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School of Chemical and Bio Engineering
Process Engineering

**Investigation of heat recovery targets for efficient use of energy in brewery via
thermal pinch analysis**

By
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(Process Engineering stream)

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Approval page

I hereby, submit this thesis work in partial fulfillment for the requirements of Masters of Science (MSc.) in Chemical Engineering (Process Engineering stream) entitled as “Investigation of heat recovery targets for efficient use of energy in brewery via thermal pinch analysis.”

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Declaration

I, Selam Berhe, declare that this thesis entitled “Investigation of heat recovery targets for efficient use of energy in brewery via thermal pinch analysis” is my own original work and submitted in partial fulfillment of the requirements for the degree of Master science in Chemical Engineering (Process Engineering stream); that has not been presented and will not be presented in this or any other university for a similar or any other degree awards, but it includes others’ work as a reference sources such as articles which have been fully acknowledged and they are included in the references as well. I have done the thesis under the supervision of Dr.Eng. Abubeker Yimam, lecturer at AAiT, AAU school of Chemical and Bio Engineering.

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This thesis has been submitted to the University with my approval as the University supervisor.

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ABSTRACT

Brewing industry is currently expanding in high rate. The rising cost of energy and environmental concerns have led the brewing industry to search for techniques of reducing energy consumption in brewery operations. High energy costs and the need to reduce on CO₂ emissions have brought to the fore the importance of reduction of energy usage in beer production. It is important that brewing process be analyzed to identify and evaluate opportunities for saving energy in specific process applications. In this study, pinch analysis was applied to a typical Ethiopian based large scale brewery(Meta Abo Brewery) to target for the minimum energy requirements of the process. It presents a methodology aimed at investigating the energy recovery target for the brewery by applying thermal pinch analysis; and analyzed four cases for different values of a design parameter which is minimum temperature difference (ΔT_{min}). The different steps of the analysis are presented. Pinch analysis spreadsheet was used for the analysis. At the chosen minimum temperature differences within the possible range of 0 - 45 °C, the minimum cooling and heating utility requirements of the brewery were studied and determined to be 1288.8 KW and 188.04 KW respectively and 805.19 KW of total heat recovery by two separate routes is possible for case 1. It was observed that using the technique, significant amount of energy could be recovered through process to process heat exchange in all four cases even though the amount of maximum energy recovery decreases as the minimum temperature difference increases. Furthermore, the heat exchange network(HEN) for all cases is designed. It is recommended that results from this study could be used in the design or retrofit of a heat exchanger network of the brewery for improved energy efficiency. Considerations can also be made for various values of ΔT_{min} within the possible range so as to work on the economic analysis for capital and energy cost tradeoff.

Key words: brewery, energy target, ΔT_{min} , HEN, pinch analysis, energy recovery.

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NOMENCLATURE

Latin letters and symbols

ADP	Adenosine diphosphate
ATP	Adenosine triphosphate
CC	Composite curve
C_p	Specific heat capacity
CP	Heat capacity flow rate
CP_C	Heat capacity flow rate of cold stream
CP_H	Heat capacity flow rate of hot stream
GCC	Grand composite curve
GHG	Greenhouse gas
°P	Degree Plato
HEN	Heat Exchanger Network
HI	Heat integration
ΔH	Change in enthalpy(heat load)
$\Delta H_{\text{interval}}$	Interval heat load
Q	Heat duty
$Q_{C\text{min}}$	Minimum cold utility requirement
$Q_{H\text{min}}$	Minimum hot utility requirement
\dot{M}	Mass flow rate
N_C	Number of cold process stream
N_H	Number of hot process stream
PA	Pinch analysis
PP	Pinch point
PT	Pinch temperature
PTA	Problem Table Algorithm
SCC	Shifted composite curve
SG	Specific gravity
T_{actual}	Actual stream temperature

T_{interval}	Interval / shifted temperature
T_S	Source temperature
$T_{S,\text{interval}}$	Shifted source temperature
T_t	Target temperature
$T_{t,\text{interval}}$	Shifted target temperature
ΔT	Change in temperature
ΔT_{min}	Minimum temperature difference
TAM	Time average model
TSM	Time slice model
\tilde{V}	Volumetric flow rate
P	Density

Miscellaneous quantities

Quantity	Symbol	Unit
Density	ρ	Kg/m^{-3}
Heat load	ΔH	W
Mass	M	Kg
Mass flow rate	\dot{M}	Kg/s
Specific heat	C_p	$\text{J kg}^{-1} \text{K}^{-1}$
Specific heat flow rate	CP	JK^{-1}
Temperature	T	K
Time	t	S
Volumetric flow rate	\tilde{V}	m^{-3}

Units

Symbol	Description
BTU	British thermal unit
HL	Hectoliter
HL/Hr	Hectoliter per hour

°C	Degrees Celsius
°F	Degrees Fahrenheit
K	Degrees Kelvin
Kg/M ³	Kilogram per cubic meter
Kg/ s	Kilogram per second
KJ/KgK	Kilojoule per kilogram kelvin
KW	Kilowatt
KW/K	Kilowatt per degrees kelvin
KWh	Kilowatt hour
MJ/HL	Mega joule per hectolitre
W	Watt

1. INTRODUCTION

Breweries use significant amounts of water and energy to produce drinks (in this case beer). In the current trend of high energy price, energy efficiency improvement of industrial processes represents an important way to reduce production costs. The brewing process is energy-intensive, especially in the brewhouse, where mashing and wort boiling are the main heat consuming processes with high energy consumption. Energy was considered a very interesting commodity because its significance in the world's economy has been increased from time to time, and its price has been pushed continuously to higher levels by speculative investments. The situation remains the same till present, and there is no sign of a significant price decrease in the future. Cleaner production (CP) is continuously advocated for in Brewery industry in order to reduce consumption and emissions. For an effective CP, the brewer should go green by adopting new brewing technology with efficient energy consumption, reduction in odor emission, efficient water consumption for cleaning and cooling purposes, the prevention of losses, and the reuse of treated wastewater.

In the top-down approach developed for analyzing energy efficiency of industrial processes in the food industry, pinch analysis is used to identify the possible heat recovery by heat exchange between the streams to be cooled down and the streams to be heated up (Muller 2007). Pinch analysis targets the minimum heat requirement of a process through the graphical representation of the process energy requirements, called composite curves, and describes how it is possible to achieve the determined energy targets with a correctly designed network of heat exchangers. The systemic approach consists of the identification and characterization of the main process unit operations (puos). The top-down approach shows that more than 80% of the energy consumption can be explained by describing only 20% of the units of a factory. For these important puos, models are used to characterize the set of hot and cold streams that are needed to achieve the operation. The choice of the minimum approach temperature ΔT_{\min} allowed by the heat exchangers enables the determination of the process minimum energy requirements in heating and cooling. Grand composite curve analysis helps towards identifying opportunities for energy-efficient utility integration to satisfy the energy requirements, such as combined heat and power (CHP) systems or heat pumps.

Optimal utility integration can be achieved using a mixed-integer linear programming (milp) formulation, as described by Marechal and Kalitventze. This paper presents the implementation of the process integration methodology on a brewery.

1.1 Problem statement and justification

Mankind currently faces several challenges for the global society to stay in a business as usual mode of living. It can be considered that the global society is and has always been in a state of flux. However, from a western society perspective, the last few decades were fairly stable in terms of food and energy supply (there was plenty available) and environmental conditions. Nowadays, with an ever more connected global society, it becomes clear that this relatively stable situation is not stable and does not apply to the vast majority of the global society. As the global human population grows and strives for a higher standard of living, the pressure on clean water sources, energy and food supply and the natural environment becomes even larger. Next, to water, energy is in high demand. Breweries have been putting plenty of resources and effort to bring about this most popular beverage in the world to the consumers. Most breweries faced by the rising of energy costs, stricter by environmental regulations and emission; and taxes on energy usage. From the audit findings, several savings opportunities have been identified e.g. preheating of boiler makeup water, improve condensate recovery, fitting of boiler economizers. However, the audits have not tackled energy use and utilization in the process areas, and how these can be optimized. Production process areas are the main users of the utilities generated and any inefficiency observed in the process of plant equipment and processes, results in high utilities consumptions and costs. The high energy and utilities costs can be reduced if a systematic study was done in all high energy-consuming processes in the brewery, to determine and recommend the optimal use of the utilities. The study intends to determine the energy consumption of individual wort boiling process and other inter related processes of cooling and hot water generation in the process plant, investigate the heat recovery targets and specific ways of optimizing these processes to improve the efficient use of energy via thermal pinch analysis.

1.2 Objectives

1.2.1 General objective

The main objective of this thesis was to investigate the heat recovery targets for efficient energy use in the brewing process via thermal pinch analysis.

1.2.2 Specific objectives

- To collect and evaluate data from the case study necessary for the pinch study.
- To determine the minimum energy requirements for efficient use of energy in the case study
- To show the representation of heat cascading and energy recovery opportunity graphically using composite curves.
- To calculate the amount of energy that can be recovered (heat recovery target).
- To design a heat exchange network for maximum energy recovery.

1.3 Description of case study

This research was conducted in Meta Abo Brewery Share Company which is based in sebeta, Ethiopia. The company was founded in 1963 that manufactures and markets beer. As of January 2012 Meta abo brewery Share Company operates as a subsidiary of Diageo Plc. Diageo is a global leader in alcohol beverage with an outstanding collection of brands across spirits and beer categories.

1.4 Research Questions

1. What data should be extracted from the process plant which are necessary for performing thermal pinch analysis?
2. What are the procedures to investigate heat recovery targets via process integration?
3. How much energy can be saved in the beer processing plant case study (Meta Abo Brewery) using pinch technology?

1.5 Significance of the study

It can't be refuted that any process plant set goals targeting to improve the company's bottom line. The objectives of the manufacturing industry are related to quality, safety, vendor selection, efficiency and most importantly cost. If there is one thing that manufacturing industries are committed to put their best effort on is apparently increasing their profit by any promising means. This study presented one possible way to decrease the usage of energy utility so as to cut the potential expenditure which covers the energy bills.

1.6 The scope of the study

The study was limited to the investigation of heat recovery targets for efficient energy use via thermal pinch analysis in the beer processing plant. The procedure involved data extraction from the Process plant, energy audit, performing thermal pinch analysis using the extracted data to identify heat recovery targets and finally design the heat exchanger network for efficient usage of energy.

2. REVIEW OF LITERATURE

2.1 Introduction to energy usage in brewing process.

The brewing process is energy intensive, especially in the brewhouse, where mashing and wort boiling are the main heat consuming processes. Energy consumption is equal to 3-8% of the production costs of beer (Rudolf and Udo 2008), making energy efficiency improvement an important way to reduce costs, especially in times of high-energy price increases. The imperative to reduce energy consumption has led to the development of new processes and technical solutions that consume less energy (Unterstein 1992). These include dynamic wort boiling with an internal boiler (Michel and Vollhals, 2003) and use of the Jetstar (Huppmann GmbH, Germany) internal boiler for a simmering boil, with a submerged wort flow and stripping phase to reduce undesired volatiles, are good examples of sustainable improvement in wort boiling combined with reduced thermal stress and increased wort quality (Michel and Vollhals, 2002).

In the Top-Down approach developed by (Muller 2007). For analyzing the energy efficiency of industrial processes in the food industry, Pinch Analysis is used to identify the possible heat recovery by heat exchange between the streams to be cooled down and the streams to be heated up. Pinch Analysis targets the minimum heat requirement of a process through the graphical representation of the process energy requirements, called composite curves, and describes how it is possible to achieve the determined energy targets with a correctly designed network of heat exchangers (Linnhof et al 1994). The Top-Down approach shows that more than 80% of the energy consumption can be explained by describing only 20% of the units of a factory. For these important PUOs, models are used to characterize the set of hot and cold streams that are needed to achieve the operation (Muller 2007). The choice of the minimum approach temperature ΔT_{\min} allowed by the heat exchangers enables the determination of the process Minimum Energy Requirements in heating and cooling. Grand composite curve analysis helps towards identifying opportunities for energy efficient utility integration to satisfy the energy requirements, such as combined heat and power (CHP) systems or heat pumps (Becker et al 2009). Optimal utility integration can be achieved using a Mixed Integer Linear Programming (MILP) formulation, as described by Maréchal and Kalitventzeff. (Marechal and Kalitventzeff 1998).

2.2 Brewing process

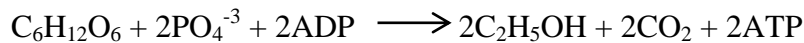
The brewing process uses malted barley and/or cereals, unmalted grains and/or sugar/corn syrups (adjuncts), hops, water, and yeast to produce beer. Most brewers use malted barley as their principal raw material. Depending on the location of the brewery and incoming water quality, water is usually pre-treated with a reverse osmosis carbon filtration or other type of filtering system.

The first step of brewing, milling and carbon filtration, takes place when malt grains are transported from storage facilities and milled in a wet or dry process to ensure that one can obtain a high yield of extracted substances (UNEP, 1996). Sometimes the milling is preceded by steam or water conditioning of the grain. The mixture of milled malt, gelatinized adjunct and water is called mash. The purpose of mashing is to obtain a high yield of extract (sweet wort) from the malt grist and to ensure product uniformity. Mashing consists of mixing and heating the mash in the mash tun, and takes place through infusion, decoction or a combination of the two. During this process, the starchy content of the mash is hydrolysed, producing liquor called sweet wort. In the infusion mashing process, hot water between 160 and 180 °F (71 to 82 °C) is used to increase the efficiency of wort extraction in the insulated mashing tuns. The mashing temperature is dictated by wort heating using steam coils or jackets. In decoction mashing, a portion of the mashing mixture is separated from the mash, heated to boiling and re-entered into the mash tun. This process can be carried out several times, and the overall temperature of the wort increases with each steeping. Part of this mash is evaporated. This process requires an estimated 12 to 13 kBtu/barrel for medium-sized breweries (Hackensellner, 2000). The type of mashing system used depends on a number of factors such as grist composition, equipment and type of beer desired (Hardwick, 1994). Infusion mashing is less energy intensive than decoction mashing requiring roughly 8 to 10 kBtu/barrel of fuel (Hackensellner, 2000). Following the completion of the mash conversion, the wort is separated from the mash. The most common system in large breweries is a lauter tun or a mash filter (Galitsky et al., 2003; O'Rourke, 1999). A more traditional system is the use of a combined mash tun/lauder tun, usually termed a mashing kettle or vessel. In the combined mashing vessel, the wort run off is directed through a series of slotted plates at the bottom of the tun. The mash floats on top of the wort.

This tends to be the slowest wort separation system although it is the lowest cost in terms of capital outlay (Galitsky et al., 2003; O'Rourke,1999). With the use of the lauter tun, the converted mash is transferred to a lautering vessel where the mash settles on a false bottom and the wort is extracted. Lautering is a complex screening procedure that retains the malt residue from mashing on slotted plates or perforated tubes so that it forms a filtering mass. The wort flows through the filter bed (Hardwick, 1994; Galitsky et al., 2003). In both the combined mashing vessel and the lauter tun, the grains are also sparged (i.e., sprayed and mixed) with water to recover any residual extract adhering to the grain bed. The extracted grain, termed "spent grain," is most often used as animal feed. In a mash filter, the mash is charged from the mash mixer. The filter is fitted with fine pore polypropylene sheets that forms a tight filter bed and allows for very high extraction efficiency (in excess of 100% laboratory extract) (Galitsky et al., 2003; O'Rourke,1999). However, the quality of the filtered wort may be affected through the use of a mash filter process and may not be applicable for all types of brewing. The next step, wort boiling, involves the boiling and evaporation of the wort (about a 4-12% evaporation rate) over a 1-1.5 h period. The boil is a strong rolling boil and is the most fuelintensive step of the beer production process. (Hackensellner2000) estimates 44-46 kBtu/barrel is used for conventional wort boiling systems in Germany. The boiling sterilizes the wort, coagulates grain protein, stops enzyme activity, drives off volatile compounds, causes metal ions, tannin substances and lipids to form insoluble complexes, extracts soluble substances from hops and cultivates colour and flavour. During this stage, hops, which extract bitter resins and essential oils, can be added. Hops can be fully or partially replaced by hop extracts, which reduce boiling time and remove the need to extract hops from the boiled wort. If hops are used, they can be removed after boiling with different filtering devices in a process called hop straining. As with the spent mashing grains, some breweries sparge the spent hops with water and press to recover wort. In order to remove the hot break, the boiled wort is clarified through sedimentation, filtration, centrifugation or whirlpool. After clarification, the cleared hopped wort is cooled. Cooling systems may use air or liquids as a cooling medium. Atmospheric cooling uses air stripping columns while liquid cooling uses plate heat exchangers. Wort enters the heat exchanger at approximately 205-210 °F (96-99 °C) and exits cooled to pitching temperature. Pitching temperatures vary depending on the type of beer being produced. Pitching temperature for lagers run between 43-59 °F (6-15 °C), while pitching temperatures for ales are higher at 54-

77 °F (12-25 °C) (Bamforth, 2001). The amount of heat potentially recovered from the wort during cooling by a multiple stage heat exchanger is 35-36 kBtu/barrel (Hackensellner, 2000). Certain brewers aerate the wort before cooling to drive off undesirable volatile organic compounds. A secondary cold clarification step is used in some breweries to settle out trub, an insoluble protein precipitate, present in the wort obtained during cooling.

Once the wort is cooled, it is oxygenated and blended with yeast on its way to the fermentor. The wort is then put in a fermentation vessel. For large breweries, the cylindrical fermentation vessels can be as large as 4000-5000 barrel tanks (Bamforth, 2001). During fermentation, the yeast metabolizes the fermentable sugars in the wort to produce alcohol and carbon dioxide (CO₂) as shown in the equation below:



where ADP, adenosine diphosphate; ATP, adenosine triphosphate.

Behind this simplified chemical reaction is a series of complex biochemical reactions. These reactions, known as the “Glycolytic pathway” or “Embden-Myerhof-Parnas pathway”, involve a number of enzymes and the reactions take place anaerobically inside the cells of brewing yeast. There are five sugars which may be present in wort which are readily utilized by standard brewer’s yeast in fermentation, and these include glucose, fructose, sucrose, maltose and maltotriose. These sugars are the main source of carbon compounds for all the structural materials of yeast cells. The sugars are always taken up by the yeast in the same sequence; first glucose, fructose and sucrose then maltose and lastly maltotriose. Sucrose is hydrolysed by the invertase enzyme in the yeast’s cell wall and splits into one glucose molecule and one fructose molecule, both of which may be assimilated into the glycolytic pathway. The enzymes responsible for the transport of maltose and maltotriose through the yeast cell membrane (permeases) are ‘blocked’ by the presence of the simpler monosaccharides and so their uptake is delayed. The production of alcohols other than ethanol is linked with nitrogen uptake by yeast. The yeast requires nitrogen (in the form of amino acids extracted from the malt) in order to make protein and other nitrogenous cell components. Examples of higher alcohols formed as by-products of nitrogen metabolism are propanol, isobutanol and isoamyl alcohol.

All these by products have some environmental implications if the effluents are discharged into the environment. The fermentation process also generates significant heat that must be dissipated

in order to avoid damaging the yeast. Fermenters are cooled by coils or cooling jackets. In a closed fermenter, CO₂ can be recovered and later reused. Fermentation time will vary from a few days for ales to closer to 10 days for lagers. The rate is dependent on the yeast strain, fermentation parameters (like the reduction of unwanted diacetyl levels) and taste profile that the brewer is targeting (Bamforth, 2001).

At the conclusion of the first fermentation process, yeast is removed by means of an oscillating sieve, suction, a conical collector, settling or centrifugation. Some of the yeast is reused while other yeast is discarded. Some brewers also wash their yeast. Some brewing methods require a second fermentation, sometimes in an aging tank, where sugar or fresh, yeasted wort is added to start the second fermentation. The carbon dioxide produced in this stage dissolves in the beer, requiring less carbonation during the carbonation process. Carbonation takes place in the first fermentation also. Yeast is once again removed with either settling or centrifugation.

Beer aging or conditioning is the final step in beer production. The beer is cooled and stored in order to settle yeast and other precipitates and to allow the beer to mature and stabilize. For beers with a high yeast cell count, a centrifuge may be necessary for preclarification and removal of protein and tannin material (UNEP 1996). Different brewers age their beer at different temperatures, partially dependent on the desired taste profile. Ideally, the beer at this stage is cooled to approximately 30 °F (-1 °C), although this varies in practice from 30-50 °F (-1-10 °C). Beer is held at conditioning temperature for several days to over a month and then chill proofed and filtered. A kieselguhr (diatomaceous earth) filter is typically used to remove any remaining yeast. Brewers use stabilizing agents for chill proofing. Colouring, hop extracts and flavor additives are dosed into the beer at some breweries. The beer's CO₂ content can also be trimmed with CO₂ that was collected during fermentation. The beer is then sent to a bright (i.e., filtered) beer tank before packaging. In high gravity brewing, specially treated water would be added during the conditioning stage. This can be a significant volume, as high as 50% (Bamforth 2001).

Finally, the beer must be cleaned of all remaining harmful bacteria before bottling. One method to achieve this, especially for beer that is expected to have a long shelf life, is pasteurization, where the beer is heated to 140 °F (60 °C) to destroy all biological contaminants. Different

pasteurization techniques are tunnel or flash pasteurization. Energy requirements for pasteurization can vary from 19 to 23 kWh per 1000 bottles for tunnel pasteurization systems (Hackensellner 2000). Other estimates are 14-20 kBtu/ barrel. An alternative approach is the use of sterile filtration. However, this technology is new, and some believe these systems may require as much extra energy as they save (Bamforth 2001).

2.3 Operation of brewing

Breweries are operated in batch mode due to the biological processes involved (Muster-Slawitsch et al 2010). Pinch analysis and practical heat recovery projects for batch systems are more difficult to undertake using this system than for continuous processes (Kemp 2007) since the hot and cold streams in batch processes don't exist over the entire process time (Christian et al 2014), thus restricting heat exchange options. Another consequence arises from the fact that batch processes are not as energy intensive compared to continuous bulk systems leading to a less consideration in a methodical search for process integration opportunities (Gundersen and Naess 1988) that have been effective in continuous processes. Nonetheless approaches for targeting and integration in batch processes have been reported by several authors (Foo et al 2008) (Atkins et al 2010) and a complete review of the techniques can be found in (Fernandez et al 2012).

The two widely used models for analysis of batch processes for integration are the time slice model (TSM) and time average model (TAM). The time slice model was derived from the Pinch Analysis for continuous processes (Kemp and Deakin 1989) (Golwelker 1994). with the process streams being sectioned when a change in heat flow occurs. As a result, steady state conditions prevail in every created time "slice" enabling the application of Pinch Analysis on these time intervals and the results can be combined to receive the minimum amount of external utilities.

Nevertheless, heat streams occurring when a medium is heated or cooled in a vessel (dynamic heat streams) cannot be processed by the TSM (Christian et al 2014) as these streams have to be converted to have steady-state behavior. The Time Average Model (TAM) was introduced by (Kemp and Macdonald 1988) to identify potentials for energy integration in batch processes basing on a procedure adapted from Pinch Analysis for continuous processes. Ignoring the

discontinuous nature of process streams in batch mode, the energy of each stream is averaged over each batch cycle time. Hence, the minimum requirements for external heating and cooling as well as the internally exchanged heat can easily be determined as if the process is in “continuous” mode. Pinch analysis of the brewing process allows for the determination of targets for maximum heat exchange within each batch, identifying key matches that achieve most heat recovery, analysis of utility systems and reduction of peak loads (Kemp 2007) for the process to meet an energy target resulting into an efficient energy utilization.

