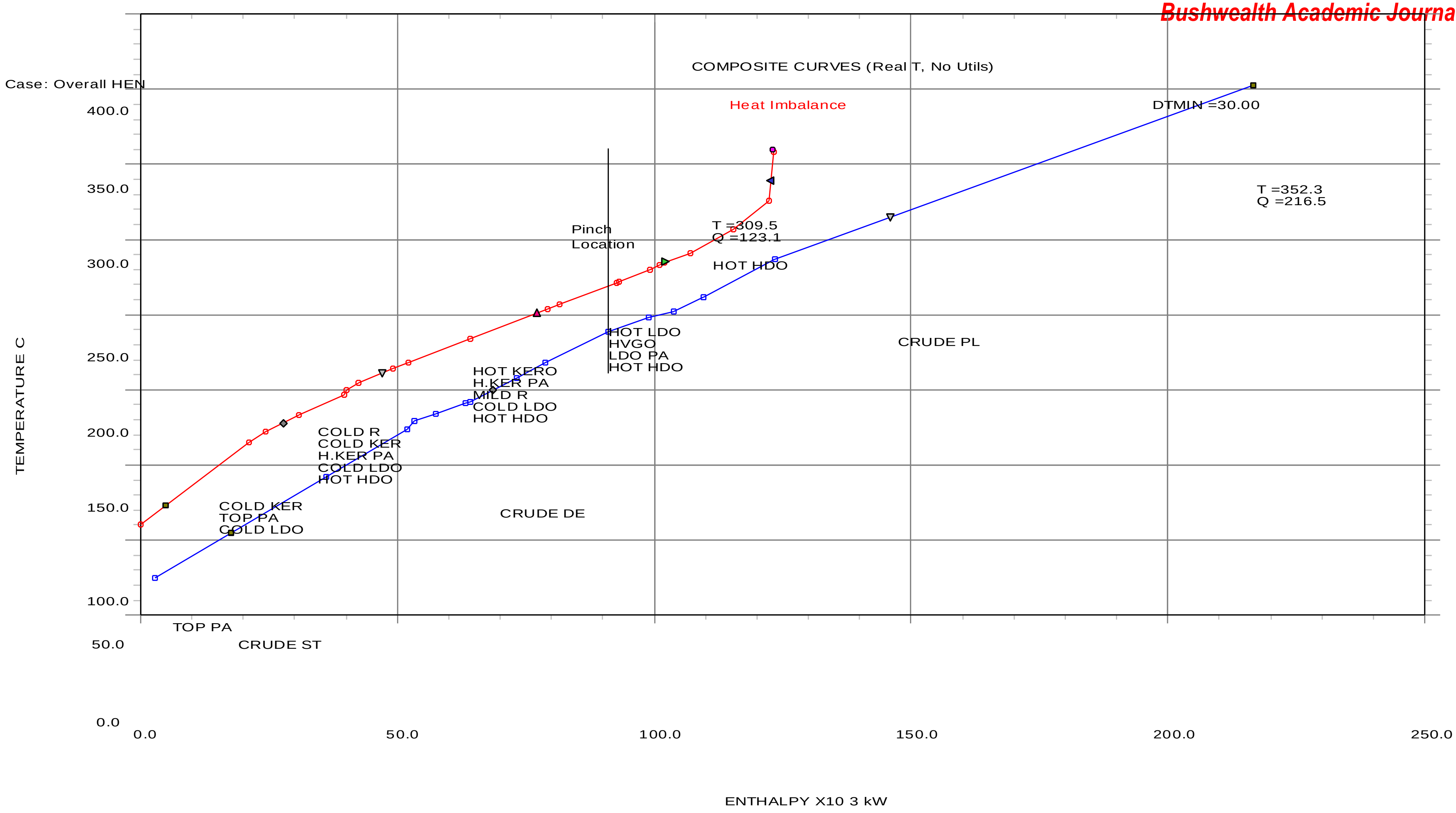


Figure F.2: *Composite Curves of Overall HEN for* $T_{min} = 30^{0}C$