2.4 Pinch analysis(PA) and HEN

Pinch Technology is a systematic methodology for energy saving in processes and total sites. The methodology is based on thermodynamic principles. Using Pinch Technology, it is possible to identify appropriate changes in the core process conditions that can have an impact on energy savings. Pinch Technology extends to the site level, wherein appropriate loads on the various steam mains can be identified in order to minimise the site wide energy consumption. Pinch Technology therefore provides a consistent methodology for energy saving, from the basic heat and material balance to the total site utility system (Linnhoff et al 1998). It is a ‘Systematic and General Methods for Designing Integrated Production Systems ranging from Individual Processes to Total Sites, with special emphasis on the Efficient Use of Energy and reducing Environmental Effects.’ (Gundersen 2000).

The first key concept of pinch analysis is setting energy targets. “Targets” for energy reduction have been a key part of energy monitoring schemes for many years. Typically, a reduction in plant energy consumption of 10% per year is demanded. However, like “productivity targets” in industry and management, this is an arbitrary figure.

A 10% reduction may be very easy on a badly designed and operated plant where there are many opportunities for energy saving, and a much higher target would be appropriate. However, on a “good” plant, where continuous improvement has taken place over the years, a further 10% may be impossible to achieve. Ironically, however, it is the manager of the efficient plant rather than the inefficient one who could face censure for not meeting improvement targets. Targets obtained by pinch analysis are different. They are absolute thermodynamic targets, showing what

the process is inherently capable of achieving if the heat recovery, heating and cooling systems are correctly designed (Kemp 2007).

PA has proved itself to be a considerable potential for reducing the overall energy demand and emissions across a site, leading to a more effective and efficient site utility system. One of the first works was Hohmann (Hohmann 1971) in his PhD thesis at the University of Southern California, USA. His work introduced thermodynamics-based reasoning for evaluating the minimum energy requirements of a Heat Exchanger Network (HEN) synthesis problem. Various approaches dealing with the optimum HEN synthesis have since been published. The comprehensive overview of HEN synthesis presented by Gundersen and Naess (Gundersen and Naess 1990) and the overview of process synthesis presented earlier by Nishida et al. (Nishida et al 1977) provided considerable impetus for further research and development within this field as can be witnessed in the more recent overview by Furman and Sahinidis (Furman and Sahinidis 2002).

The concept of heat integration (HI) based on Recovery Pinch was built upon in Hohmann's PhD thesis (Hohmann 1971) by two research groups: firstly, the two part paper of Linnhoff and Flower (Linnhoff and Flower 1978) and Flower and Linnhoff (Flower and Linnhoff 1978), followed up by the Linnhoff PhD thesis (B. Linnhoff 1979) and secondly, by the group around Umeda et al. (Umeda et al 1978). Hohmann (Hohmann 1971) is considered to be the first to provide a systematic way of obtaining energy targets by using his Feasibility Table. A lesser known part leading to the Problem Table Algorithm (PTA) was published at that time by master of science (MSc) student Bodo Linnhoff at ETH Zurich (B. Linnhoff 1972).

3. MATERIALS AND METHODS

3.1 Data collection and evaluation

Data necessary for the thermal pinch study has been collected and evaluated from the case study (Meta Abo Brewery) of actual daily readings of the process plant.

3.1.1 Inputs used for data collection

The following data was obtained. Sources of the required data are given.

A) Energy Input

Operational reading of the plant was the sources. Energy input rating was expressed in MJ/HL. The stated value was converted to metric (SI) unit, which is widely used in the analysis.

B) Flow rate

Flow rate of process streams, Cool and hot utility streams were Obtained from reading of flow meters installed in the plant, plant process or production records. ratings were expressed in a variety of units such as hectoliter/hour, Kilogram/hour.

C) Process temperatures

For boiling and cooling, hot water, chilled water, energy storage tank, etc. The temperature readings were obtained with the use of temperature sensors. These were expressed in conventional units such as degrees Celsius ($^{\circ}\text{C}$) or Kelvin (K).

3.1.2 Data evaluation

The assessment data evaluation was required for translation of the raw data collected during the assessment into useful information such as;

- flow measurements for process and utility streams in SI units.
- energy input for heating purpose
- energy used for cooling

The evaluation depended on the process and degree of detail required. Calculation methods were developed using standard formulas, equations.

3.2 Methods

3.2.1 data analysis

An actual industrial brewing process which is located in Sebeta, Ethiopia(Meta Abo Brewery) was taken for a case study and relevant data has been collected, evaluated and finally pinch analysis to investigate energy recovery target has been studied. The collected data from the case study were fed to Pinch analysis spreadsheet as it performs energy target calculations using Problem Table Algorithm.

3.2.2 Analysis procedure

3.2.2.1 Identification of the hot, cold and utility streams in the process

- Hot streams are those that must be cooled or are available to be cooled
- Cold streams are those that must be heated
- Utility streams are used to heat or cool process streams(hot and streams) when heat exchange between process streams is not practical or economic. a number of different hot utilities(steam, hot water) and cold utilities(cooling water, refrigerant) are used.

3.2.2.2 Thermal data extraction for process streams

for each hot and cold process streams identified the following thermal data is extracted from the process readings.

- Supply temperature (T_s): the temperature at which the stream is available in $^{\circ}\text{C}$.
- Target temperature(T_t): the temperature the stream must be taken to in $^{\circ}\text{C}$.
- Heat capacity flow rate(CP): the product of the mass flow rate(\dot{M}) in Kg/s and specific heat capacity(C_p) in KJ/Kg $^{\circ}\text{C}$.

$$CP = \dot{M} * C_p$$

- Enthalpy change(ΔH): associated with a stream passing through the heat exchanger is given by the first law of thermodynamics (energy equation).

First law of thermodynamics energy equation: $H = Q \pm W$

Where, Q represents heat supply or demand associated with the stream which is given by the relationship:

$$Q = CP * (T_s - T_t)$$

In a heat exchanger, no mechanical work (W) is being performed:

$$W = 0 \text{ (zero)}$$

As a result the enthalpy change is equal to the heat supply or demand (Q)

$$\Delta H = Q = CP * (T_s - T_t)$$

The specific heat values have been assumed to be temperature independent within the operating range.

3.2.2.3 Selection of ΔT_{\min} value

The design of any heat transfer equipment must always adhere to the second law of thermodynamics that prohibits any temperature crossover between the hot and cold streams which implies a minimum heat transfer driving force must always be allowed for feasible heat transfer design. Thus the temperature of the hot and cold streams at any point in the exchanger must always have a minimum temperature difference (ΔT_{\min}). This ΔT_{\min} value represents the bottleneck in the heat recovery that serves as the design parameter. In mathematical terms, at any point in the exchanger

$$\text{Hot stream temperature } (T_H) - \text{Cold stream temperature } (T_C) = \Delta T_{\min}$$

The collected data was fed to a simple pinch spreadsheet along with the selected design parameter which is the minimum temperature difference.

3.2.2.4 A targeting procedure: the “Problem Table” algorithm

Problem table algorithm provides a method of calculating energy targets (minimum energy requirements) and energy recovery target algebraically. The procedure follows the steps stated below.:

Step 1: convert the actual stream temperatures, T_{actual} in to interval or shifted temperature

Step 2: note any duplicated interval temperatures

Step 3: rank the interval temperatures in order of their magnitude showing the duplicating temperatures only once in order.

Step 4: carry out heat balance for the stream falling within each temperature interval.

STEP 5: Cascade the heat surplus from one interval to the next down the column of interval temperatures by assuming there is no heat load in the hot utility and subsequently adding the heat loads at each stream.

3.2.2.5 Generation of composite and grand composite curves

Composite curves(CC): consists of temperature - Enthalpy (T – H) profiles of heat availability in the process(hot composite curve) and heat demands in the process (cold composite curve) together in a graphical representation which used to set energy targets ahead of HEN design.

Shifted composite curves(SCC): this curve is obtained when the composite curves are re-plotted on axes of shifted temperature. The shifted curves just touched at the pinch temperature, and show even more clearly than the composite curves that the pinch divides the process into two.

Grand composite curves (GCC): shows the variation of heat supply and demand within the process, relative to the pinch, at a given shifted temperature. Thus, the GCC is a plot of the net heat flow against the shifted (interval) temperature, which is simply a graphical plot of the Problem Table (heat cascade) and shows the minimum heating and cooling requirements clearly.

3.2.2.6 HEN design

Identification of process stream matches for maximum heat recovery and designing heat exchanger network using pinch design method along with three feasibility criteria, which are;

- 1) CP feasibility criterion
- 2) Number count feasibility criterion
- 3) CP difference feasibility criterion

The three golden rules of pinch study has been taken under consideration;

- 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.

Pinch Analysis of the brewery was performed using the following key hypotheses:

- Thermal losses during heat transfer were neglected.
- The time average model (TAM), where the process operations are taken as being simultaneous, was considered as the approach of choice since in reality the brewery units are operated in batch mode.
- The process streams physical properties were constant at the given process temperatures.

4. RESULTS AND DISCUSSION

A pinch analysis on typical Brewery case study (Meta abo brewery) has been studied to investigate heat recovery target and to design a heat exchange network(HEN) for maximum energy recovery (MER) and minimum energy requirement.

4.1 Process Description

The brewery studied corresponds to a typical brewing process described in [Figure 1](#) and is divided in two stages:

Hot Stage (mashing & wort boiling): The malt/water mixture is combined in a mash tun. The mash is heated from 52 to 78 °C then sent to a lautertun where the mash mixture is filtered and spent grain is separated. The clarified wort goes to an energy intensive wort kettle where it is boiled to 99 °C with hops to develop a beer flavour. The wort is clarified in a whirlpool with actual temperature of 96 °C to remove the hops and eventually cooled to a pitching temperature of 12 °C before it undergoes fermentation.

Cold Stage: Wort fermentation using yeast as a catalyst at 12 °C takes place by converting the sugars to alcohol for about two weeks. The beer is then cooled down to 4 °C before it is sent to maturation(aging) stage. The beer is then chilled to -1 °C in maturation tank and clarified before being stored in insulated tanks where it ends its maturation.

The stream data for the pinch study in [Table 2](#) indicates a total energy requirement of 3087.2397 KW with the heating and cooling loads of 993.2297 KW and 2094.01 KW respectively for the current system not utilizing process to process heat recovery.

4.2 Data extraction flow diagram

Data extraction relates to the extraction of information required for pinch analysis from a given process heat and material balance or actual process readings (in this case actual process readings have been taken). Pinch analysis principles have been applied to identify the energy saving potential (or target) for the process and subsequently to aid the design of the heat exchanger network to achieve that targeted saving.

In order to start the pinch analysis the necessary thermal data must be extracted from the process. In an actual study however, these duties should be included. 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. No existing heat exchanger is assumed unless it is excluded from pinch analysis for specific reasons.

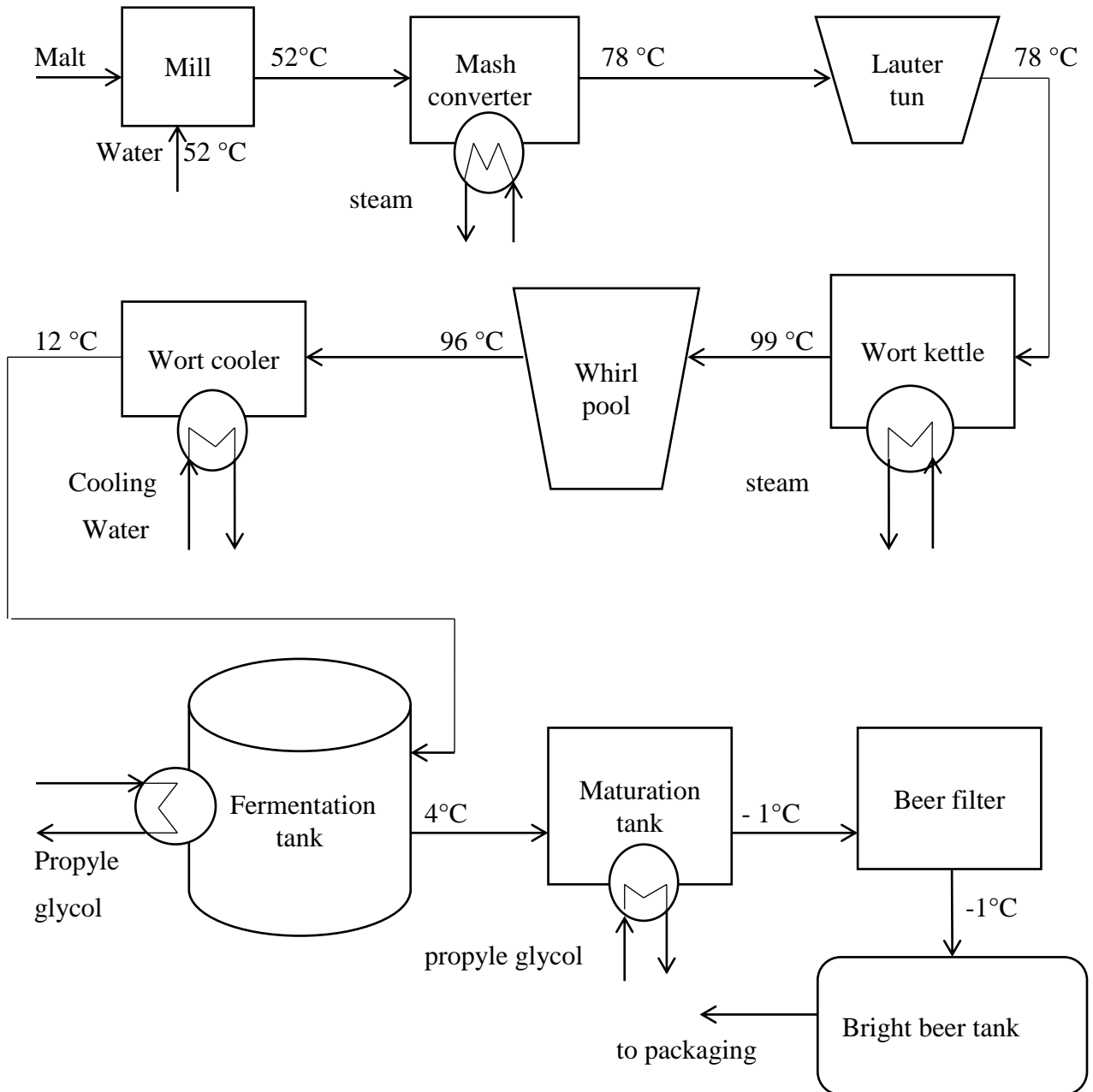


Figure 1. process flow block diagram of the case study.

Physical properties of streams were taken from actual reading to calculate the flowrate in metric units (kilogram per second). Here are the physical properties of some of the streams which their flowrate reading weren't in metric unit.

Table 1. Physical properties and flow rates of process streams.

S / N	Process streams	°P	SG	ρ (Kg/M ³)	\tilde{V} (Hl/Hr)	\dot{M} (Kg/S)
1	Mash	20	1.083	1083	200	6.02
2	Wort	17	1.070	1070	170	5.053
3	Sweet wort	14	1.057	1057	190	5.58
4	Green beer	12.5	1.050	1050	250	7.29
5	Matured green beer	12	1.048	1048	250	7.27

Table 2. Extracted process streams data.

S/N	Process	\dot{M} (Kg/S)	T _s (° C)	T _T (° C)	C _p (KJ/Kg.K)	ΔH (KW)
1	Mashing	6.02	52	78	3.6	563.42
2	Wort boiling	5.053	78	99	4.05	429.7577
3	Wort cooling	6.42	96	12	3.7	1734.264
4	Fermentation	7.29	12	4	3.8	221.616
5	Maturation	7.27	4	-1	3.8	138.13

4.3 Selection of suitable minimum temperature difference (ΔT_{\min})

Selection of a “suitable” ΔT_{\min} value, in determined range serves as the design parameter.

Since for a given value of ΔT_{\min} , the utility quantities predicted are the minima required to solve the heat recovery problem, a plot of energy targets versus ΔT_{\min} in Figure 2 shows that the possible range for the minimum temperature difference is $0 < \Delta T_{\min} < 45^\circ\text{C}$.

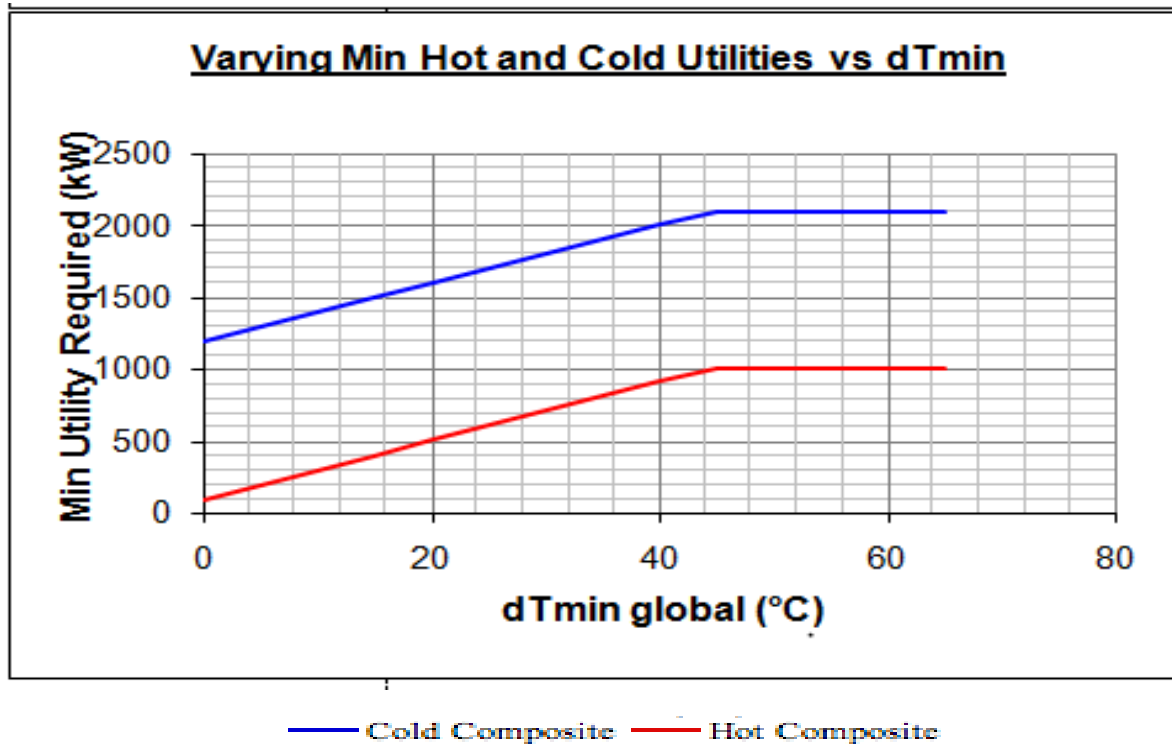


Figure 2. Minimum temperature difference vs minimum utility required plot.

From the figure above, an increase in ΔT_{\min} leads to an increase in energy costs since there is greater external minimum energy demand which warrants an increase in the requirement for the extra heat transfer utilities. Furthermore, It should be noted that as ΔT_{\min} increases, there is a decrease in the heat transferred within the system which requires a lower heat transfer area and therefore leading to a decrease in capital costs.

4.4 Case 1

ΔT_{\min} of 5 °C has been taken for the first case

4.4.1 A targeting procedure: the “Problem Table” algorithm

Step 1: convert the actual stream temperatures, T_{actual} in to interval or shifted temperature T_{interval} by subtracting half of minimum temperature difference ($\Delta T_{\min} / 2$) from hot stream temperatures and adding half of minimum temperature difference ($\Delta T_{\min} / 2$) to the cold stream temperatures.

I.e. Hot stream: $T_{\text{interval}} = T_{\text{actual}} - \Delta T_{\min} / 2$

Cold stream: $T_{\text{interval}} = T_{\text{actual}} + \Delta T_{\min} / 2$

ΔT_{\min} as a design parameter, Various ΔT_{\min} (5 to 20 with five interval in between) with in the possible range for typical process plant have been taken to identify the of maximum heat recovery target with respect to the taken ΔT_{\min} . A detailed procedure is presented below.

Table 3. Extracted data of process streams of case 1.

Stream Name	T_s (°C)	T_t (°C)	\dot{M} (Kg/s)	C_p (KJ/KgK)	CP (KW/K)	ΔH (KW)	Stream Type	$T_{S,\text{interval}}$ (°C)	$T_{T,\text{interval}}$ (°C)
S1	52	78	6.020	3.6	21.672	563.472	COLD	54.5	80.5
S2	78	99	5.053	4.05	20.465	429.757 65	COLD	80.5	101.5
S3	96	12	5.580	3.7	21.646	1734.26 4	HOT	93.5	9.5
S4	12	4	7.290	3.8	27.702	221.616	HOT	9.5	1.5
S5	4	-1	7.270	3.8	27.626	138.13	HOT	1.5	-3.5

Step 2: note any duplicated interval temperatures

80.5, 9.5 and 1.5 were duplicated as shown in the above table.

Step 3: rank the interval temperatures in order of their magnitude showing the duplicating temperatures only once in order.

101.5, 93.5, 80.5, 54.5, 9.5, 1.5, -3.5

Step 4: carry out heat balance for the stream falling within each temperature interval.

$$\Delta H_{\text{interval}} = (\Sigma CP_H - \Sigma CP_C) \Delta T_{\text{interval}}$$

$$\Delta T_{\text{interval}} = (T_i - T_{i+1})_{\text{interval}}$$

For any interval i . The results are shown in Table 5, and the last column indicates whether an interval is in heat surplus or heat deficit. It would therefore be possible to produce a feasible network design based on the assumption that all “surplus” intervals rejected heat to cold utility, and all “deficit” intervals took heat from hot utility. However, this would not be very sensible, because it would involve rejecting and accepting heat at inappropriate temperatures. Now, however, exploited a key feature of the temperature intervals. Namely, any heat available in interval i is hot enough to supply any duty in interval $i + 1$.

There were seven temperature intervals excluding the duplicated temperatures (taking only one from the duplicated ones). The temperature difference between each descending temperature intervals and the difference between the summation of heat capacities of hot and cold process streams which lay on the same interval temperature difference are taken to calculate the interval heat duty. The difference of summation of heat capacities between cold and hot streams ($\Sigma CP_H - \Sigma CP_C$) was calculated in Table 4 according to the process streams which lay on the same interval temperature difference ($\Delta T_{\text{Interval}}$) taken from the stream population figure presented below.

Table 4. Interval temperatures with their corresponding CPnet representation of case 1.

T_{interval}	$\Delta T_{\text{Interval}}$	$\Sigma CP_H - \Sigma CP_C$	Actual values
101.5	-	-	-
93.5	8	$0 - S2^C$	$0 - 20.465$
80.5	13	$S3^C - S2^C$	$20.646 - 20.46465$

54.5	26	$S3^H - S1^C$	20.646 – 21.672
9.5	45	$S3^H - 0$	20.646 – 0
1.5	8	$S4^H - 0$	27.702 – 0
-3.5	5	$S5^H - S1^C$	27.626 – 0








Stream Population	$\Delta T_{interval}$	$\sum CP_H - \sum CP_C$
101.5 $S2^C$	-	-
93.5 	8	-20.465
80.5 $S1^C$ 	13	0.1814
54.5 	26	-1.026
9.5 	45	20.646
1.5 $S3^H$ 	8	27.702
-3.5 $S4^H$  $S5^H$ 	5	27.626

Figure 3. Temperature intervals and corresponding net heat capacity of case 1.

Table 5. Problem table of case 1.

$T_{interval}$	Interval	$T_{(i+1)} - T_i$	CP_{net}	$\Delta H_{interval}$	Surplus/ Deficit
°C		°C	KW/K	KW	
101.5					
	1	8	-20.4647	-163.7172	D
93.5					

	2	13	0.1814	2.3576	S
80.5					
	3	26	-1.026	-26.676	D
54.5					
	4	45	20.646	929.07	S
9.5					
	5	8	27.702	221.616	S
1.5					
	6	5	27.626	138.13	S
-3.5					

STEP 5: Cascade the heat surplus from one interval to the next down the column of interval temperatures by assuming there is no heat load in the hot utility and subsequent adding the heat loads at each interval.

Shift Temperature °C	Interval	From hot utility	From hot utility
101.5		▼ 0	▼ 188.04
	1	-163.717	-163.7172
93.5		▼ -163.717	▼ 24.318
	2	2.35755	2.35755
80.5		▼ -161.36	▼ 26.676
	3	-26.676	-26.676
54.5		PINCH ▼ -188.04	▼ 0
	4	929.07	929.07
9.5		▼ 741.03	▼ 929.07
	5	221.616	221.616

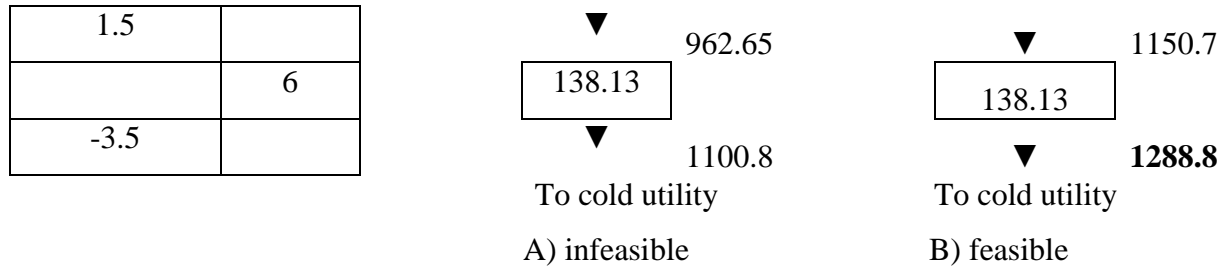


Figure 4. Feasible and Infeasible heat cascade of case 1.

Table 6. Results of problem table algorithm of case 1.

Hot Pinch	57 °C
Cold Pinch	52 °C

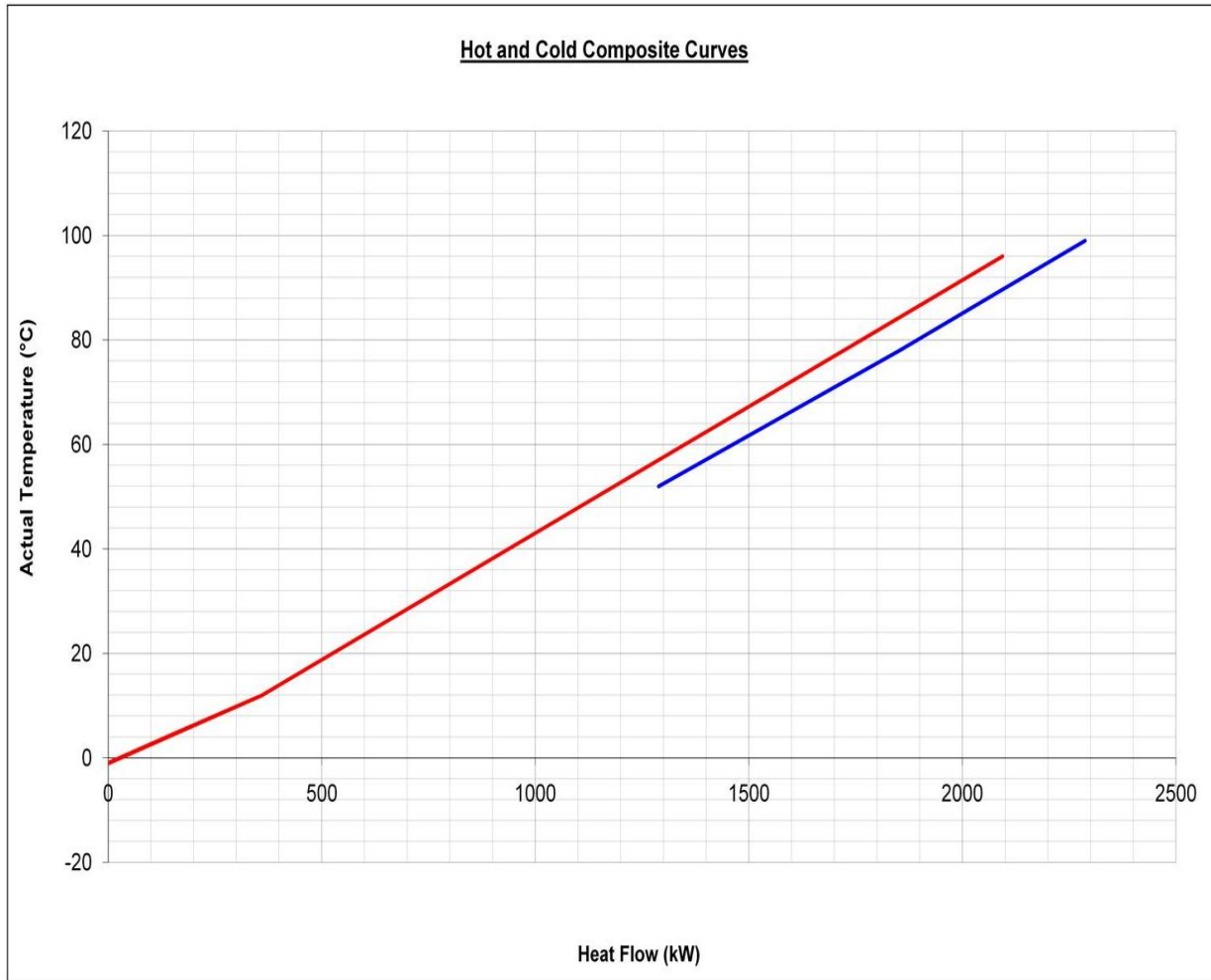
Min Hot Utility	188.04 KW
Min Cold Utility	1288.8 KW

The total heat recovered by heat exchange is found by adding the heat loads for all the hot streams and all the cold streams (2094.01 and 993.22965 KW), respectively. Subtracting the cold and hot utility targets (1288.8 and 188.04KW) from these values gave the total heat recovery, 805.19 KW by two separate routes . The cold utility target minus the hot utility target should equal the bottom line of the infeasible heat cascade, which is 1100.8 KW. These calculations provided useful cross-checks that the stream data and heat cascades have been evaluated correctly.

4.4.2 Graphical representation of thermal pinch case 1.

The overlap between the composite curves (CC) represents the maximum amount of heat recovery possible within the process which is 805.19 KW. The “overshoot” at the bottom of the hot composite represents the minimum amount of external cooling utility required which is 1228.8 KW and the “overshoot” at the top of the cold composite represents the minimum amount of external heating which is 188.04 KW. Finally the pinch point at which the minimum temperature difference(ΔT_{min}) is observed that defines the minimum driving force in the heat

exchanging unit is located at the ultimate approach between the hot and cold composite curve which is 54.5°C in composite curve plot or at the intersection point of the shifted hot and cold composite curve in the shifted composite curve plot.



— Cold Composite — Hot Composite

Figure 5. Composite curve of case 1.

This graphical illustration gave similar results as the numerical analysis (problem table) stated in the targeting procedure.

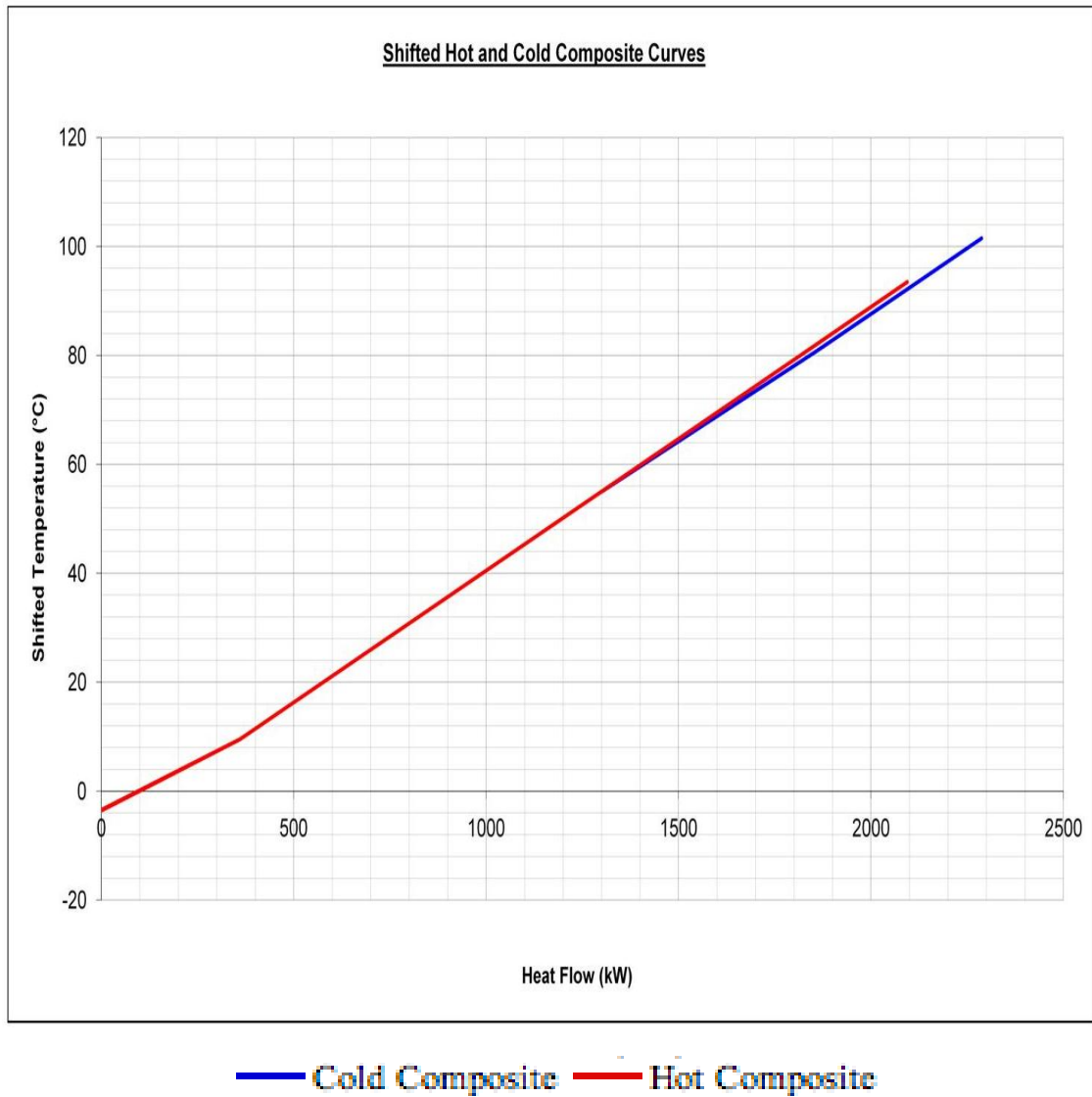


Figure 6. Shifted composite curve of case 1.

The composite curves are re-plotted on axes of shifted temperature, the shifted composite curves, Figure 6 has been obtained. The shifted curves just touched at the pinch temperature, and show even more clearly than the composite curves that the pinch divides the process into two.

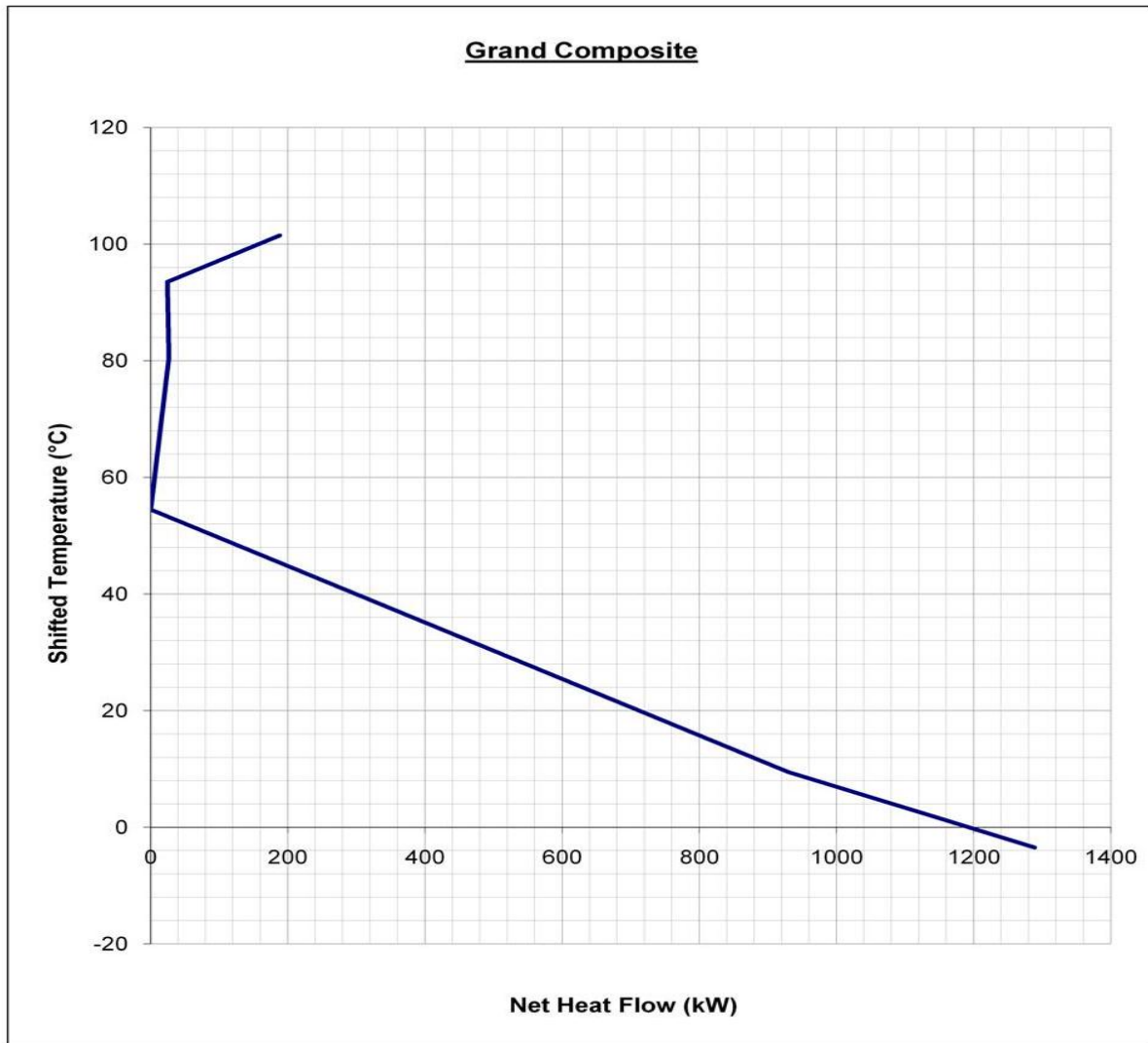


Figure 7. Grand composite curve of case 1.

The grand composite curve (GCC), represented the difference between the heat available from the hot streams and the heat required by the cold streams, relative to the pinch, at a given shifted temperature. Thus, the GCC is a plot of the net heat flow against the shifted (interval) temperature, which is simply a graphical plot of the Problem Table (heat cascade). The GCC touches the Y-axis at the pinch point for a given minimum temperature difference. At the top end of the GCC we could find the minimum heating utility requirement and the minimum cooling utility requirement at the bottom end of the curve.

4.4.3 Heat exchange network design for maximum energy recovery

Pinch design method was used for the heat exchange network design which is a novel method for the design of heat exchanger networks. The method is the first to combine sufficient simplicity to be used by hand with near certainty to identify “best” designs, even for large problems. “Best” designs feature the highest degree of energy recovery possible with a given number of capital items. Moreover, they feature network patterns required for good controllability, plant layout, intrinsic safety, etc. The three golden rules of pinch study were taken under consideration as a guideline for designing the HEN which are;

- 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.

4.4.3.1 Design above the pinch

In above the pinch design the hot stream temperatures should be cooled down to the pinch temperature. Three feasibility criteria were applied for the identification of essential matches at the pinch, of available design options and of the need to split streams. The heat capacities and loads of the streams above the pinch with their corresponding source and target temperature are presented in table 7. These pinch matches are taken for all the other cases since the thermal data is exact same.

$$\Delta H = \dot{M} * C_p \int_{T_s}^{T_t} \Delta T = CP (T_t - T_s) \quad , \quad CP = \dot{M} * C_p$$

Table 7. Thermal data of hot end pinch matches.

Stream Name	T _s (° C)	T _T (° C)	CP (KJ/Kg.K)	ΔH (KW)
S1	52	78	21.672	563.472
S2	78	99	20.46465	429.75765
S3	96	12	20.646	1734.264

Three feasibility criteria which have been applied to the problem were:

1. CP feasibility criterion
2. Number count feasibility criterion
3. CP difference criterion

The first feasibility criterion for above the pinch design, $CP_H \leq CP_C$ has been applied first to all process streams of hot end to identify the hot end pinch matches. However, there were two cold streams with 563.472 and 429.75765 KW heat loads and only one hot stream with 1734.264 KW heat load. So, regardless of stream CPs, the hot stream cannot be cooled to pinch temperature (57°C) by interchanging only with one cold stream because the hot stream needed 805.19 KW energy to cool it down to the pinch point. Fortunately there were two cold streams which can bring the hot stream to pinch temperature. The *only* way to bring the temperature of the hot stream to the pinch point is to split the hot stream into two parallel branches so it could match with both cold streams. Now, the second feasibility criterion has to be applied, $N_H \leq N_C$. The number of cold streams is equal to the number of hot streams (one full and one split branch) and so the hot stream can now be interchanged down to pinch temperature as shown in Figure 8. So far, the first two feasibility criteria were fulfilled. The third feasibility criterion was CP difference at the pinch. it is convenient to define the “CP difference” first.

For a hot end pinch match: $CP \text{ difference} = CP_C - CP_H$

The difference of CP between all the cold and hot streams which has been matched.

For a cold end pinch match: $CP \text{ difference} = CP_H - CP_C$

The difference of CP between all the hot and cold streams which has been matched.

Similar equations has been taken for differences in the overall sum of CPs of hot and cold streams.

Immediately above the pinch:

$$\text{Overall CP difference} = \sum_1^{NC}(\text{CPC}) - \sum_1^{NH}(\text{CPH}), \text{ NC \& NH are number of cold and hot stream.}$$

immediately below the pinch:

$$\text{overall CP difference} = \sum_1^{NH}(\text{CPH}) - \sum_1^{NC}(\text{CPC}) .$$

The third feasibility criterion above the pinch was to check whether the CP difference of the hot end streams is equal to the overall CP difference immediately above the pinch.

hot end pinch match: two hot end pinch matches were identified (two hot streams with two cold streams). Two hot streams(one full and one split), 11.15547 and 9.49053 respectively with total CP of 20.646. Two full cold streams, with 21.672 and 20.46465 CPs and 42.13665 in total.

$$\begin{aligned} \text{CP difference} &= \text{CP}_C - \text{CP}_H \\ &= 42.13665 - 20.646 = 21.49065 \end{aligned}$$

The number of overall streams available were the same as the hot end pinch match streams.

$$\begin{aligned} \text{Overall CP difference} &= \sum_1^{NC}(\text{CPC}) - \sum_1^{NH}(\text{CPH}) \\ &= (21.672 + 20.46465) - (9.49053 + 11.15547) \\ &= 21.49065 \end{aligned}$$

Finally the CP differences of the hot end pinch matches and the overall streams available were equal which means the CP differences criterion is fulfilled.

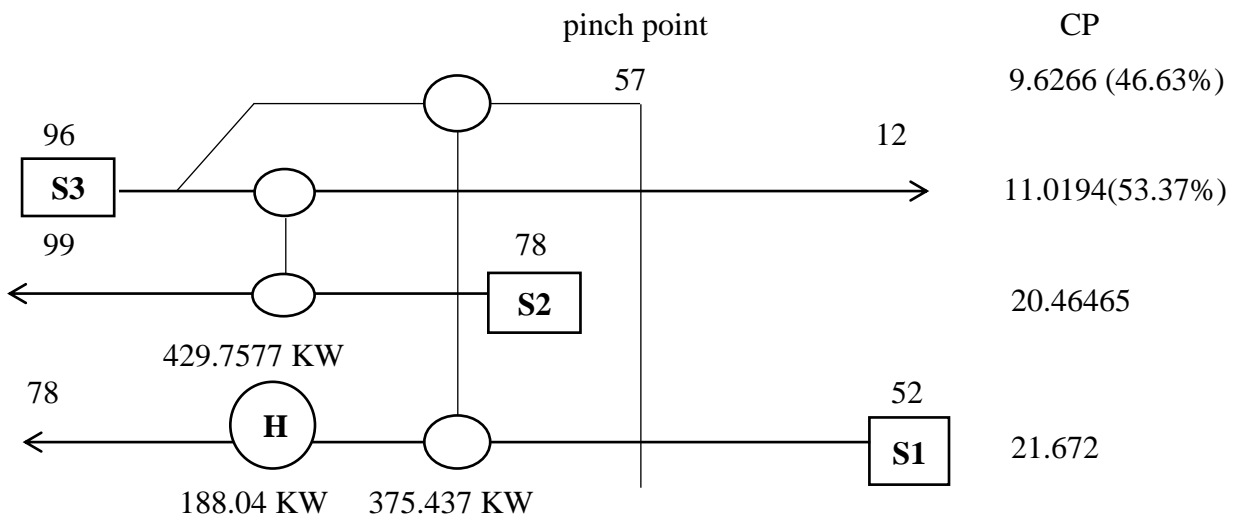


Figure 8. Design above the pinch of case 1.

4.4.3.2 Design below the pinch

Below the pinch, the design steps follow the same philosophy, only with design criteria that mirror those for the “above the pinch” design. Now, it is required to bring cold streams to pinch temperature by interchange with hot streams, since it’s impossible to use utility heating below the pinch. In this analysis, only three hot streams exist below the pinch, with no cold stream to match. There were no any pinch match in below the pinch design. There fore, external cooling utility was needed to bring the hot streams to their target temperature.