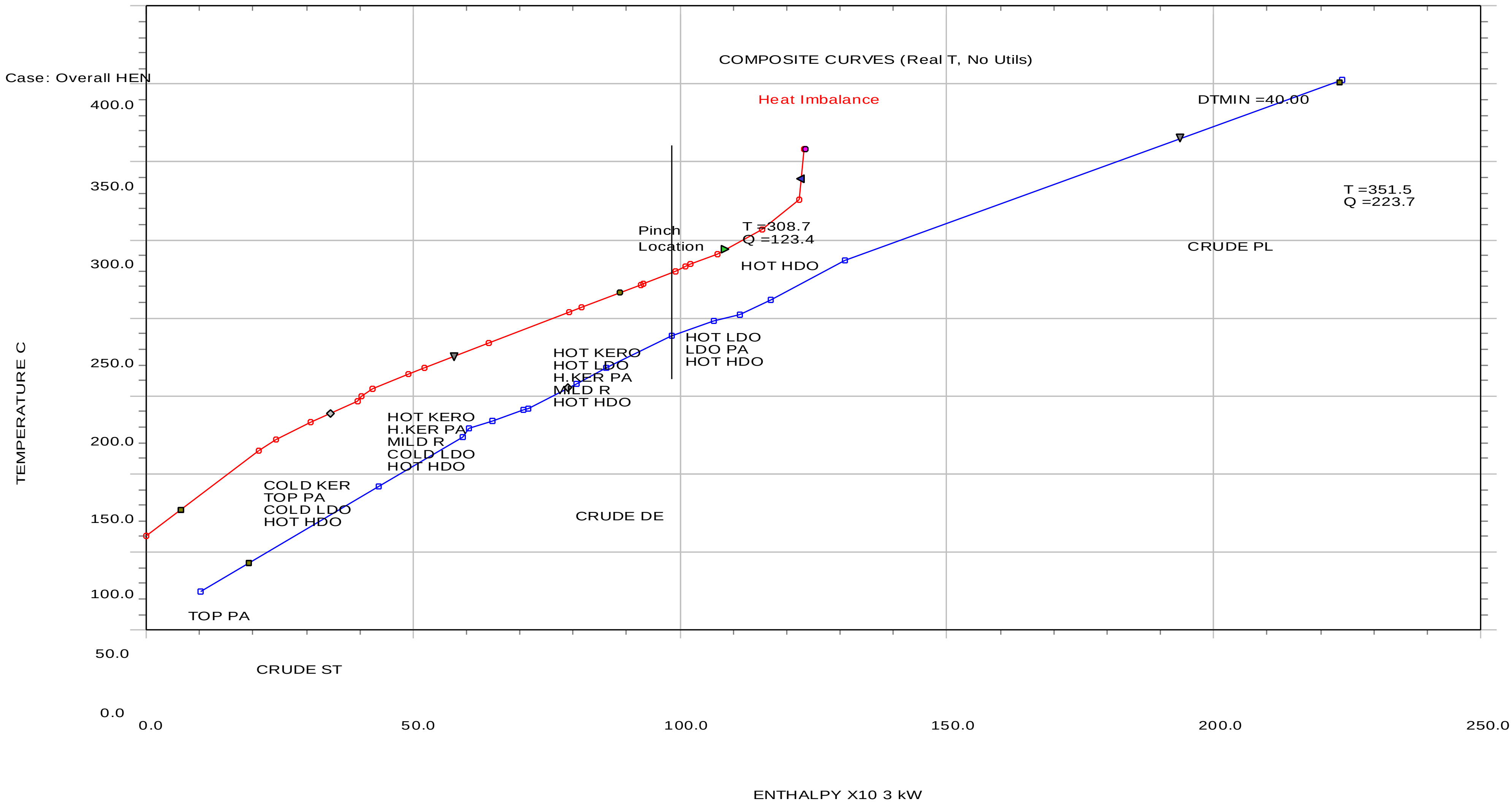


Figure F.3: *Composite Curves of Overall HEN for $\Delta T_{min} = 40^{o}C$*

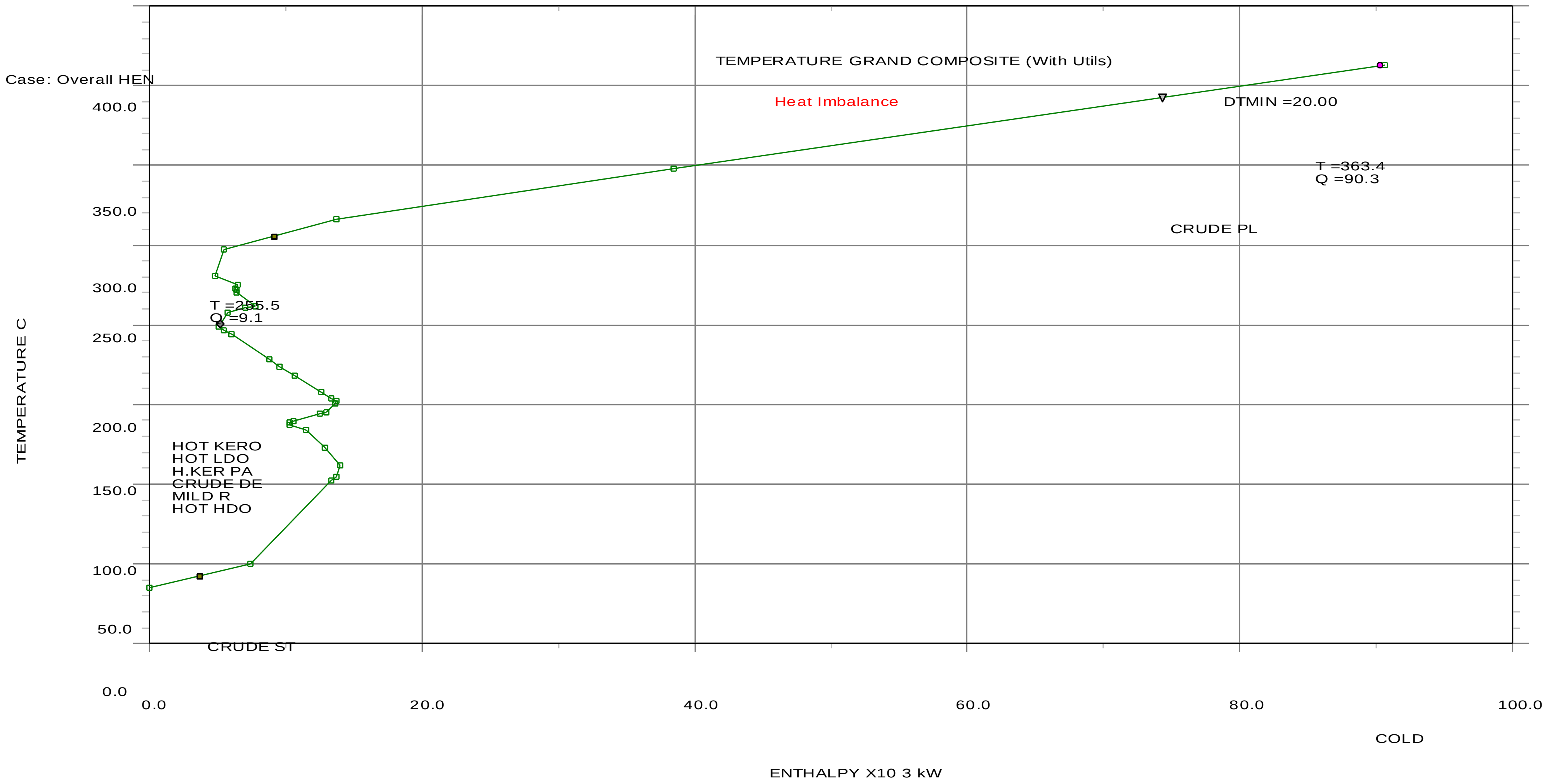


Figure F.4: *Grand Composite Curve of Overall HEN