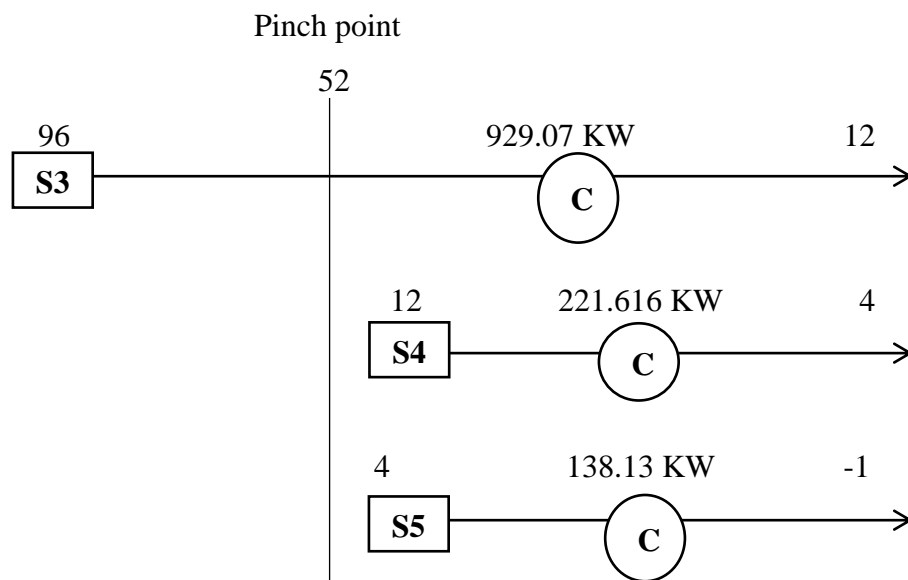


Figure 9. Design below the pinch of case 1.

Putting the “hot end” and “cold end” designs (above the pinch and below the pinch designs) together gives the completed design as shown in Figure 10.

It achieves best possible energy performance for a ΔT_{\min} of 5°C incorporating two exchangers, one heater and three coolers. In other words, six units of heat transfer equipment in all. Minimum energy requirement, and maximum energy recovery of 1476.86 KW and 805.19 KW respectively have been achieved using completed HEN design using pinch design method.

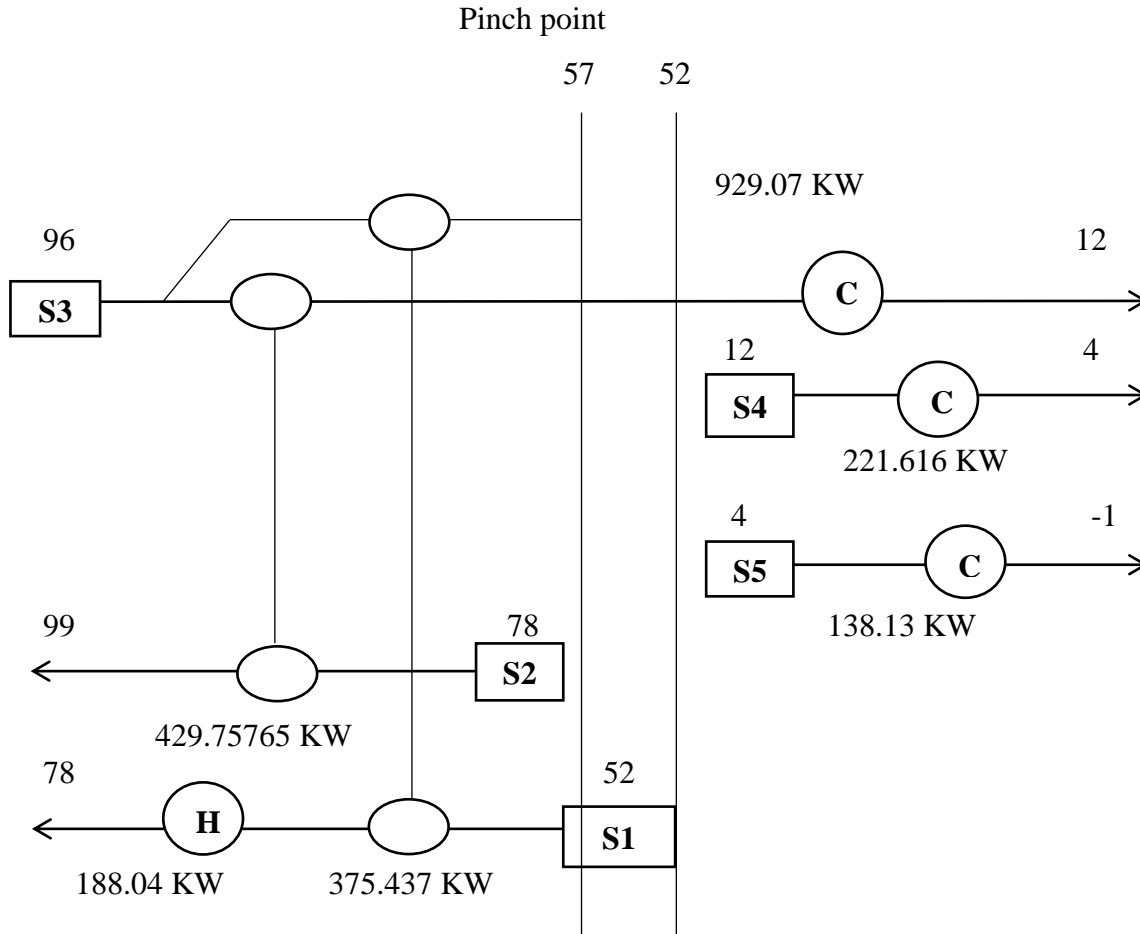


Figure 10. Completed HEN design of case 1.

4.5 Case 2

For ΔT_{min} of 10 °C;

4.5.1 A targeting procedure: the “Problem Table” algorithm

Same exact procedure has been followed as in the first analysis for the rest of all analysis with different minimum temperature difference to analyze the problem table algorithm and HEN design using pinch design method. The results and discussion are presented below.

Table 8. Extracted data of process streams of case 2.

Stream Name	T _S	T _T	\dot{M}	C _p	ΔH	Stream Type	T _{S, interval}	T _{T, interval}
	°C	°C	Kg/s	KJ/KgK	KW		°C	°C
S1	52	78	6.020	3.6	563.472	COLD	57.0	83.0
S2	78	99	5.053	4.05	429.7577	COLD	83.0	104.0
S3	96	12	5.580	3.7	1734.264	HOT	91.0	7.0
S4	12	4	7.290	3.8	221.616	HOT	7.0	-1.0
S5	4	-1	7.270	3.8	138.13	HOT	-1.0	-6.0

Step 2: note any duplicated interval temperatures

83, 7 and -1 were duplicated as shown in the above table.

Step 3: rank the interval temperatures in order of their magnitude showing the duplicating temperatures only once in order.

104, 91, 83, 57, 7, -1, -6

Step 4: carry out heat balance for the stream falling with in each temperature interval.

$$\Delta H_{\text{interval}} = (\sum CP_H - \sum CP_C) \Delta T_{\text{interval}}$$

$$\Delta T_{\text{interval}} = (T_i - T_{i+1})_{\text{interval}}$$

Table 9. Interval temperatures and their corresponding CPnet representation of case 2.

T _{interval}	$\Delta T_{\text{Interval}}$	$\sum CP_H - \sum CP_C$	Actual values
104	-	-	-
91	13	0 – S2 ^C	0 – 20.46465
83	8	S3 ^C – S2 ^C	20.646 – 20.46465
57	26	S3 ^H – S1 ^C	20.646 – 21.672

7	50	$S3^H - 0$	20.646- 0
-1	8	$S4^H - 0$	27.702- 0
-6	5	$S5^H - S1^C$	27.626- 0

Stream Population	$\Delta T_{\text{interval}}$	$\sum CP_H - \sum CP_C$
104 $S2^C$	-	-
91	8	-20.46465
83 $S1^C$	13	0.1814
57	26	-1.026
7	45	20.646
-1 $S3^H$	8	27.702
-6 $S4^H$ $S5^H$	5	27.626

Figure 11. Temperature intervals and corresponding net heat capacities of case 2.

Table 10. Problem table of case 2.

T_{interval}	Interval	$T_{(i+1)} - T_i$	$C_{p_{\text{net}}}$	ΔH	Surplus/ Deficit
°C		°C	kW/K	kW	
104					
	1	13	-20.4647	-266.0405	D
91					
	2	8	0.1814	1.4508	S
83					
	3	26	-1.026	-26.676	D
57					
	4	50	20.646	1032.3	S
7					

	5	8	27.702	221.616	S
-1					
	6	5	27.626	138.13	S
-6					

STEP 5: Cascade the heat surplus from one interval to the next down the column of interval temperatures by assuming there is no heat load in the hot utility and subsequent subtracting the heat loads at each stream.

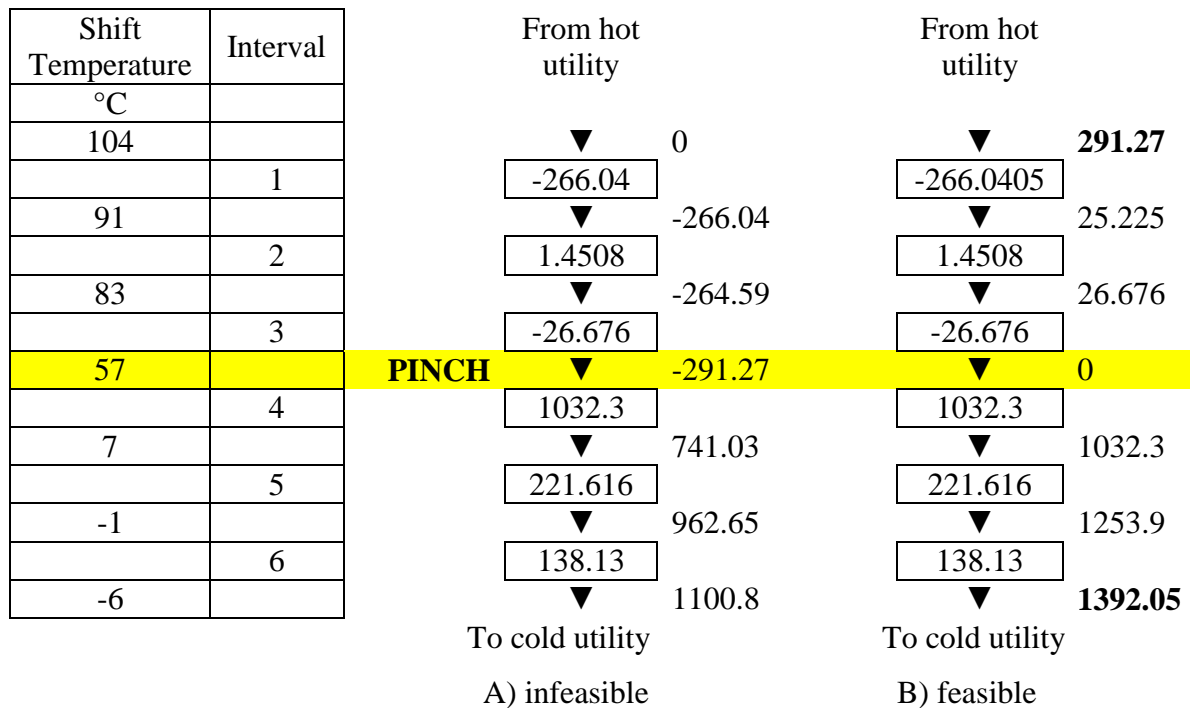


Figure 12. Feasible and Infeasible heat cascade of case 2.

Table 11. Table: results of problem table algorithm of case 2.

Hot Pinch	62 °C
Cold Pinch	52 °C
Min Hot Utility	291.27 KW
Min Cold Utility	1392.05 KW

The total heat recovered by heat exchange is found by adding the heat loads for all the hot streams and all the cold streams (2094.01 and 993.2297 KW), respectively. Subtracting the hot and cold utility targets (1392.05 and 291.27 KW) from these values gave the total heat recovery, 701.96 KW by two separate routes. The cold utility target minus the hot utility target should equal the bottom line of the infeasible heat cascade, which is 1100.8 KW. These calculations provided useful cross-checks that the stream data and heat cascades have been evaluated correctly.

4.5.2 Graphical representation of thermal pinch case 2.

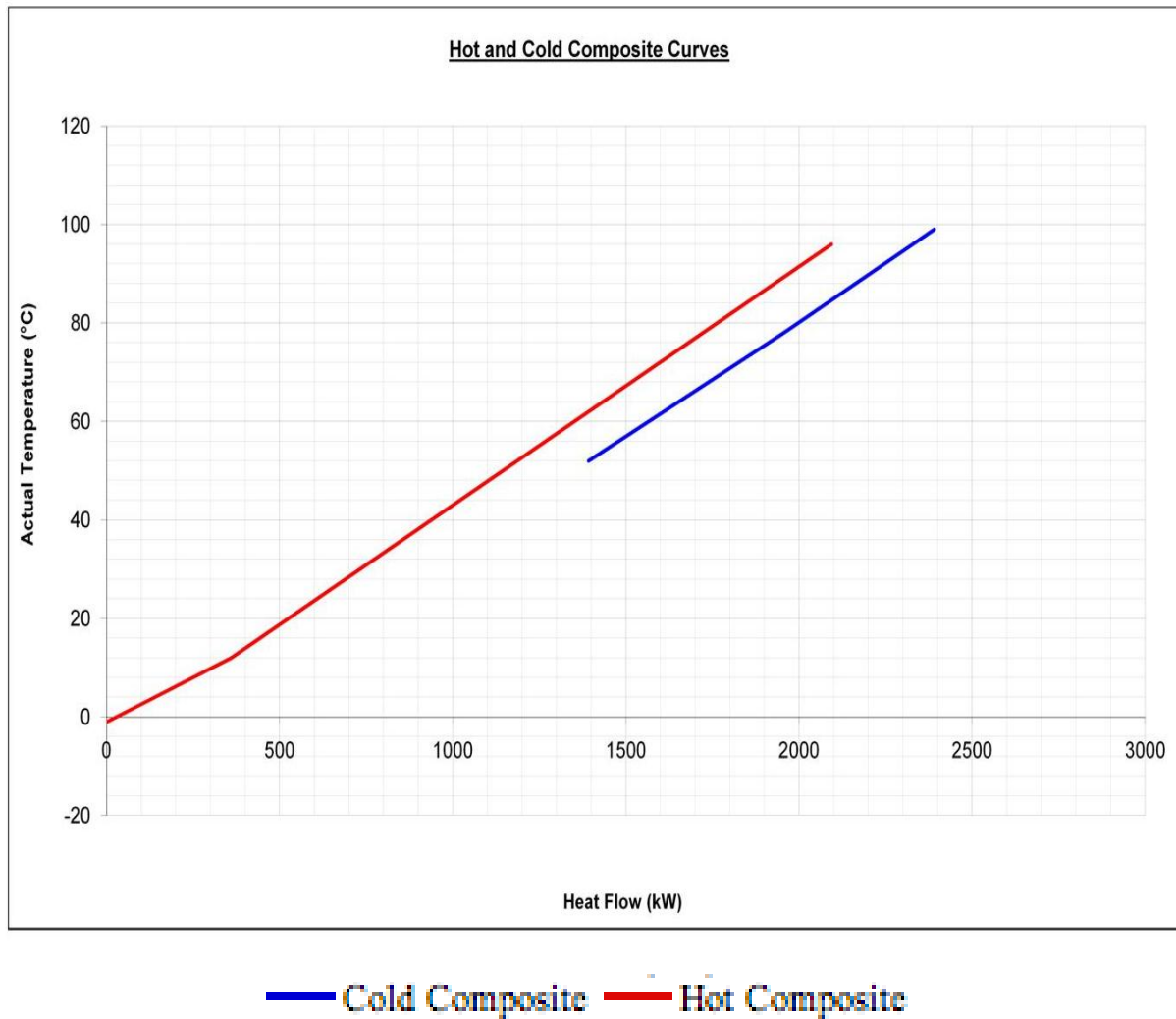
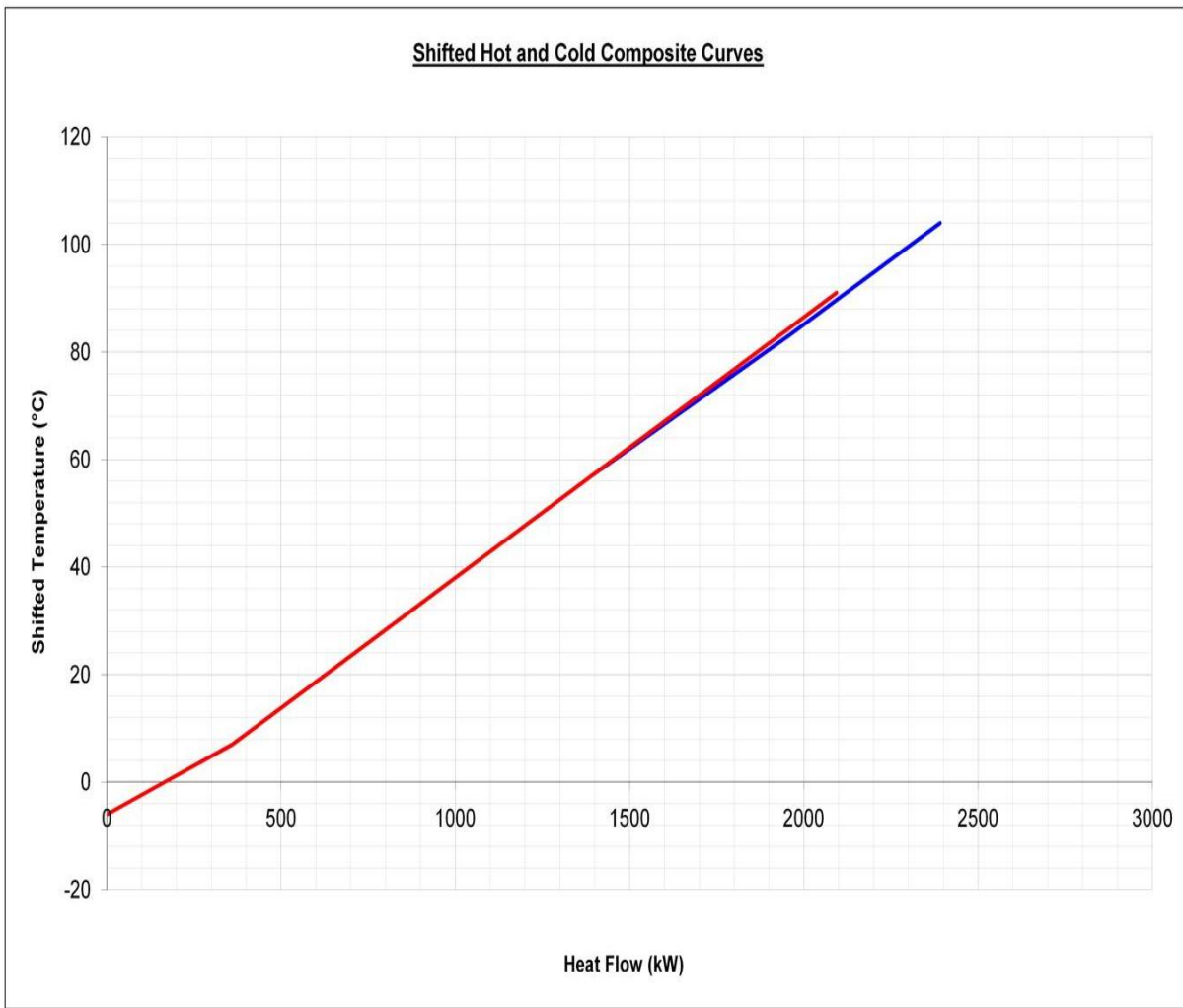


Figure 13. Composite curve of case 2.

The overlap between the composite curves represents the maximum amount of heat recovery possible within the process which is 701.9633 KW. The “overshoot” at the bottom of the hot composite represents the minimum amount of external cooling utility required which is 1392.05 KW and the “overshoot” at the top of the cold composite represents the minimum amount of external heating which is 291.27 KW. Finally the pinch point is located at the ultimate approach between the hot and cold composite curve which is 57 ° C.



— Cold Composite — Hot Composite

Figure 14. Shifted composite curve of case 2.

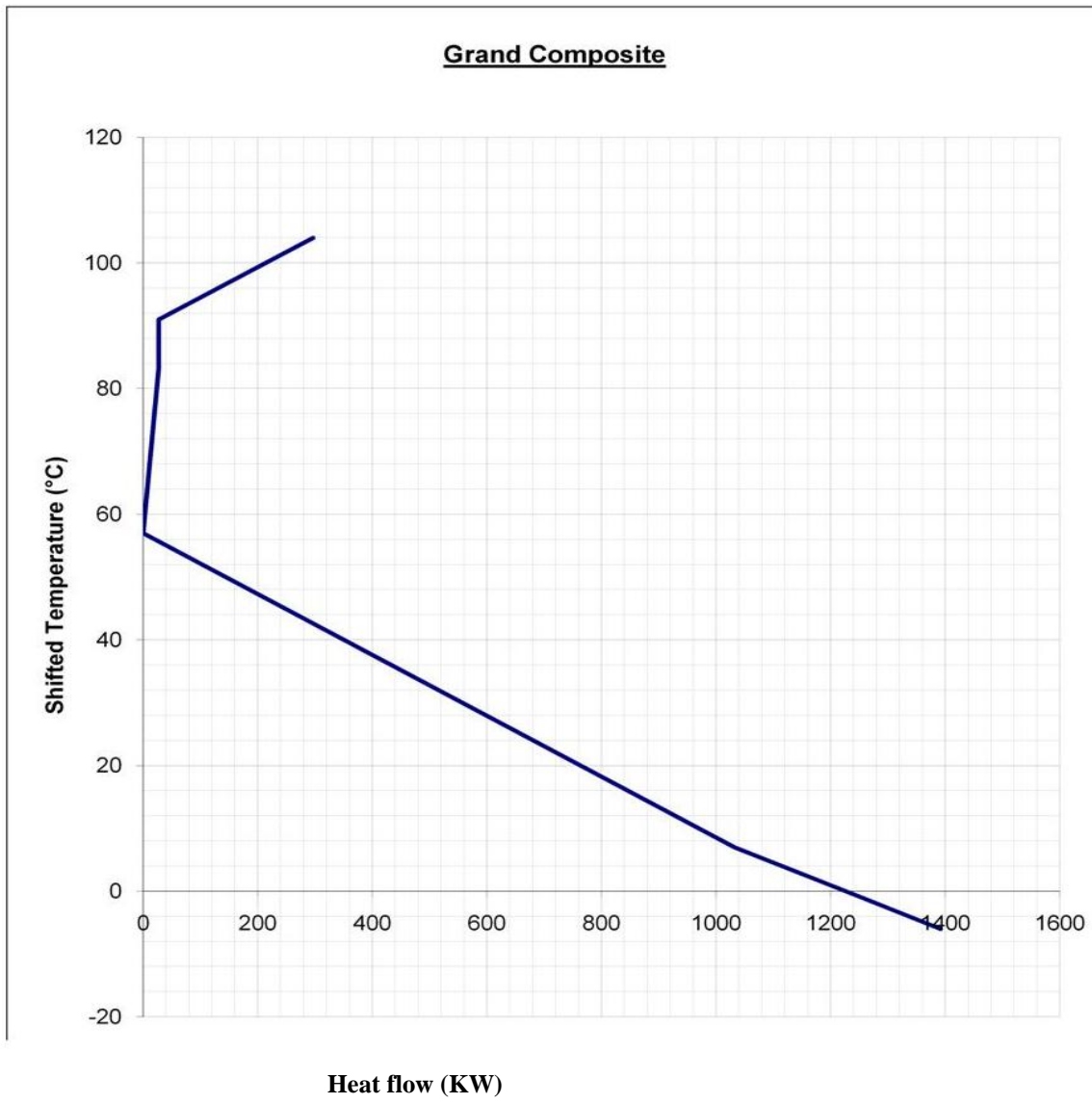


Figure 15. Grand composite curve of case 2.