for* $T_{min} = 20^{o}C$

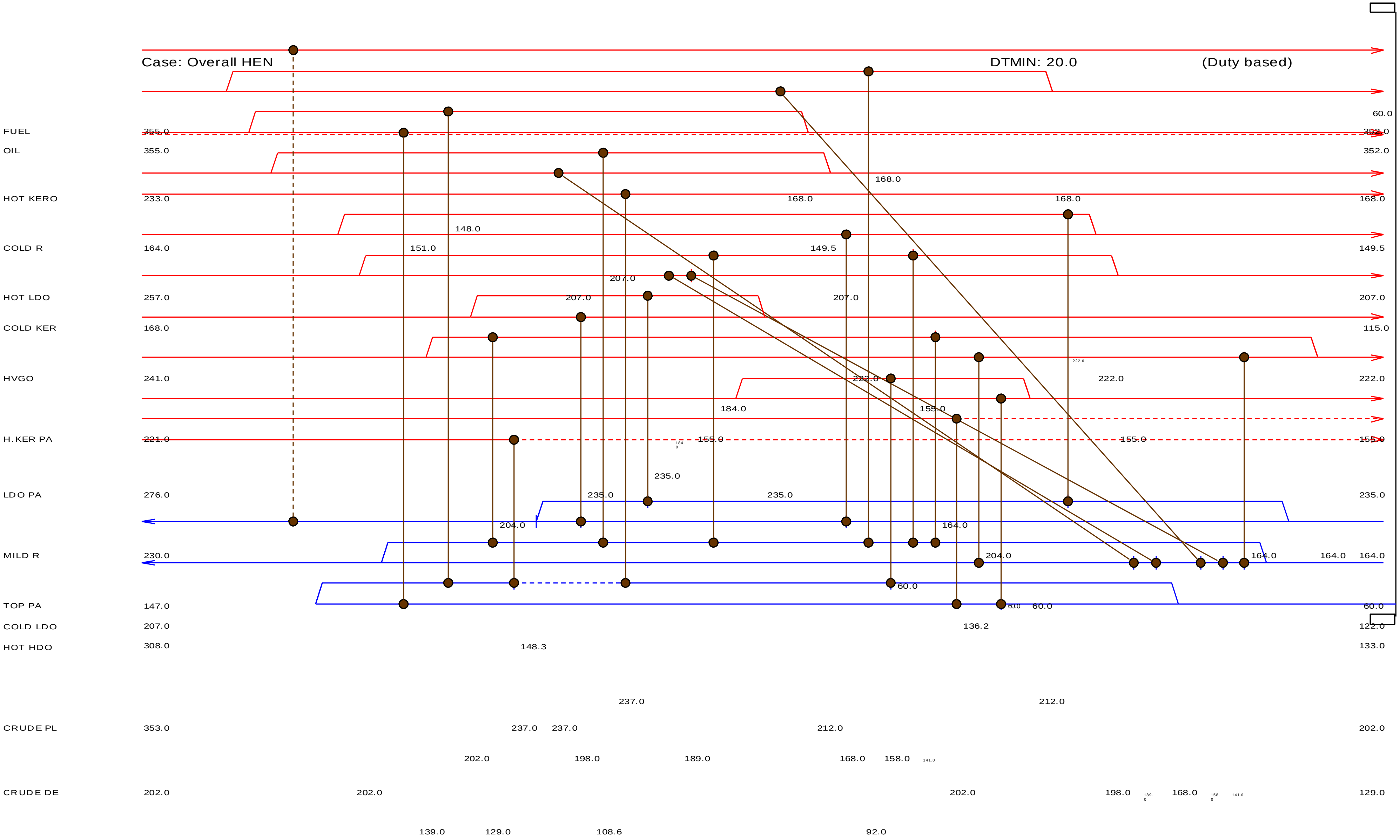
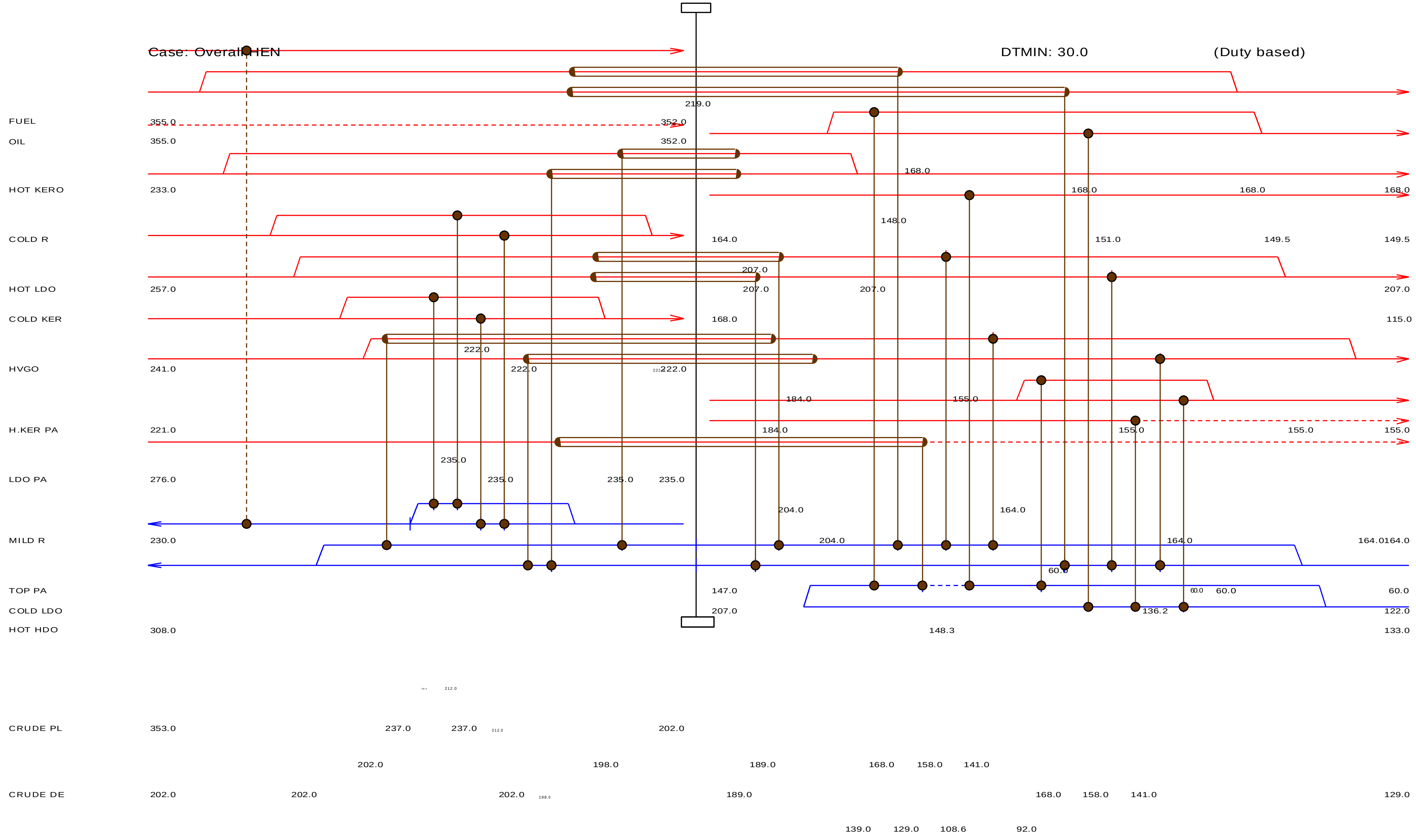

Case: Overall HEN
DTMIN: 20.0
(Duty based)
FUEL
OIL
HOT KERO
COLD R
HOT LDO
COLD KER
HVGO
H.KER PA
LDO PA
MILD R
TOP PA
COLD LDO
HOT HDO
CRUDE PL
CRUDE DE
355.0
355.0
233.0
164.0
257.0
168.0
241.0
221.0
276.0
230.0
147.0
207.0
308.0
353.0
202.0
60.0
352.0
352.0
168.0
149.5
207.0
115.0
222.0
155.0
235.0
164.0
60.0
122.0
133.0
202.0
129.0
168.0
168.0
168.0
148.0
151.0
149.5
207.0
207.0
207.0
222.0
222.0
222.0
184.0
155.0
155.0
155.0
235.0
235.0
235.0
204.0
164.0
204.0
164.0
164.0
60.0
60.0
60.0
136.2
148.3
237.0
212.0
237.0
237.0
212.0
202.0
198.0
189.0
168.0
158.0
141.0
202.0
202.0
198.0
168.0
141.0
139.0
129.0
108.6
92.0

Figure F.5: *Grid Representation of Overall HEN for* $\Delta T_{min} = 20^oC$


Case: Overall HEN
DTMIN: 30.0
(Duty based)
219.0
FUEL
355.0
352.0
OIL
355.0
352.0
168.0
HOT KERO
233.0
168.0
168.0
168.0
148.0
COLD R
164.0
151.0
149.5
149.5
207.0
HOT LDO
257.0
207.0
207.0
207.0
COLD KER
168.0
115.0
222.0
HVGO
241.0
222.0
222.0
184.0
155.0
H.KER PA
221.0
184.0
155.0
155.0
155.0
235.0
LDO PA
276.0
235.0
235.0
235.0
204.0
164.0
MILD R
230.0
204.0
164.0
164.0164.0
60.0
TOP PA
147.0
60.0
60.0
60.0
COLD LDO
207.0
136.2
122.0
HOT HDO
308.0
148.3
133.0
212.0
CRUDE PL
353.0
237.0
237.0
212.0
202.0
202.0
198.0
189.0
168.0
158.0
141.0
CRUDE DE
202.0
202.0
202.0
198.0
189.0
168.0
158.0
141.0
129.0
139.0
129.0
108.6
92.0