4.5.3 HEN design for maximum energy recovery using pinch design method

Pinch analysis method has been used for the HEN design .

4.5.3.1 Design above the pinch

Similar procedure has been taken as in the first analysis, the only differences were the minimum heating and cooling utility requirements due to the change of minimum temperature difference taken. As a result the amount of heat recovered and the external utilities needed were different. The more details on this is presented below.

The feasibility criteria :

1. $CP_H \leq CP_C$
2. $N_H \leq N_C$
3. CP difference for hot end pinch matchs = over all CP difference for above the pinch.

The CP feasibility criterion $CP_H \leq CP_C$ has been applied to all hot end streams to identify the streams which can be a perfect match for heat exchange to exploit the heat recovery. In addition to the CP feasibility criterion the “numer count” feasibility criterion $N_H \leq N_C$ has been taken for the above the pinch design. Both CP and N feasibility criterion were satisfied. And further more the third feasibility criterion has been applied to design heat exchange network using pinch design method. The CP difference criterion was also fulfilled.

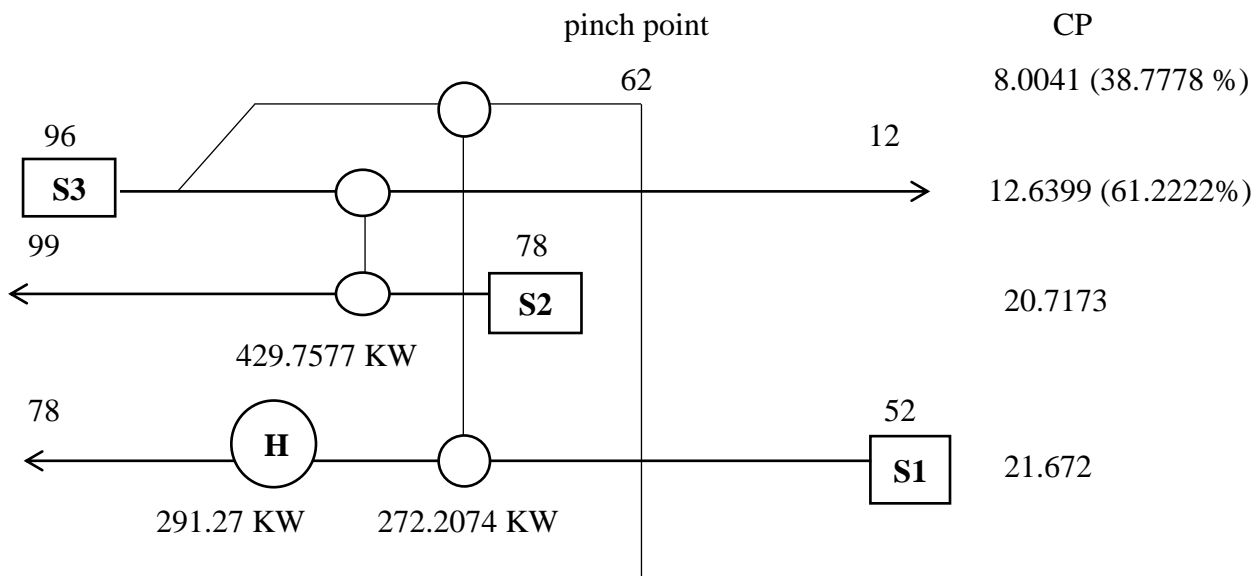


Figure 16. Above the pinch HEN Design of case 2.

4.5.3.2 Design below the pinch

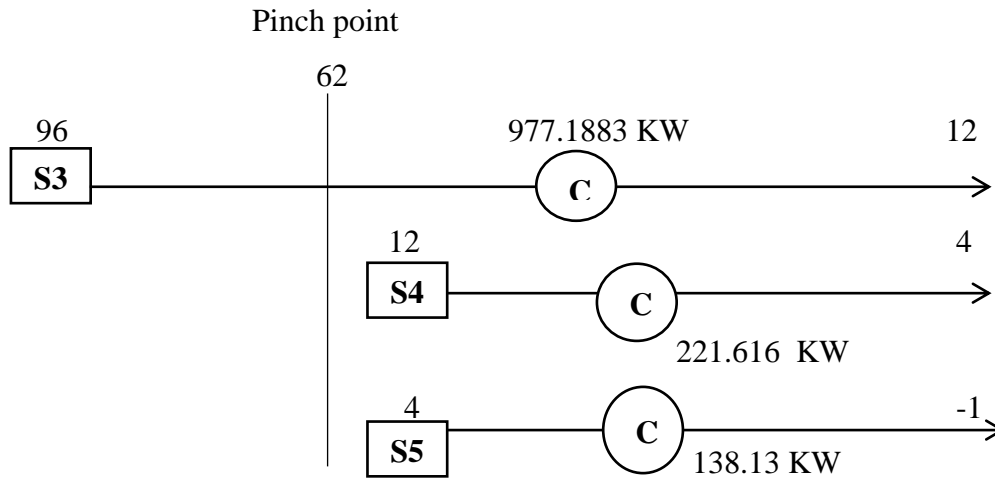


Figure 17. Below the pinch HEN design of case 2.

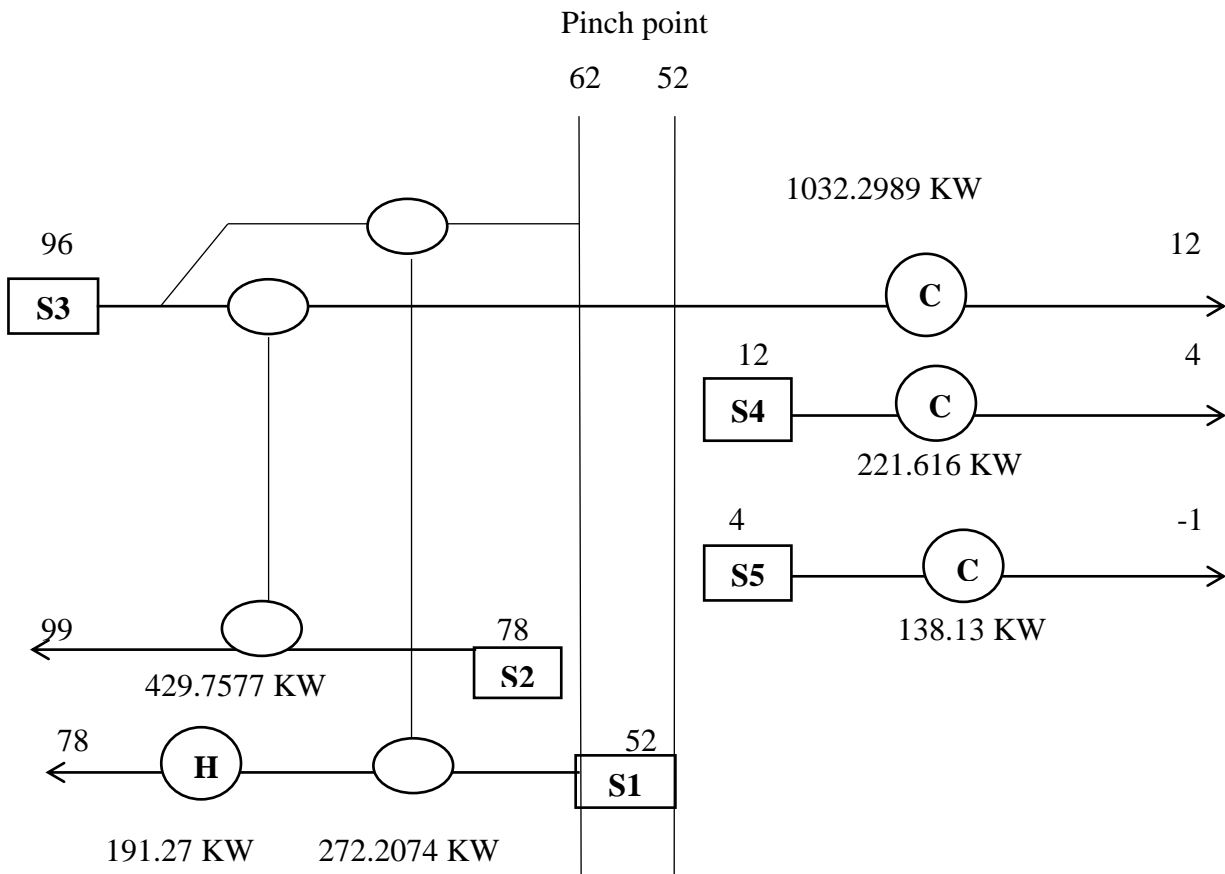


Figure 18. Completed HEN design of case 2.

Putting the “hot end” and “cold end” designs (above the pinch and below the pinch designs) together gives the completed design shown in figure 18.

To summarize the above and below the pinch designs, in the above the pinch design, hot stream S3 was splitted to match with cold streams S1 and S2 to cooled it down to the pinch temperature (57 °C) and delivered 701.9633 KW energy to both cold streams S1 & S2, and extra 1132.2989 KW external cooling utility was required, since there wasn't any pinch match in the below the pinch design to bring the hot stream to it's target temperature. Similarly, for the remained hot streams S4 & S5, an external cooling utility of 221.616 and 138.13 KW were required . For best possible energy performance of a ΔT_{min} of 10°C incorporating; two exchangers, one heater and three coolers, six units in total of heat transfer equipment were required .

4.6 case 3:

For ΔT_{min} of 15 °C;

4.6.1 A targeting procedure: the “Problem Table” algorithm

Table 12. Extracted data of process streams of case 3.

Stream Name	T _S	T _T	Ṁ	C _p	ΔH	Stream Type	T _{S, interval}	T _{T, interval}
	°C	°C	Kg/s	KJ/KgK	KW		°C	°C
S1	52	78	6.020	3.6	563.472	COLD	59.5	85.5
S2	78	99	5.053	4.05	429.7577	COLD	85.5	106.5
S3	96	12	5.580	3.7	1734.264	HOT	88.5	4.5
S4	12	4	7.290	3.8	221.616	HOT	4.5	-3.5
S5	4	-1	7.270	3.8	138.13	HOT	-3.5	-8.5

Step 2: note any duplicated interval temperatures

85.5, 4.5 and -3.5 were duplicated as shown in the above table.

Step 3: rank the interval temperatures in order of their magnitude showing the duplicating temperatures only once in order.

106.5, 88.5, 85.5, 59.5, 4.5, -3.5, -8.5

Step 4: carry out heat balance for the stream falling with in each temperature interval.

$$\Delta H_{\text{interval}} = (\sum CP_H - \sum CP_C) \Delta T_{\text{interval}}$$

$$\Delta T_{\text{interval}} = (T_i - T_{i+1})_{\text{interval}}$$

Table 13. Interval temperature and their corresponding CPnet representation of case 3.

T_{interval}	$\Delta T_{\text{Interval}}$	$\sum CP_H - \sum CP_C$	Actual values
106.5	-	-	-
88.5	18	$0 - S2^C$	$0 - 20.46465$
85.5	3	$S3^C - S2^C$	$20.646 - 20.46465$
59.5	26	$S3^H - S1^C$	$20.646 - 21.672$
4.5	55	$S3^H - 0$	$20.646 - 0$
-3.5	8	$S4^H - 0$	$27.702 - 0$
-8.5	5	$S5^H - S1^C$	$27.626 - 0$







Stream Population	$\Delta T_{\text{interval}}$	$\sum CP_H - \sum CP_C$
106.5 $S2^C$	-	-
88.5 	18	-20.46465
85.5 $S1^C$ 	3	0.184
59.5 	26	-1.026
4.5 	55	20.646
-3.5 $S3^H$ 	8	27.702
-8.5 $S4^H$  $S5^H$	5	27.626

Figure 19. Temperature intervals and corresponding net of heat flow of case 3.

Table 14. Problem table of case 3.

T_{interval}	Interval	$T_{(i+1)}-T_i$	$C_{p_{\text{net}}}$	ΔH	Surplus/ Deficit
°C		°C	kW/K	kW	
106.5					
	1	18	-20.4647	-368.3637	D
88.5					
	2	3	0.1814	0.5441	S
85.5					
	3	26	-1.026	-26.676	D
59.5					
	4	55	20.646	1135.53	S
4.5					
	5	8	27.702	221.616	S
-3.5					
	6	5	27.626	138.13	S
-8.5					

STEP 5: Cascade the heat surplus from one interval to the next down the column of interval temperatures by assuming there is no heat load in the hot utility and subsequent subtracting the heat loads at each stream.

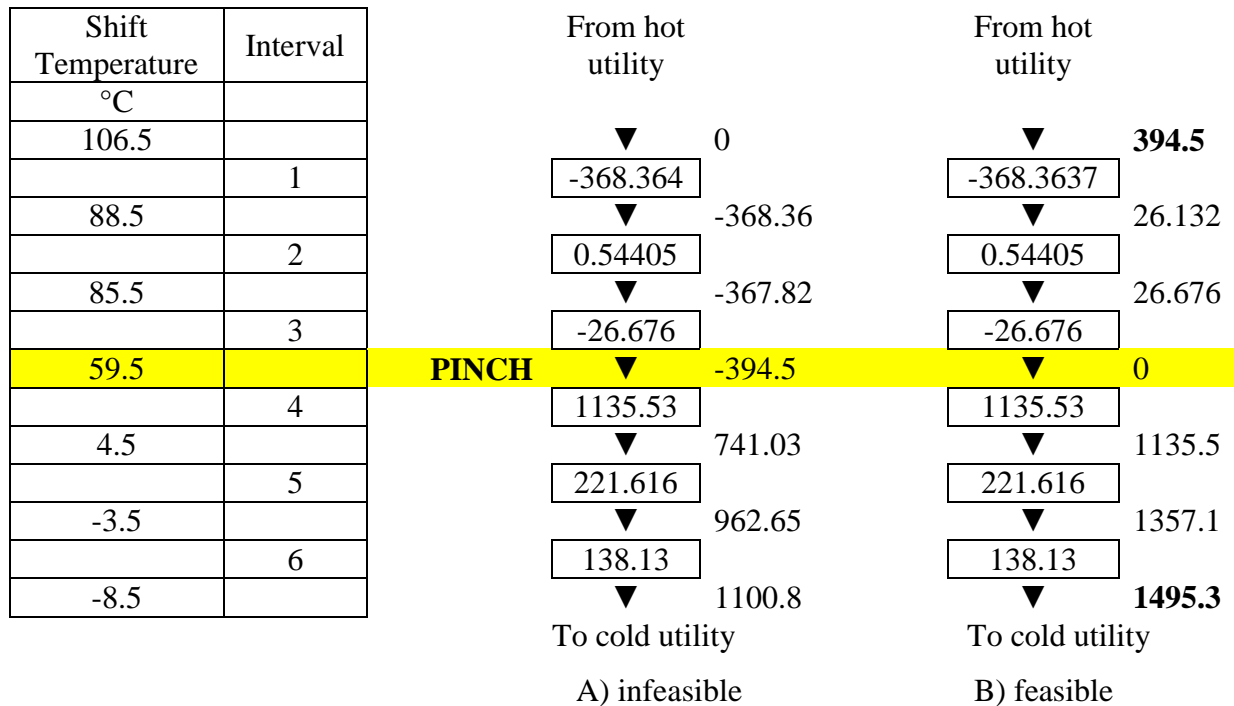


Figure 20. Feasible an Infeasible heat cascade of case 3.

Table 15. Problem table results of case 3.

Hot Pinch	67 °C
Cold Pinch	52 °C

Min Hot Utility	394.5 kW
Min Cold Utility	1495.3 kW

The total heat recovered by heat exchange is found by adding the heat loads for all the hot streams and all the cold streams (2094.01 and 993.2297 kW), respectively. Subtracting the hot and cold utility targets (1495.28 and 394.5 KW) from these values gave the total heat recovery, 598.73 KW by two separate routes. The cold utility target minus the hot utility target should equal the bottom line of the infeasible heat cascade, which is 1100.8 KW. These calculations provided useful cross-checks that the stream data and heat cascades have been evaluated correctly.

4.6.2 Graphical representation of thermal pinch case 3.

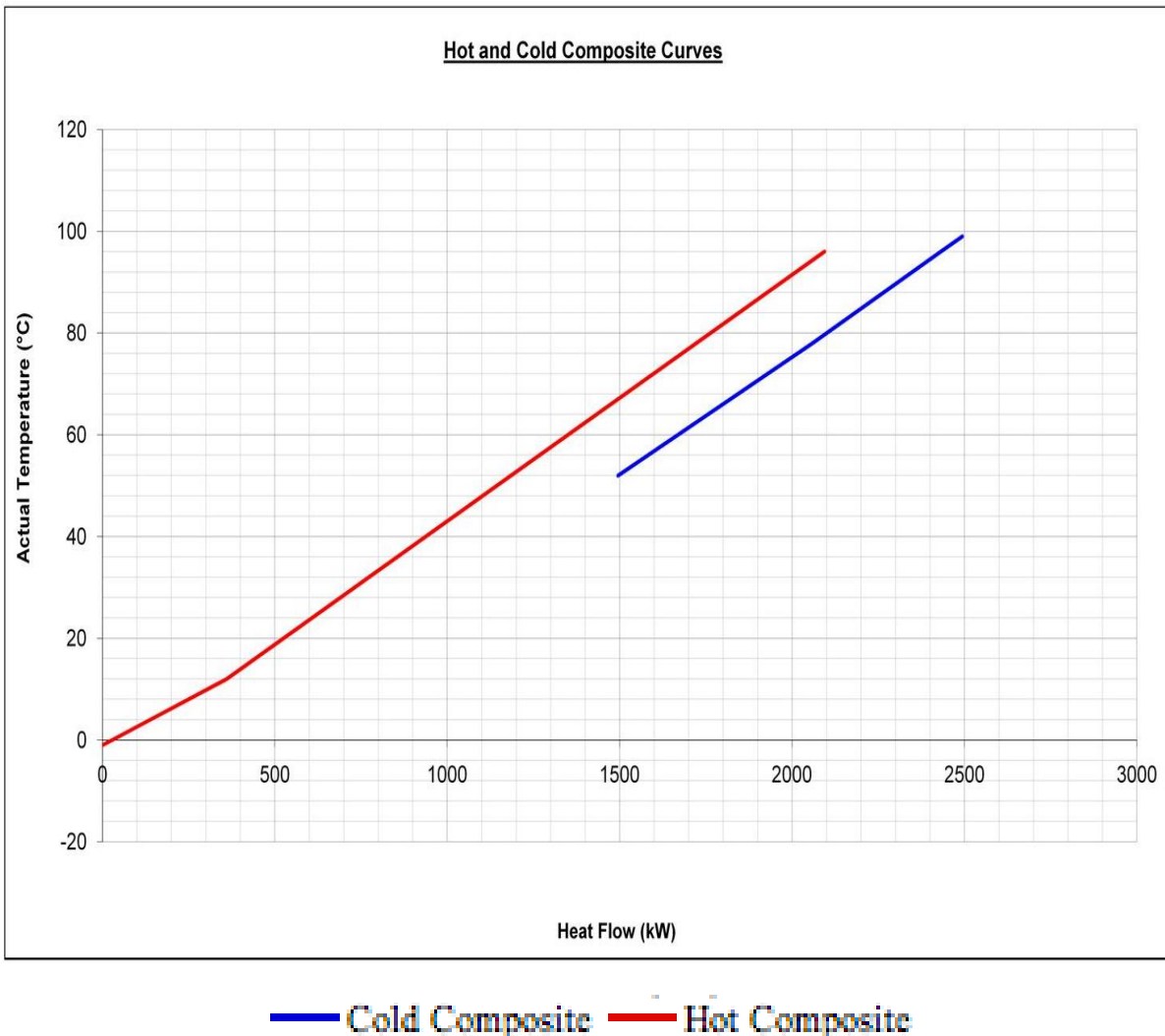


Figure 21. Composite curve of case 3.

The overlap between the composite curves represents the maximum amount of heat recovery possible within the process which is 598.73 KW. The “overshoot” at the bottom of the hot composite represents the minimum amount of external cooling utility required which is 1495.3 KW and the “overshoot” at the top of the cold composite represents the minimum amount of external heating which is 394.5 KW. Finally the pinch point is located at the ultimate approach between the hot and cold composite curve which is 59.5 ° C.

This graphical illustration gave similar results as the numerical analysis (problem table) stated earlier.

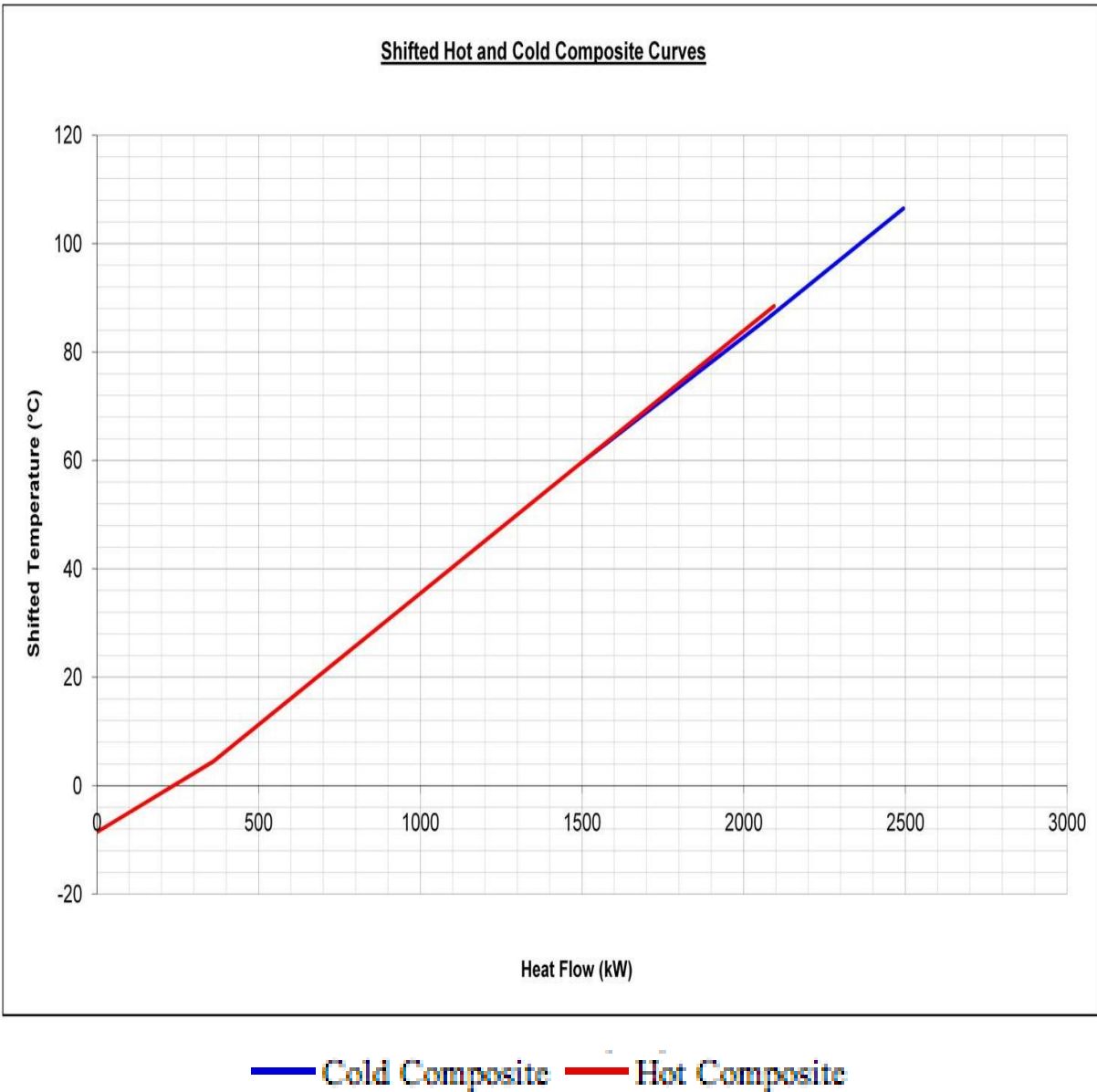


Figure 22. Shifted composite curve of case 3.