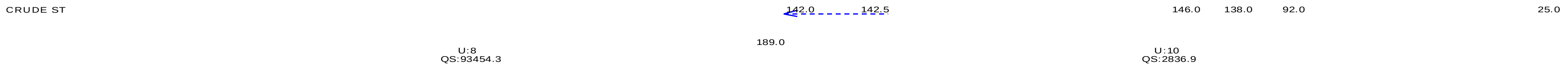
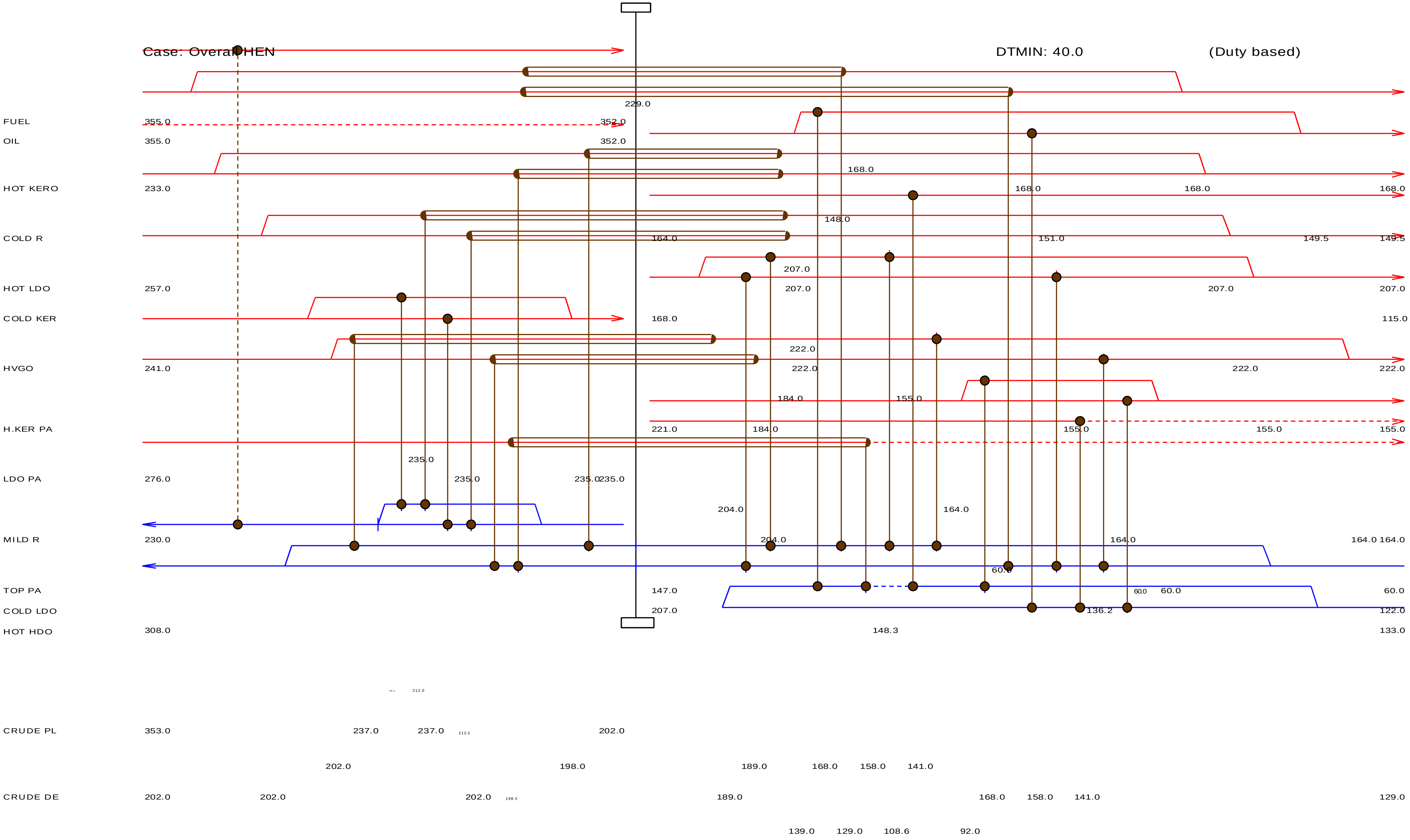


Figure F.6: *Grid Representation of Overall HEN for* $\Delta T_{min} = 30^{o}C$


Case: Overall HEN
DTMIN: 40.0
(Duty based)
229.0
FUEL
355.0
352.0
OIL
355.0
352.0
168.0
HOT KERO
233.0
168.0
168.0
168.0
148.0
COLD R
164.0
151.0
149.5
149.5
207.0
HOT LDO
257.0
207.0
207.0
207.0
COLD KER
168.0
115.0
222.0
HVGO
241.0
222.0
222.0
222.0
184.0
155.0
H.KER PA
221.0
184.0
155.0
155.0
155.0
235.0
LDO PA
276.0
235.0
235.0
235.0
204.0
164.0
MILD R
230.0
204.0
164.0
164.0
164.0
60.0
TOP PA
147.0
60.0
60.0
60.0
COLD LDO
207.0
136.2
122.0
HOT HDO
308.0
148.3
133.0
212.0
CRUDE PL
353.0
237.0
237.0
212.0
202.0
202.0
198.0
189.0
168.0
158.0
141.0
CRUDE DE
202.0
202.0
202.0
198.0
189.0
168.0
158.0
141.0
129.0
139.0
129.0
108.6
92.0

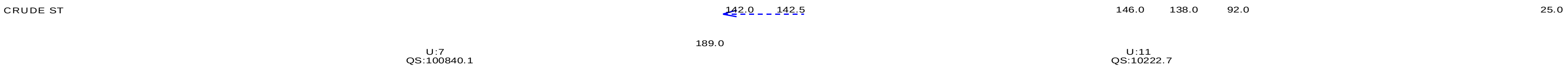


Figure F.7: *Grid Representation of Overall HEN for* $T_{min} = 40^{o}C$

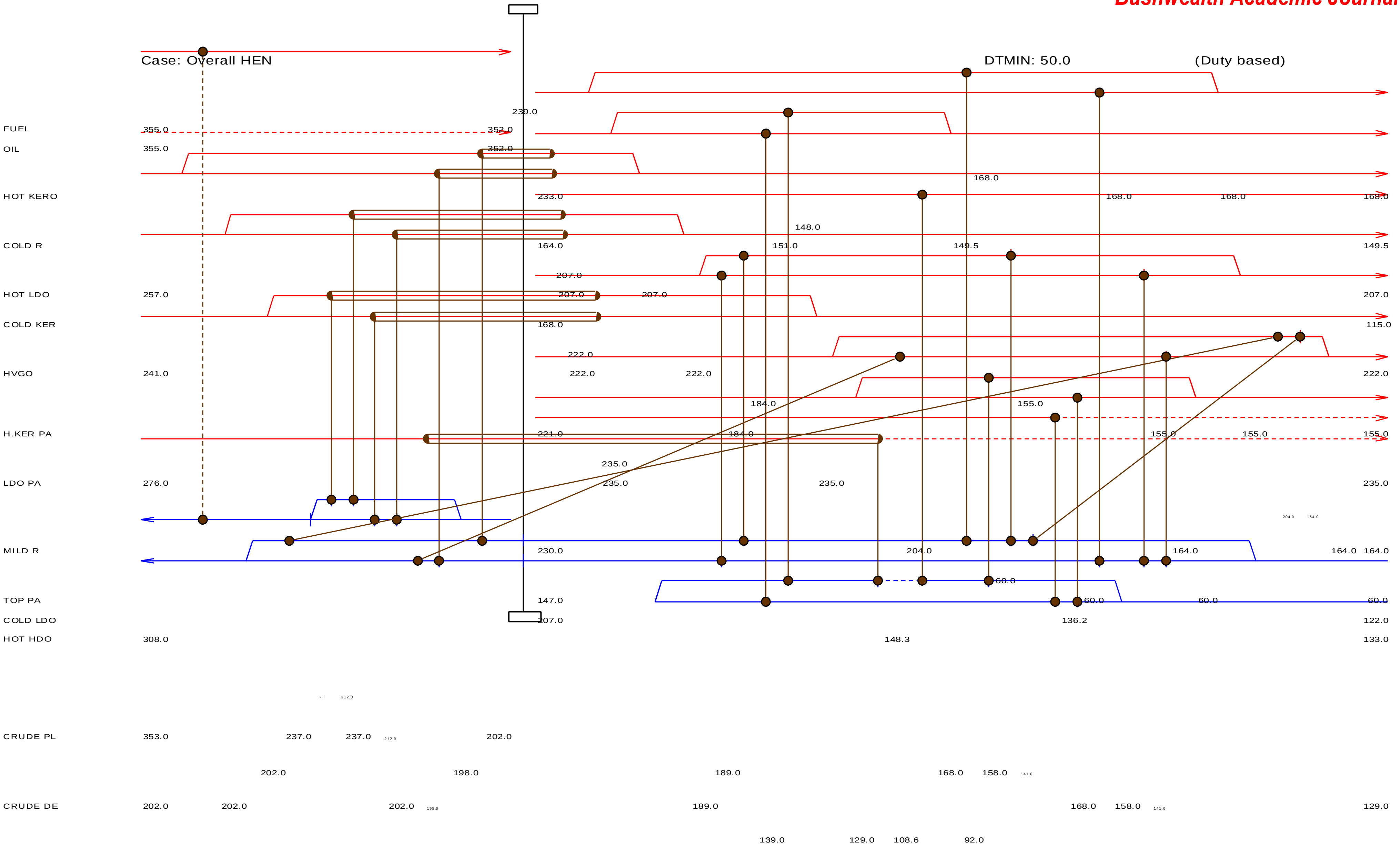

Case: Overall HEN
DTMIN: 50.0
(Duty based)
FUEL
OIL
HOT KERO
COLD R
HOT LDO
COLD KER
HVGO
H.KER PA
LDO PA
MILD R
TOP PA
COLD LDO
HOT HDO
CRUDE PL
CRUDE DE
355.0
352.0
355.0
352.0
239.0
168.0
233.0
168.0
168.0
168.0
148.0
164.0
151.0
149.5
149.5
207.0
257.0
207.0
207.0
207.0
168.0
115.0
222.0
241.0
222.0
222.0
222.0
184.0
155.0
221.0
184.0
155.0
155.0
155.0
235.0
276.0
235.0
235.0
235.0
204.0
164.0
230.0
204.0
164.0
164.0
164.0
60.0
147.0
60.0
60.0
60.0
207.0
136.2
122.0
308.0
148.3
133.0
212.0
353.0
237.0
237.0
212.0
202.0
202.0
198.0
189.0
168.0
158.0
141.0
202.0
202.0
202.0
198.0
189.0
168.0
158.0
141.0
129.0
139.0
129.0
108.6
92.0