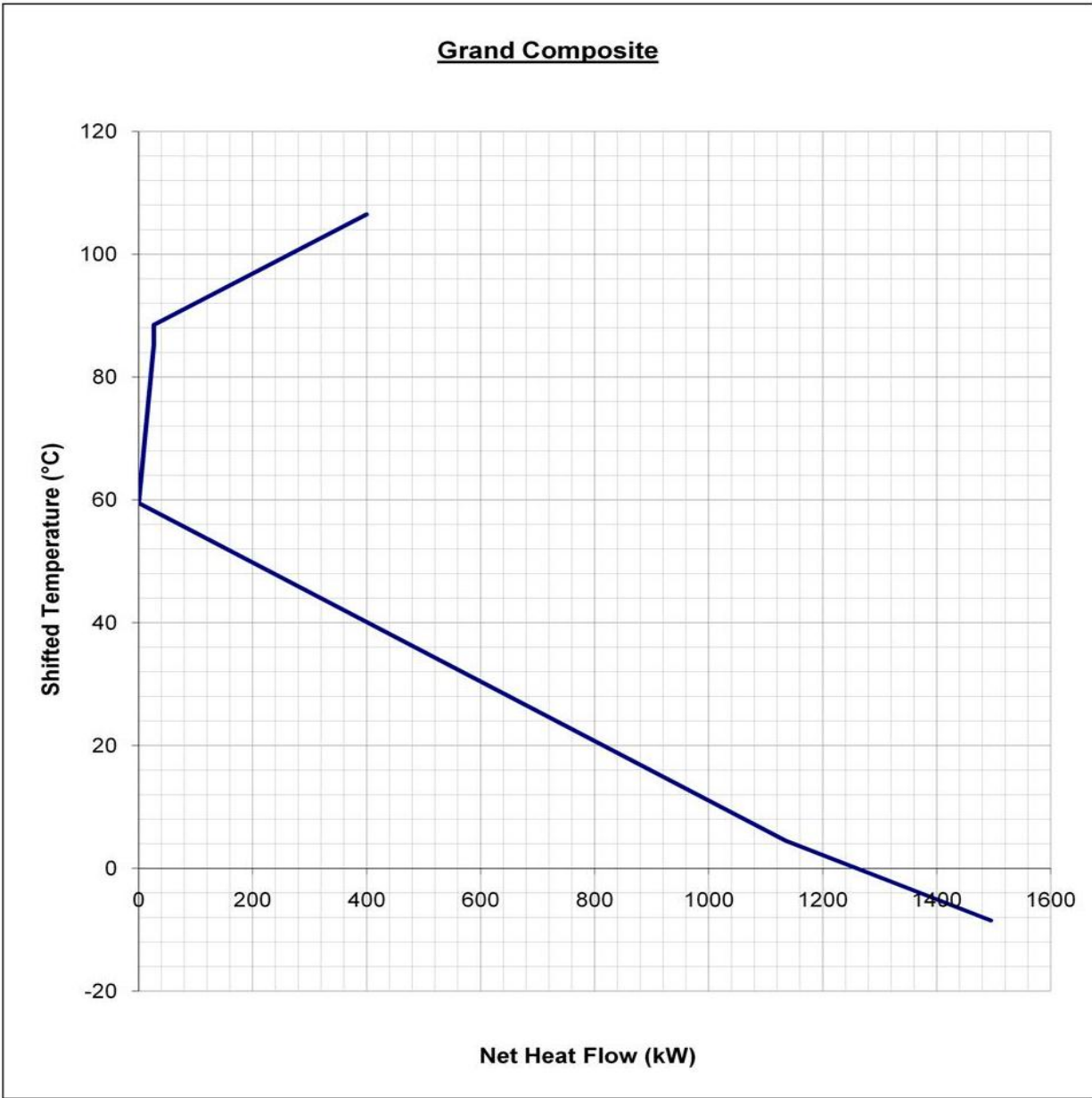


Figure 23. Grand composite curve of case 3.

4.6.3 Heat exchange network design for maximum energy recovery

Pinch design method was taken for the HEN design.

4.6.3.1 Design above the pinch

The feasibility criteria :

1. $CP_H \leq CP_C$
2. $N_H \leq N_C$
3. CP difference for hot end pinch matches = over all CP difference for above the pinch.

The CP feasibility criterion $CP_H \leq CP_C$ has been applied to all hot end streams to identify the streams which can be a perfect match for heat exchange to exploit the heat recovery. In addition to the CP feasibility criterion the “numer count” feasibility criterion $N_H \leq N_C$ has been taken for the above the pinch design. Both CP and N feasibility criterion were satisfied. And further more the third feasibility criterion has been applied to design heat exchange network using pinch design method. The CP difference criterion was also fulfilled.

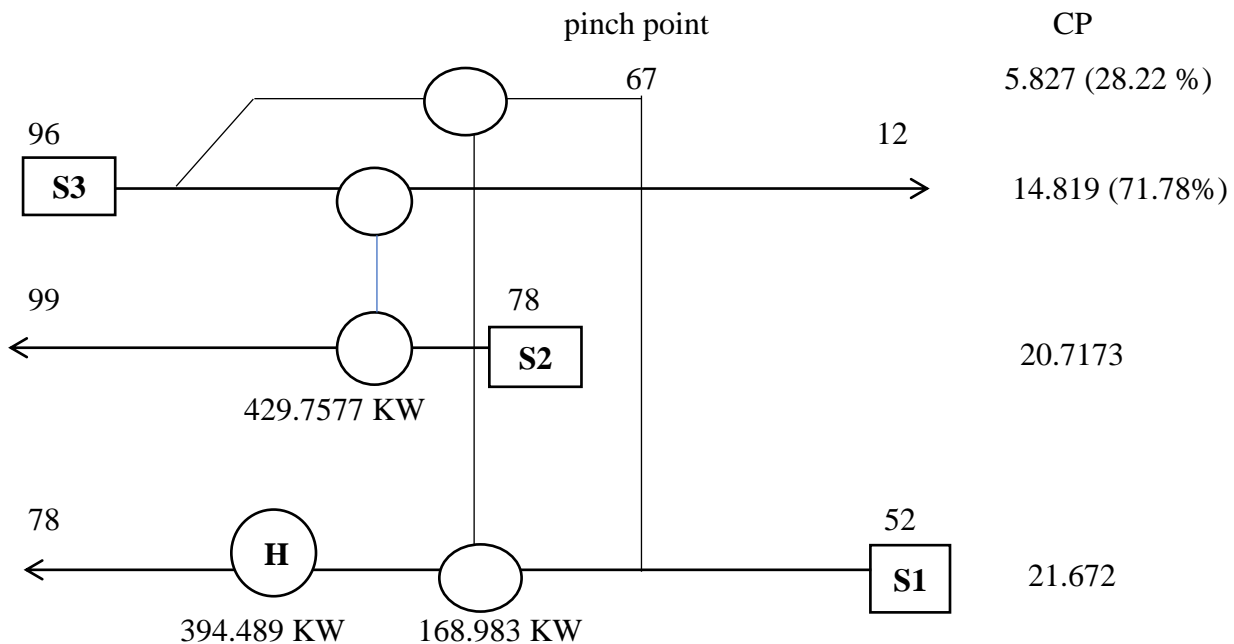


Figure 24. Above the pinch HEN Design of case 3.

4.6.3.2 Design below the pinch

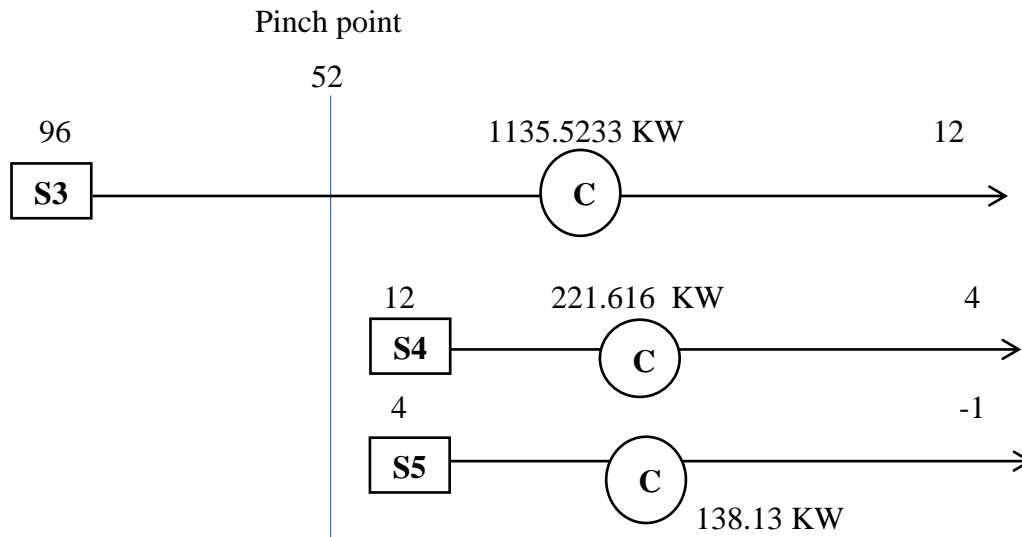


Figure 25. Below the pinch HEN design of case 3.

Putting the “hot end” and “cold end” designs (above the pinch and below the pinch designs) together gives the completed design shown in figure 25. To summarize the above and below the pinch designs, in the above the pinch design, hot stream S3 was splitted to match with cold streams S1 and S2 to cooled it down to the pinch temperature (59.5 °C) and delivered 598.7407 KW energy to both cold streams S1 & S2, and extra 1135.5233 KW external cooling utility was required, since there wasn't any pinch match in the below the pinch design to bring the hot stream to it's target temperature. Similarly, for the remained hot streams S4 & S5, an external cooling utility of 221.616 and 138.13 KW were required . For best possible energy performance of a ΔT_{\min} of 15°C incorporating; two exchangers, one heater and three coolers, six units in total of heat transfer equipment were required .

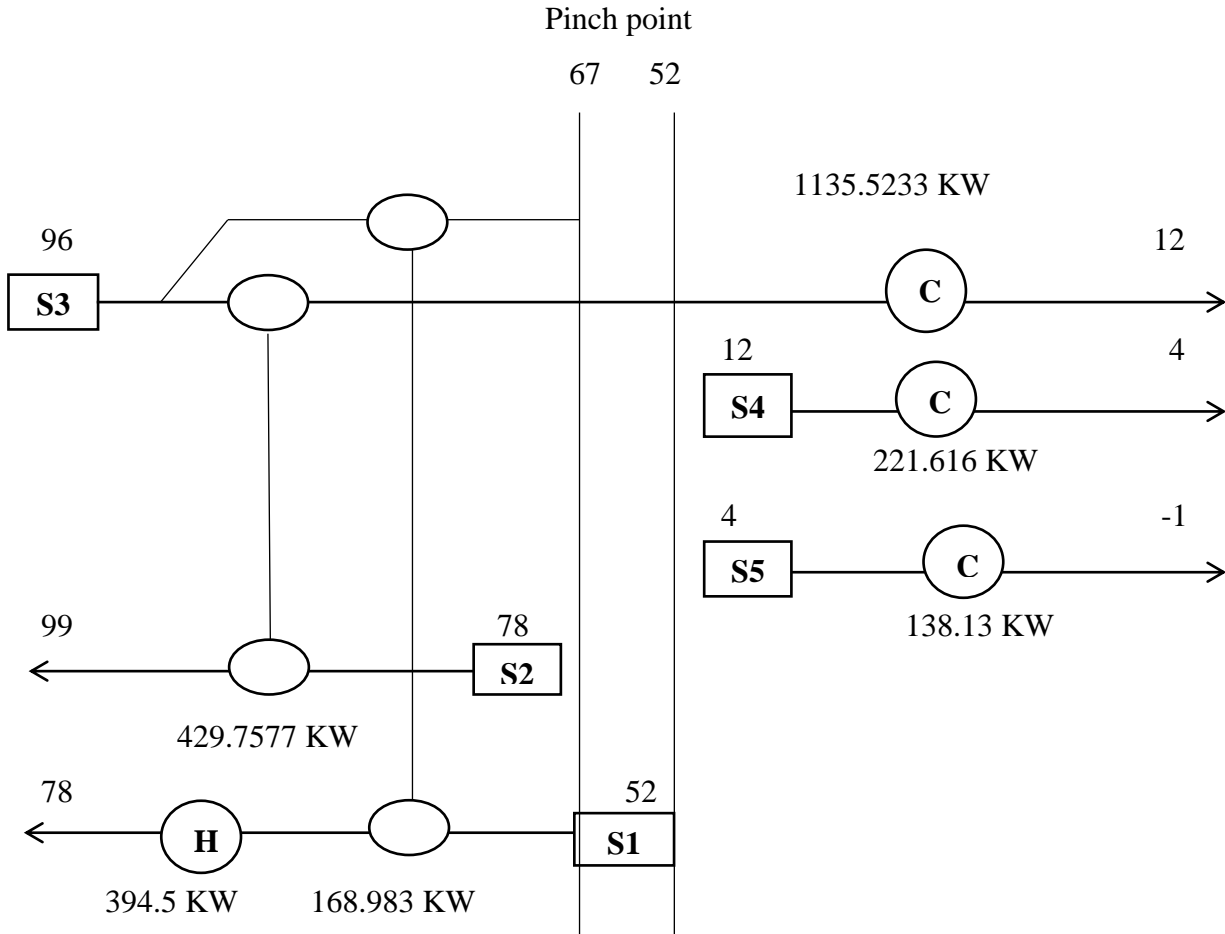


Figure 26. Completed HEN design of case 3.

4.7 case 4:

20 °C of ΔT_{\min} was taken.

4.7.1 A targeting procedure: the “Problem Table” algorithm

similar procedure has been followed. The results and discussion are presented below.

Table 16. Extracted data of process stream for case 4.

Stream Name	T _S	T _T	\dot{M}	C _p	ΔH	Stream Type	T _{S, interval}	T _{T, interval}
	°C	°C	kg/s	kJ/kgK	kW		°C	°C
S1	52	78	6.020	3.6	563.472	COLD	62	88
S2	78	99	5.053	4.05	429.7577	COLD	88	109
S3	96	12	5.580	3.7	1734.264	HOT	86	2
S4	12	4	7.290	3.8	221.616	HOT	2	-6
S5	4	-1	7.270	3.8	138.13	HOT	-6	-11

Step 2: note any duplicated interval temperatures

88, 2 and -6 were duplicated as shown in the above table.

Step 3: rank the interval temperatures in order of their magnitude showing the duplicating temperatures only once in order.

109, 88, 86, 62, 2, -6, -11

Step 4: carry out heat balance for the stream falling with in each temperature interval.

$$\Delta H_{\text{interval}} = (\sum CP_H - \sum CP_C) \Delta T_{\text{interval}}$$

$$\Delta T_{\text{interval}} = (T_i - T_{i+1})_{\text{interval}}$$

Table 17. Interval temperatures and their corresponding CPnet representation of case 4.

T _{interval}	$\Delta T_{\text{Interval}}$	$\sum CP_H - \sum CP_C$	Actual values
109	-	-	-
88	21	0 – S2 ^C	0 – 20.46465
86	2	S3 ^C – S2 ^C	20.646 – 20.46465

62	24	$S3^H - S1^C$	20.646 – 21.672
2	60	$S3^H - 0$	20.646 – 0
-6	8	$S4^H - 0$	27.702 – 0
-11	5	$S5^H - S1^C$	27.626 – 0

Stream Population	$\Delta T_{interval}$	$\sum CP_H - \sum CP_C$
109 $S2^C$	-	-
88	21	-20.46465
86 $S1^C$	2	0.181
62	24	-1.026
2	60	20.646
-6 $S3^H$	8	27.702
-11 $S4^H$ $S5^H$	5	27.626

Figure 27. Temperature intervals and corresponding net heat flow of case 4.

Table 18. Problem table of case 4.

$T_{interval}$	Interval	$T_{(i+1)} - T_i$	CP_{net}	ΔH	Surplus/ Deficit
°C		°C	KW/K	KW	
109					
	1	21	-20.4647	-429.7577	D
88					
	2	2	-21.672	-43.344	D
86					
	3	24	-1.026	-24.624	D
62					
	4	60	20.646	1238.76	S

2					
	5	8	27.702	221.616	S
-6					
	6	5	27.626	138.13	S
-11					

STEP 5: Cascade the heat surplus from one interval to the next down the column of interval temperatures by assuming there is no heat load in the hot utility and subsequent subtracting the heat loads at each stream.

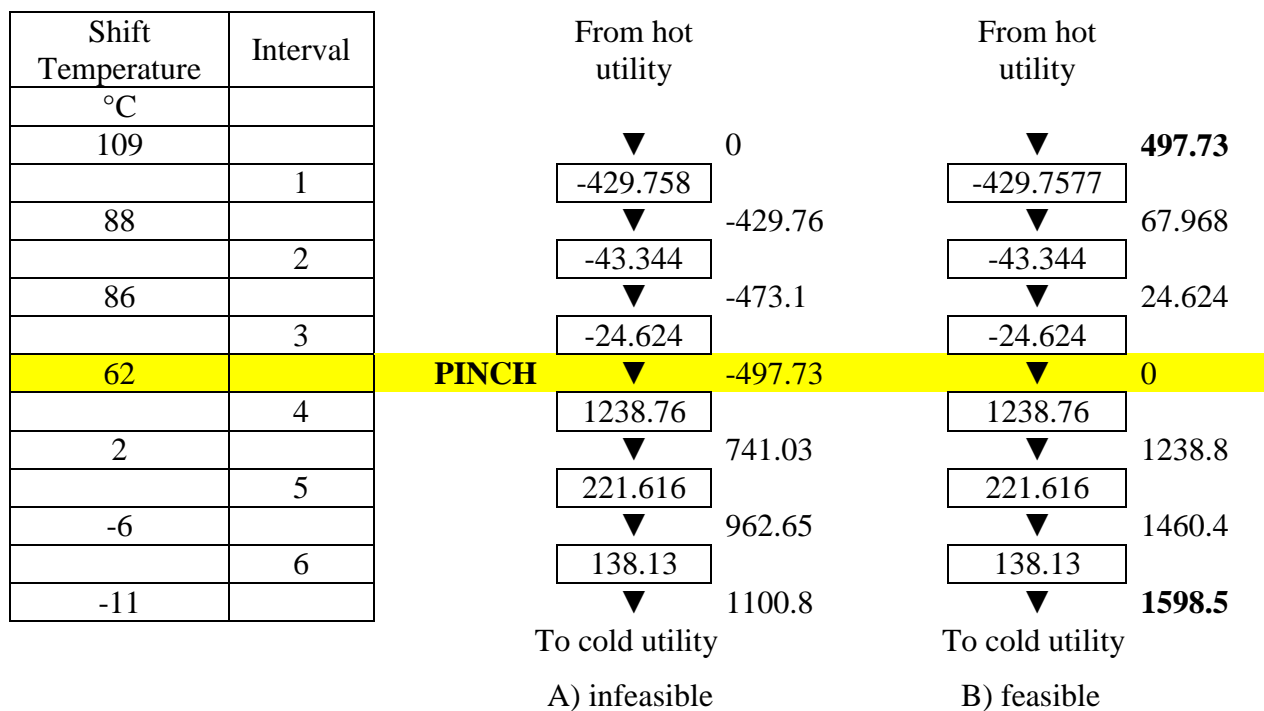


Figure 28. Feasible an Infeasible heat cascade of case 4.

Table 19. Problem table results of case 4.

Hot Pinch	72 °C
Cold Pinch	52 °C

Min Hot Utility	497.73 kW
Min Cold Utility	1598.51 kW

The total heat recovered by heat exchange is found by adding the heat loads for all the hot streams and all the cold streams (2094.01 and 993.2297 KW), respectively. Subtracting the hot and cold utility targets (1598.51 and 497.73KW) from these values gave the total heat recovery, 495.5 KW by two separate routes. The cold utility target minus the hot utility target should equal the bottom line of the infeasible heat cascade, which is 1100.8 KW. These calculations provided useful cross-checks that the stream data and heat cascades have been evaluated correctly.

4.7.2 Graphical representation of thermal pinch case 4.

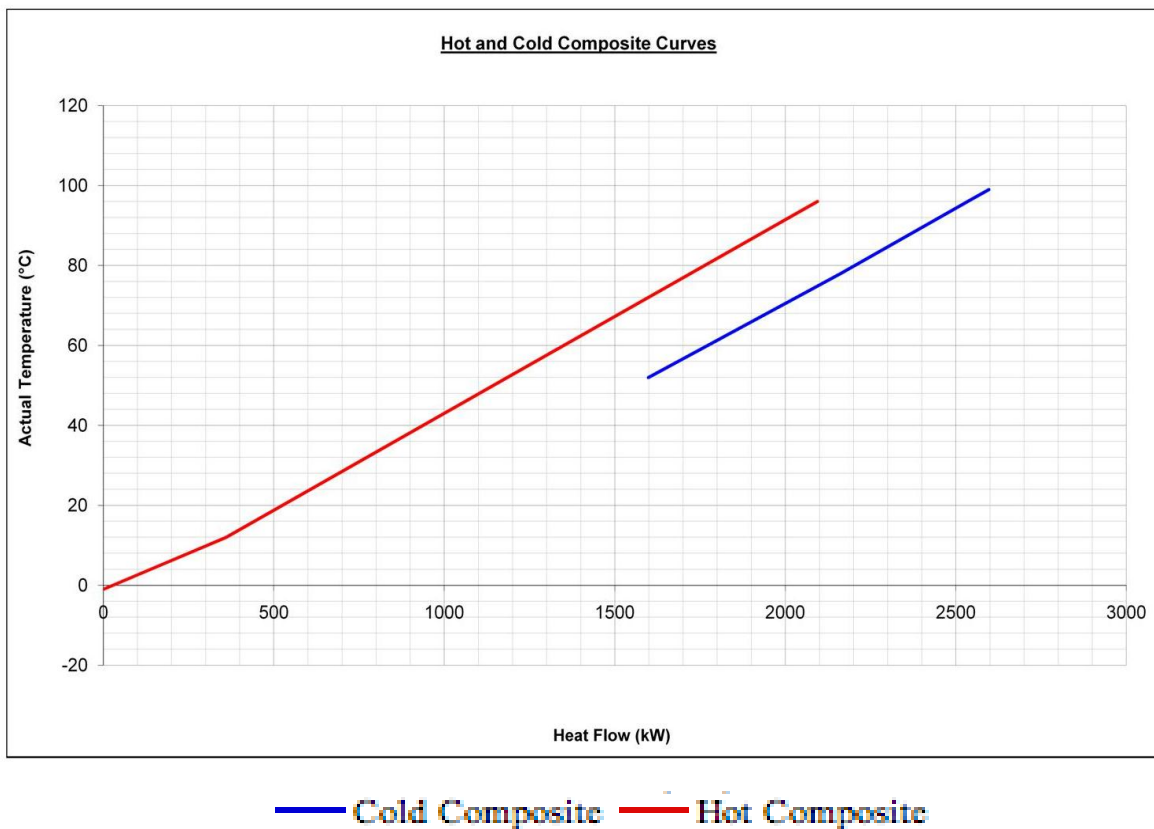
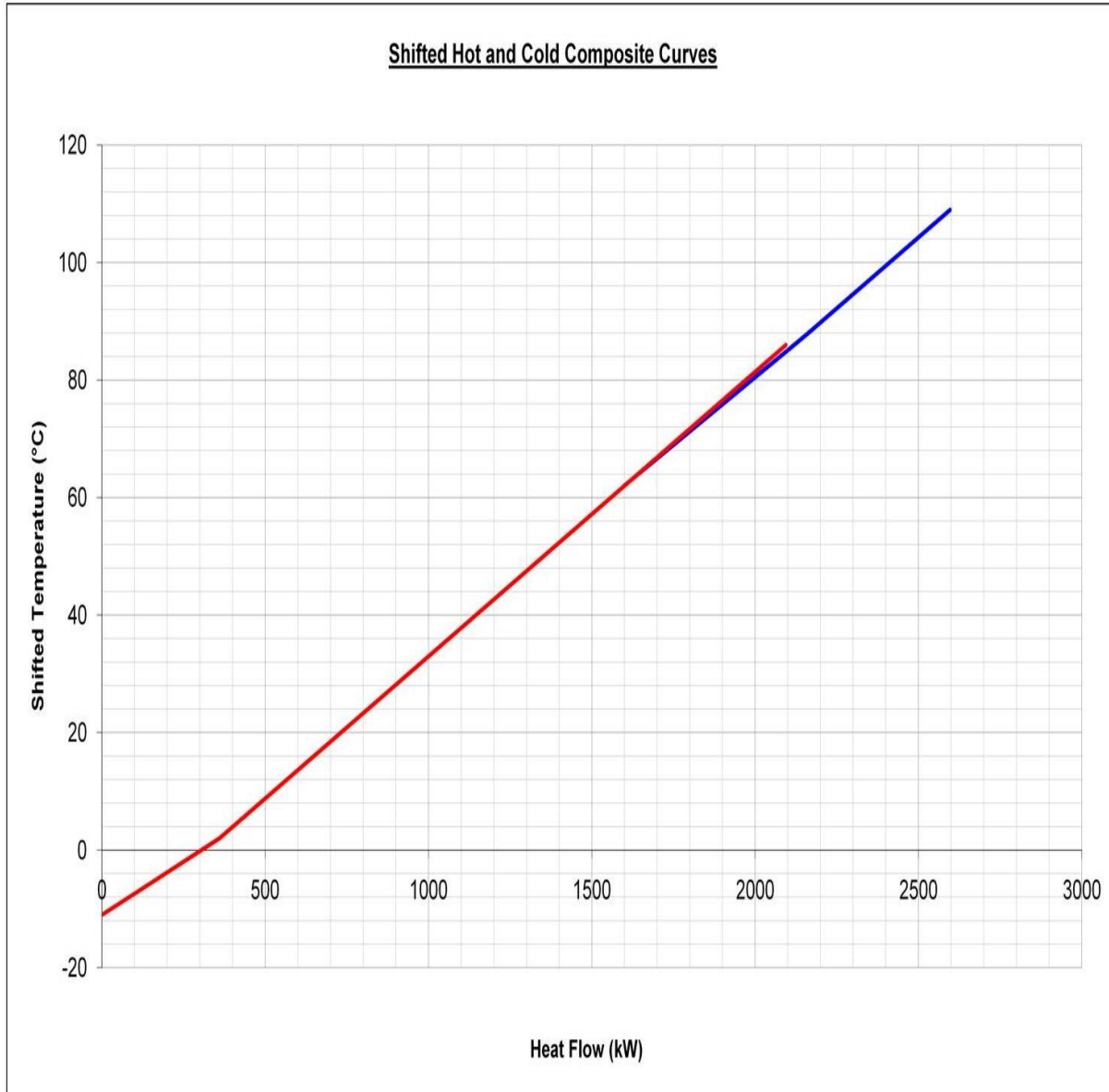


Figure 29. Composite curve of case 4.

The overlap between the composite curves represents the maximum amount of heat recovery possible within the process which is 495.5 KW. The “overshoot” at the bottom of the hot composite represents the minimum amount of external cooling utility required which is 1598.31 KW and the “overshoot” at the top of the cold composite represents the minimum amount of

external heating which is 497.73 KW. Finally the pinch point is located at the ultimate approach between the hot and cold composite curve which is 62 ° C.

The graphical illustration below gave similar results as the numerical analysis (problem table) stated earlier.



— Cold Composite — Hot Composite

Figure 30. Shifted composite curve of case 4.

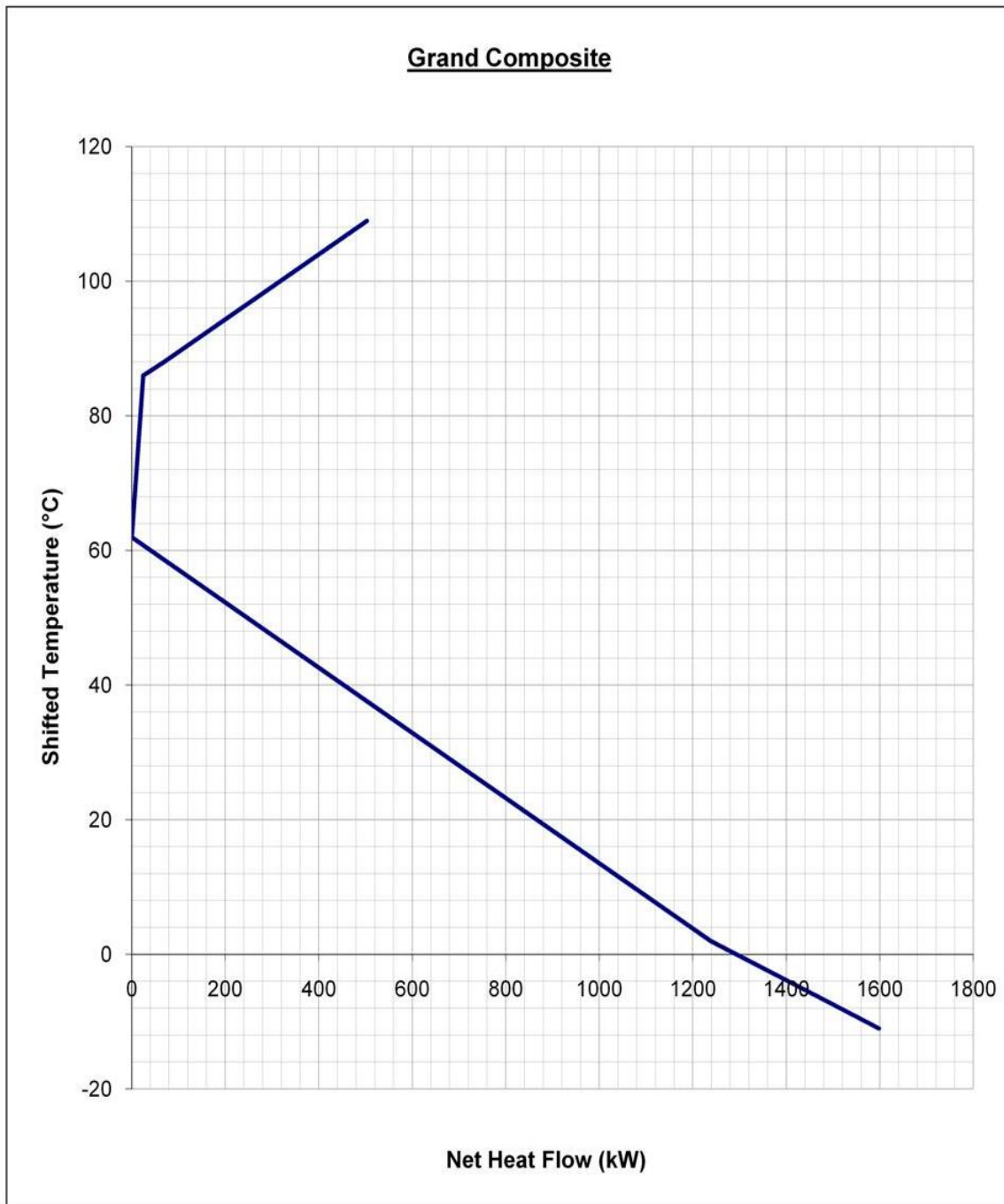


Figure 31. Grand composite curve of case 4.

4.7.3 Heat exchange network design for maximum energy recovery

Pinch design method was used for the HEN design.

4.7.3.1 Design above the pinch

The feasibility criteria :

1. $CP_H \leq CP_C$
2. $N_H \leq N_C$
3. CP difference for hot end pinch matches = over all CP difference for above the pinch.

The CP feasibility criterion $CP_H \leq CP_C$ has been applied to all hot end streams to identify the streams which can be a perfect match for heat exchange to exploit the heat recovery. In addition to the CP feasibility criterion the “numer count” feasibility criterion $N_H \leq N_C$ has been taken for the above the pinch design. Both CP and N feasibility criterion were satisfied. And further more the third feasibility criterion has been applied to design heat exchange network using pinch design method. The CP difference criterion was also fulfilled.

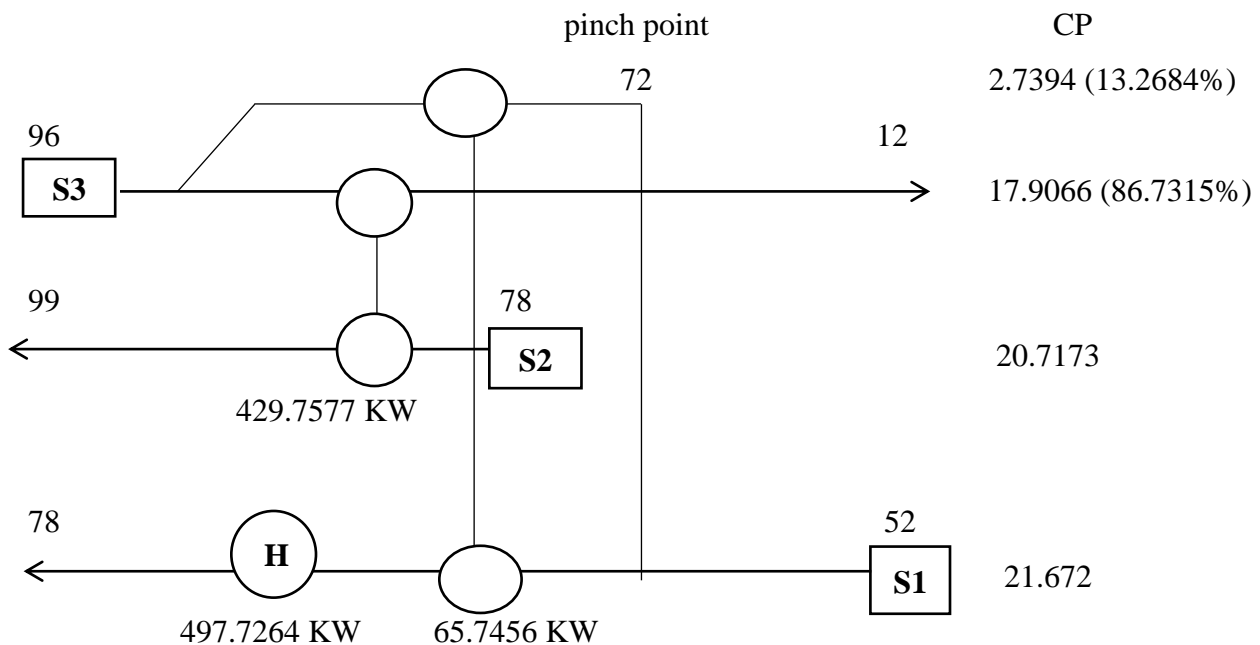


Figure 32. Above the pinch HEN Design of case 4.

4.7.3.2 Design below the pinch

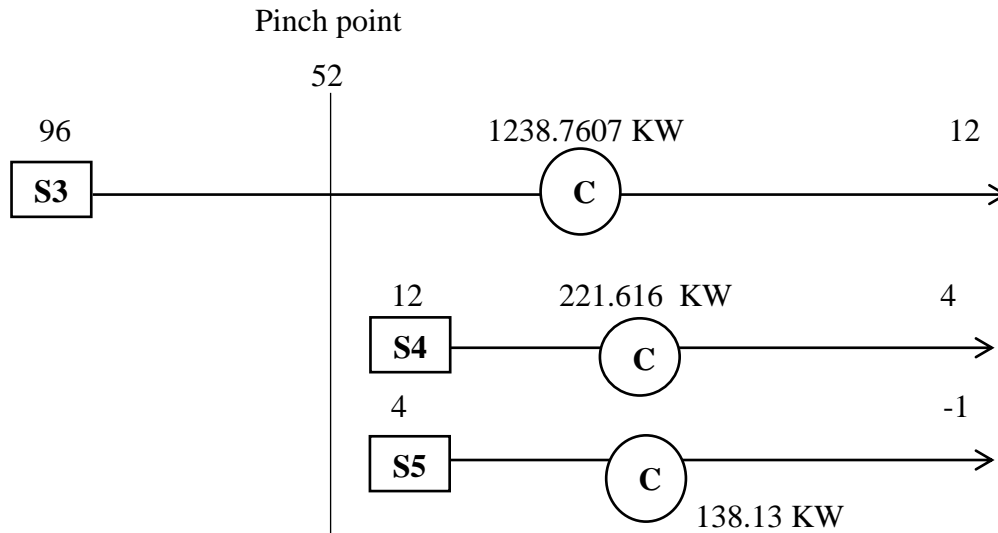


Figure 33. Below the pinch HEN design of case 4.

Putting the “hot end” and “cold end” designs (above the pinch and below the pinch designs) together gives the completed design shown in figure 33. To summarize the above and below the pinch designs, in the above the pinch design, hot stream S3 was splitted to match with cold streams S1 and S2 to cooled it down to the pinch temperature (62 °C) and delivered 495.5033 KW energy to both cold streams S1 & S2, and extra 1238.7607 KW external cooling utility was required, since there wasn't any pinch match in the below the pinch design to bring the hot stream to it's target temperature. Similarly, for the remained hot streams S4 & S5, an external cooling utility of 221.616 and 138.13 KW were required . For best possible energy performance of a ΔT_{\min} of 20 °C incorporating; two exchangers, one heater and three coolers, six units in total of heat transfer equipment were required .

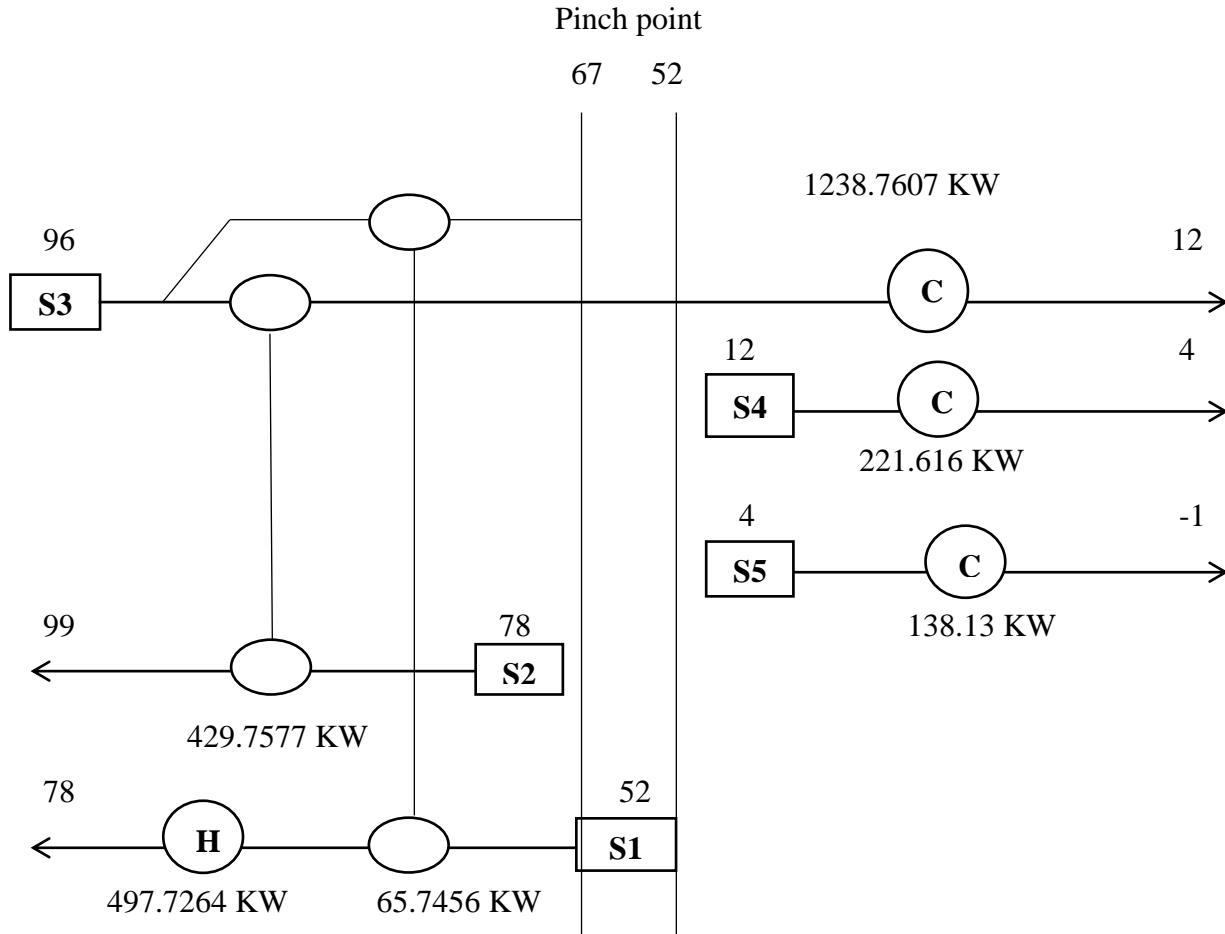


Figure 34. Completed HEN design of case 4.

4.8 Result summary

For a selection of four different design parameters which are minimum temperature differences, ΔT_{\min} (5, 10, 15 and 20 °C) within the possible range of ($0 \leq \Delta T_{\min} \leq 45$ °C), a pinch study has been executed. A pinch spreadsheet with a problem table algorithm and graphical representations has been used to investigate the heat recovery targets. In all four analyses; the pinch point has been located, the minimum utility requirements have been calculated, the maximum heat recovery targets have been identified. Furthermore, a HEN has been designed for maximum energy recovery and minimum utility requirements (MER).

Table 20. Results of all cases.

ΔT_{\min} (°C)	PP (°C)	$Q_{H\min}$ (KW)	$Q_{C\min}$ (KW)	MER (KW)	Units used for heat exchanging
5	54.5	188.04	1288.82	805.19	2 HE, 1 heater and 3 coolers
10	57	291.27	1392.05	701.96	2 HE, 1 heater and 3 coolers
15	59.5	394.5	1495.28	598.73	2 HE, 1 heater and 3 coolers
20	62	497.73	1598.51	495.5	2 HE, 1 heater and 3 coolers

The current utility requirements of the brewery (energy consumption) were compared with the results of the pinch study. As it can be seen in table 21, there was a significant amount of energy usage reduction in all four cases of the pinch study. The study provided a method to reduce the energy consumption of the brewery and its corresponding CO₂ release to the environment. i.e: massive CO₂ release corresponds with high fuel consumption for energy generation used in the brewing operation. The minimum energy requirements(Energy targets) and the maximum energy recovery target (energy saving opportunity) for four cases are presented in table 21.

Table 21. Possible utility requirement savings.

Utility	Current (KW)	Minimum requirement (KW)				MER(KW)			
		Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4
Heating	993.2297	188.04	291.27	394.5	497.73	805.19	701.96	598.73	495.5
Cooling	2094.02	1288.82	1392.05	1495.28	1598.51	805.19	701.96	598.73	495.5
Total	3087.249 7	1476.86	1683.32	1889.78	2096.24	1610.38	1403.92	1197.56	991

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This thesis was aimed to investigate the heat recovery target via thermal pinch analysis for a typical large scale brewery (Meta Abo brewery). Furthermore it established HEN design for maximum energy recovery. Pinch analysis techniques were used to investigate the heat recovery target. Minimum external utility requirements (hot and cold) of four cases with different minimum temperature difference, ΔT_{\min} (5, 10, 15 and 20 °C) within the possible range of ($0\text{ °C} \leq \Delta T_{\min} \leq 45\text{ °C}$) has been calculated. A problem table, heat cascades, shifted composite curve, and a grand composite curves were constructed, using pinch analysis spreadsheet, to determine the pinch temperature and the minimum utility requirements. The pinch temperatures were determined to be 54.5 °C, 57 °C, 59.5 °C and 62 °C for cases 1, 2, 3 and 4 respectively. The minimum hot utility requirements for the four cases were 188.04 KW, 291.27 KW, 399.8 KW and 497.73 KW respectively and minimum cold utility were 1288.82 KW, 1392.05 KW, 1495.28 KW and 1598.51 KW respectively. The optimum minimum temperature difference between the hot and cold streams was determined to be 45 °C. The heat recovery target was calculated for all cases. The energy recovery targets for the four cases were determined to be 805.19 KW, 701.96 KW, 598.73 KW and 495.5 KW respectively. It's shown that as the minimum temperature difference increases the heat recovery target decreases while the minimum utility requirements increase. As a result, it could be concluded that the utility requirements contribute to the efficiency and cost optimization of the plant. The larger the utility requirements, the more expensive the cost due to energy cost. According to the analysis conducted for this study, it has been comprehended that Case 1 provided the most significant decrease in the hot and cold utility requirement with a larger heat recovery target. As the minimum temperature difference rise the minimum utility requirements increase but the maximum heat recovery target decrease.

5.2 Recommendation

From the result of the study, it can be observed that a significant amount of heat can be saved for a selected minimum temperature difference within the possible range. It's recommended for the brewery to consider this study as one potential way for improving energy efficiency and retrofitting the existing heat exchange network design. However, a further study on economical analysis and trade off (energy and capital cost) shall be performed prior to the consideration. The time average model (TAM) used in this work gives similar results to an assumed continuous process however most brewery configurations are effected as batch processes and as such the time slice model (TSM) may be considered to give more realistic energy targets

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APPENDICES

A) INDEX of pinch analysis spreadsheet

<u>INPUT</u>	Input Data	Input problem data, i.e. stream temperatures, stream names, stream properties and dTmin criteria.
<u>PT</u>	Problem Table & Cascade	Problem table, heat cascade, pinch identification, problem type, min utility requirements.
<u>CC</u>	Composite Curves	Composite curve plot.
<u>SCC</u>	Shifted Composite Curves	Shifted composite curve plot.
<u>GCC</u>	Grand Composite Curve	Grand composite plot.
<u>GRID</u>	Grid Diagram	Schematic showing hot and cold shifted streams and the pinch location.
<u>AS</u>	Actual Streams	Schematic showing actual streams.
<u>AT</u>	Actual Intervals Table	Calculation table for actual composite curves.
<u>SS</u>	Shifted Streams	Schematic showing shifted streams.
<u>ST</u>	Shifted Intervals Table	Calculation table for shifted composite curves.
<u>DTMIN</u>	Varying dTmin global	Pinch analysis over a range of dTmin values.