Figure F.8: *Grid Representation of Overall HEN for $\Delta T_{min} = 50^{o}C$*

Table F.1: *Targeting Report of Overall HEN for $\Delta T_{min} = 20^{o}C$ and $40^{o}C$*

ASPEN PINCH (TM)

Targeting Results, Case: Overall HEN

```
*******************************************************
 *          No utilities have been placed          *
*******************************************************
```

Minimum hot utility 90617.4 kW Minimum cold utility 0.0 kW

Delta Tmin 20.0 C Pinch T Delta T (Real) Pinch temperature(s): 35.0 C 35.0 C

Total Hot utility used 0.0 kW Total Cold utility used 0.0 kW

ASPEN PINCH (TM)

Targeting Results, Case: Overall HEN

```
*******************************************************
*          No utilities have been placed          *
*******************************************************
```

Minimum hot utility 100840.1 kW
Minimum cold utility 10222.7 kW

Delta Tmin 40.0 C

Pinch T Delta T (Real) Pinch temperature(s): 209.0 C 40.0 C

Total Hot utility used 0.0 kW Total Cold utility used 0.0 kW

Cross Pinch Heat Transfer Penalties

Penalty units : kW
* denotes a near pinch

```
Hxer ID      Ti =  209.00 C
--------     --------------
10E11AB      -2359.51
10E11CD      -2359.51
10E10B       -1709.11
10E13B       -1071.17
10E13A       -1071.17
10E10A       -1709.11
10E08A       173.194
10E08B       173.194
10E04.       2131.51
--------     --------------
 Sum -->      -7801.68
```

Cross Pinch Heat Transfer Penalties

Penalty units : kW

* denotes a near pinch

No cross pinch heat exchange