<u>A1</u>	Set-up and conversions	Configuration page listing conversion factors.
<u>A2</u>	Plot tables	Tabulation of plot values.

B) INPUT

1. Select Input Method from the Dropdown list:

Mass Flowrate & Specific Heat Capacity

2. Input Global dT_{min} & select input temperature units:

10 °C

3. Select appropriate units for the input data from the drop down lists below (E15/F15).

Requires Input -	
Optional Input -	
Calculation cell -	

4. Input data: Stream Name, Temperatures & Heat/Flow Data (max 50 streams).

5. Select desired output unit set:

SI-based (kW/K)

Stream Name	Supply Temperature	Target Temperature	dT Min Contribution	Mass Flowrate	Specific Heat Capacity	Heat Flow	Stream Type	Supply Shift	Target Shift
	°C	°C	°C	kg/s	kJ/kgK	kW		°C	°C
S1	52	78		6.020	3.6	563.472	COL D	57.0	83.0
S2	78	99		5.053	4.05	429.7577	COL D	83.0	104.0
S3	96	12		5.580	3.7	1734.264	HOT	91.0	7.0
S4	12	4		7.290	3.8	221.616	HOT	7.0	-1.0
S5	4	-1		7.270	3.8	138.13	HOT	-1.0	-6.0

C) PT

Shift Temperature	Interval	$T_{i+1} - T_i$	mCp_{net}	dH		Infesible Cascade From hot	Feasible Cascade From hot	
°C		°C	kW/K	kW				
104						▼ 0	▼ 291.27	
	1	13	-20.4647	-266.0405	demand	▼ -266.04	▼ -266.0405	
91						▼ -266.04	▼ 25.225	
	2	8	0.1814	1.4508	surplus	▼ 1.4508	▼ 1.4508	
83						▼ -264.59	▼ 26.676	
	3	26	-1.026	-26.676	demand	▼ -26.676	▼ -26.676	
57						PINCH ▼ -291.27	▼ 0	
	4	50	20.646	1032.3	surplus	▼ 1032.3	▼ 1032.3	
7						▼ 741.03	▼ 103.23	
	5	8	27.702	221.616	surplus	▼ 221.616	▼ 221.616	
-1						▼ 962.65	▼ 125.39	
	6	5	27.626	138.13	surplus	▼ 138.13	▼ 138.13	
-6						▼ 110.8	▼ 139.2	

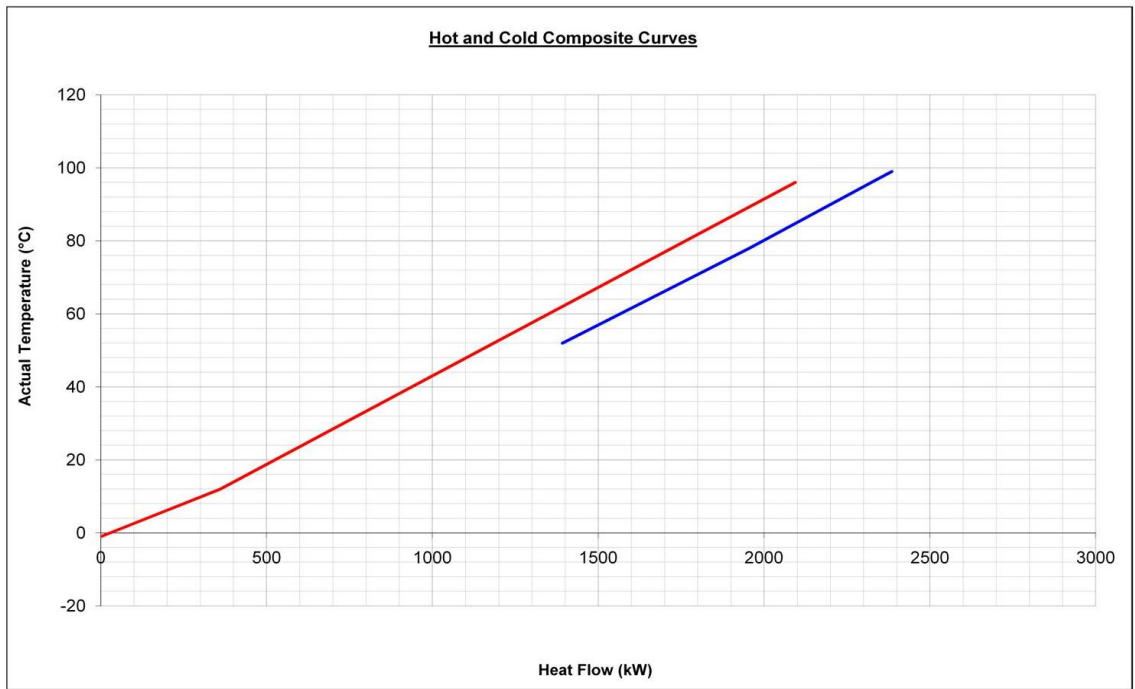
Hot Pinch	62 °C
Cold Pinch	52 °C

Min Hot Utility	291.27 kW
Min Cold Utility	1392.05 kW

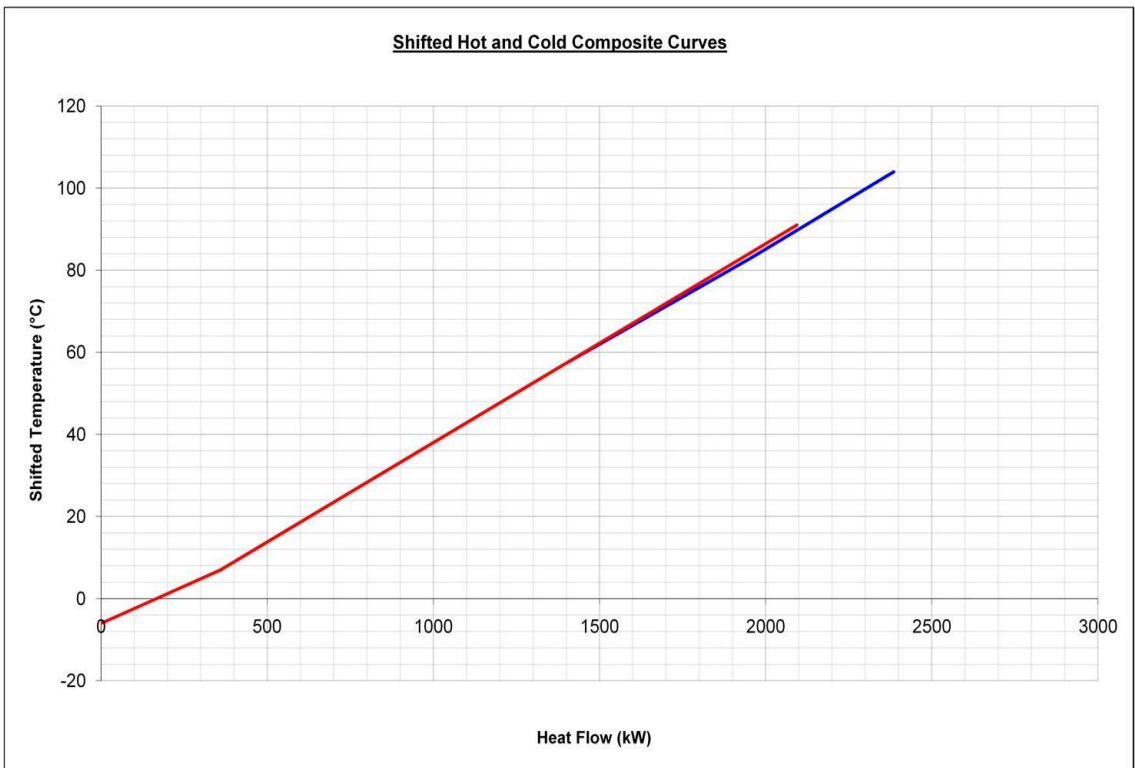
SINGLE PINCH PROBLEM	
-----------------------------	--

To cold
To cold

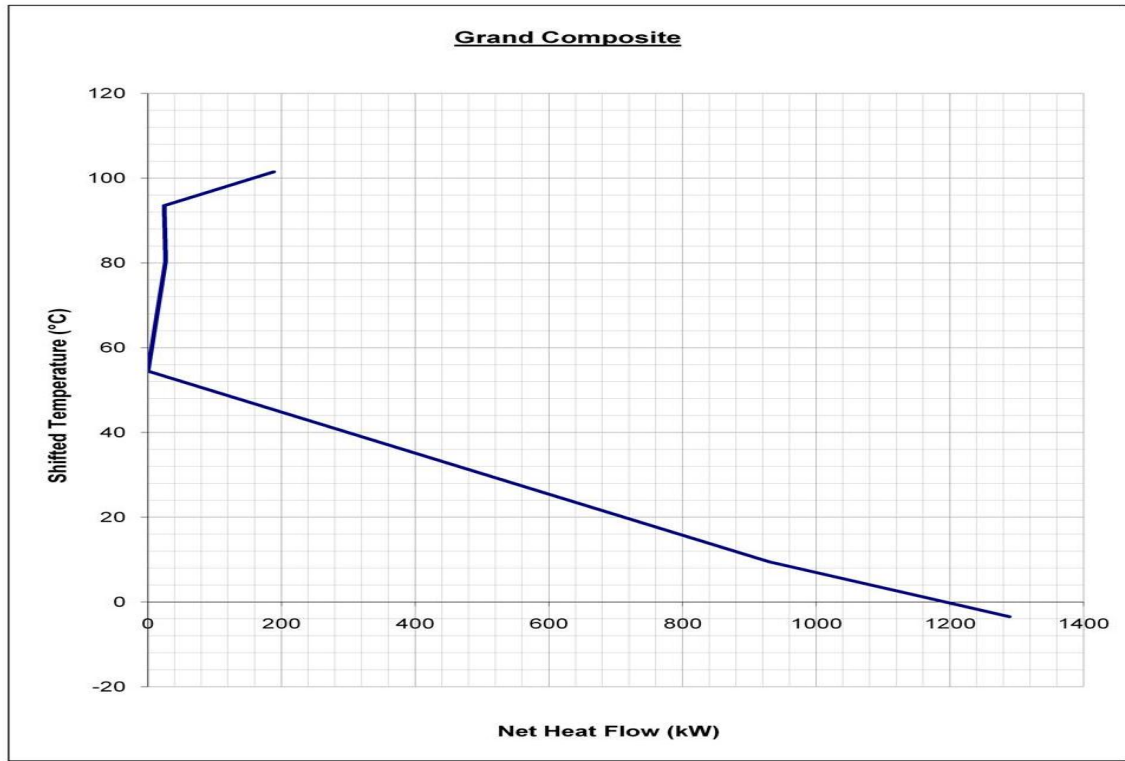
D) CC



E) SCC



F) GCC



G) GRID

Stream Name	Heat Flow (kW)	mCp (kW/K)	Interval	Interval								
				1	2	3	4	5	6			
			Shifted Temp (°C)	104	91	83	57	7	-1	-9		
S1	563.472	21.672	COLD			◀	—	•				
S2	429.75765	20.46465	COLD	◀	—	—	—	•				
S3	1734.264	20.646	HOT		•	—	—	—	—	▶		
S4	221.616	27.702	HOT						•	—	▶	
S5	138.13	27.626	HOT							•	—	▶

H) AS

Stream Heat Flow (kW)		S1 21.672	S2 20.4647	S3 20.646	S4 27.702	S5 27.626
Interval	Actual Temp (°C)	COLD	COLD	HOT	HOT	HOT
	99		▲			
1						
	96			●		
2						
	78	▲	●			
3						
	52	●				
4						
	12			▼	●	
5						
	4				▼	●
6						
	-1					▼

I) AT

Actual Temperature	$T_{(i+1)}-T_i$	C_{pHot}	dHHot	Hot Duty	C_{pCold}	dHCold	Cold Duty
	°C	kW/K	kW	kW	kW/K	kW	kW
99							#####
	3	0.0	0.0		20.4647	61.394	
96				2094.01			#####
	18	20.646	371.628		20.4647	368.3637	
78				1722.382			1955.518
	26	20.646	536.796		21.672	563.472	
52				1185.586			1392.046
	40	20.646	825.84		0.0	0.0	
12				359.746			
	8	27.702	221.616		0.0	0.0	
4				138.13			
	5	27.626	138.13		0.0	0.0	
-1				0.0			

J) SS

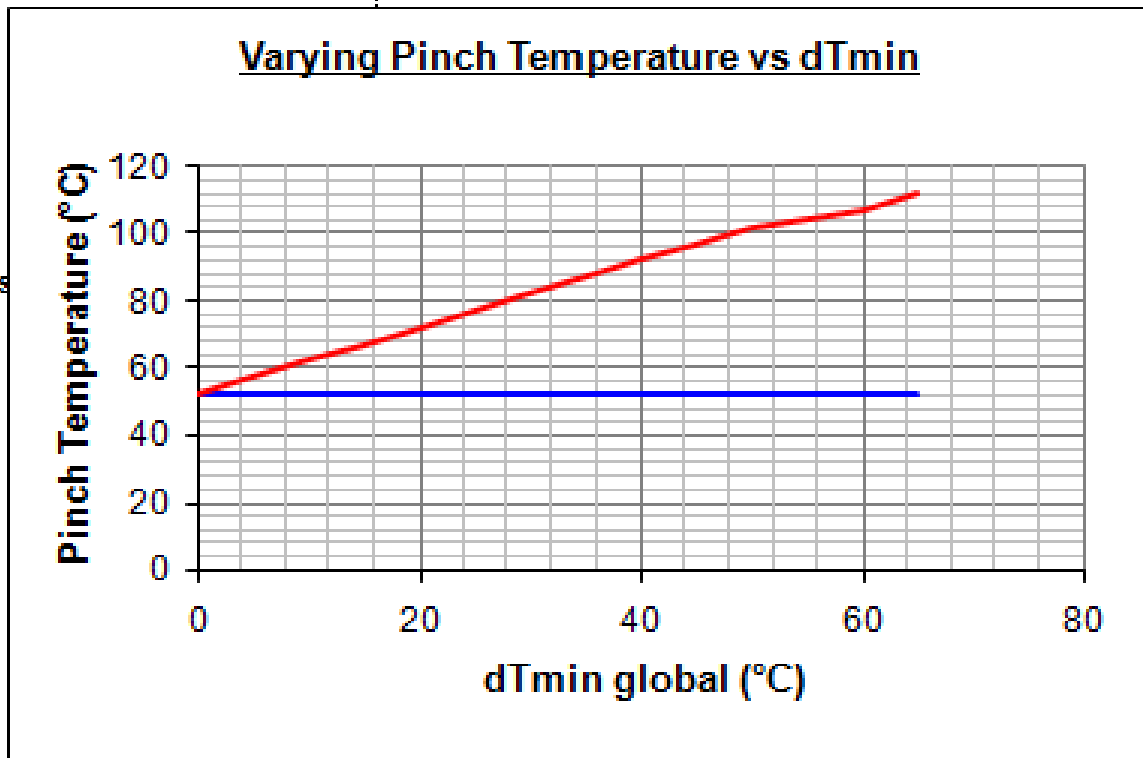
Stream		S1	S2	S3	S4	S5
mCp (kW/K)		21.672	20.4647	20.646	27.702	27.626
Heat Flow (kW)		563.472	429.7577	1734.264	221.616	138.13
Interval	Shifted Temp (°C)	COLD	COLD	HOT	HOT	HOT
	104		▲			
1	91			●		
2	83	▲	●			
3	57	●				
4	7			▼	●	
5	-1					●
6	-6					▼

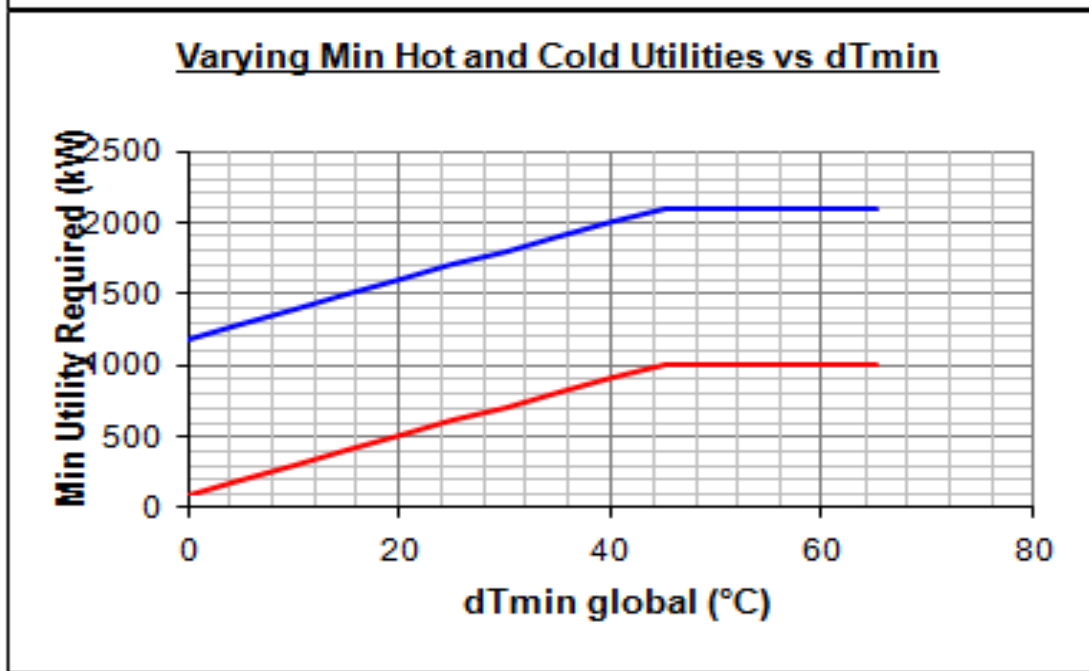
K) ST

Shifted Temperature	$T_{(i+1)} - T_i$	C_{pHot}	dHHot	Hot Duty	C_{pCold}	dHCold	Cold Duty
	°C	kW/K	kW	kW	kW/K	kW	kW
104							#####
	13	0.0	0.0		20.4647	266.0405	
91				2094.01			#####
	8	20.646	165.168		20.4647	163.7172	
83				1928.842			1955.518
	26	20.646	536.796		21.672	563.472	
57				1392.046			1392.046
	50	20.646	1032.3		0.0	0.0	
7				359.746			
	8	27.702	221.616		0.0	0.0	
-1				138.13			
	5	27.626	138.13		0.0	0.0	
-6				0.0			

L) DTmin

dTmin °C	Hot Pinch °C	Cold Pinch °C	Hot Utility kW	Cold Utility kW
0	52	52	91.11	1185.59
5	57	52	193.34	1288.82
10	62	52	296.57	1392.05
15	67	52	399.8	1495.28
20	72	52	503.03	1598.51
25	77	52	606.26	1701.74
30	82	52	709.49	1804.97
35	87	52	812.72	1908.2
40	92	52	915.95	2011.43
45	97	52	998.54	2094.01
50	102	52	998.54	2094.01
60	107	52	998.54	2094.01
65	112	52	998.54	2094.01





M) A1

Drop-Down

Temperature

Lists:

Units:

Select Input				
Data Method	Select Units	0	Select Units	0
Heat Capacity				
Flowrate	kg/s	1	kJ/kgK	1
Heat Duty	kg/h	3600	J/kgK	1000
Mass				
Flowrate &				
Specific Heat				
Capacity	lb/min	132.2773573	Btu(IT)/(lb.°F)	0.238845897
Mass				
Flowrate &				
Enthalpy	lb/h	7936.641439	kcal(IT)/(kg.°C)	0.238845897

°C
°F
K
R

Change			
	US		
	ton(short)/h	3.968320719	0
	UK		
	ton(long)/h	3.543143499	0
	ton(metric)/h	3.6	0

Output Data Unit Set:

Name of unit Symbol Relation to SI units Relation

to °C

kelvin K SI base unit $T[\text{K}] = T[^\circ\text{C}] +$

273.15

degree Celsius °C $T[^\circ\text{C}] = T[\text{K}] - 273.15$

degree Rankine °R; °Ra $T[^\circ\text{Ra}] = 1.8 \times$

$T[\text{K}]$

degree Fahrenheit °F $T[^\circ\text{F}] = T[\text{K}] \times 1.8 - 459.67$ $T[^\circ\text{F}] = 1.8 \times T[^\circ\text{C}] + 32$

SI-based (kW/K)

Metric-hour based

(MJ/h/K)

US / Imperial

(MBtu(IT)/hr/°F)

Presentation Units

Temperature °C

Heat Capacity

Flowrate kW/K

Heat Duty kW

Specific Heat Capacity

Mass Flowrate

Enthalpy Change

Conversion Factors:

Heat Capacity Flowrate	Conversion Factors	Heat Duty	Conversion Factors
Select Units		Select Units	
kW/K	1	kW	1
W/K	1000	Btu(IT)/sec	0.94781712
kcal(IT)/°Csec	0.2388459	Btu(IT)/min	56.86902722
Btu(IT)/°Fs	0.52656506	kcal(IT)/sec	0.238845897
		kcal(IT)/h	859.8452279
		hp (boiler)	0.101941995

Mass Flowrate	Conversion Factors	Specific Heat Capacity	Conversion Factors	Enthalpy Change	Conversion Factors
Select Units		Select Units		Select Units	
kg/s	1	kJ/kgK	1	kJ/kg	1
kg/h	3600	J/kgK	1000	J/kg	1000
lb/min	132.277357	Btu(IT)/(lb.°F)	0.2388459	Btu(IT)/lb	0.4299226
lb/h	3	kcal(IT)/(kg.°C)	0.2388459	kcal(IT)/k	1
US	7936.64143)		g	0.2388459
ton(short)/h	9				
UK	3.96832071				
ton(long)/h	9				
ton(metric)/h	3.54314349				
	9				
	3.6				

N) A2

Plot Tables

Cold Composite		Shift Cold Composite	
Actual Temp	Heat Load	Shift Temp	Heat Load
°C	kW	°C	kW
99	2385.28	104	2385.276
96	2323.88	91	2119.235
78	1955.52	83	1955.518
52	1392.05	57	1392.046
#N/A	#N/A	#N/A	#N/A
#N/A	#N/A	#N/A	#N/A
#N/A	#N/A	#N/A	#N/A

Hot Composite		Shift Hot Composite	
Actual Temp	Heat Load	Shift Temp	Heat Load
°C	kW	°C	kW
#N/A	#N/A	#N/A	#N/A
96	2094.01	91	2094.01
78	1722.38	83	1928.842
52	1185.59	57	1392.046
12	359.746	7	359.746
4	138.13	-1	138.13
-1	0	-6	0

Grand Composite

Shift Temp	Net Heat Load
°C	kW
104	291.2657
91	25.2252
83	26.676
57	0
7	1032.3
-1	1253.916
-6	1392.046