A CASE STUDY ON GRAPHICAL PINCH ANALYSIS APPROACH FOR MAXIMUM WATER AND ENERGY REDUCTION

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A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering (Hons.) Chemical Engineering

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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

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Signature : _________________________

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Specially dedicated to

my beloved grandmother, mother and father

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ABSTRACT

Water and energy are among the most important process utilities used in the process industries. As the price of crude oil for energy generation remain high nowadays and the scarcities of water sources all around the world, the optimum consumption of both process utilities to reduce the operating cost has become the most critical issue in all process industries. Past decades, there were numbers of research methods have been developed for targeting of the optimum usage of process utilities. The previous researches were mainly divided into graphical approach and numerical approach. However, in previous studies, certain research gaps that could not be solved still existed. From the previous research, the author has realised that graphical approach to the minimisation of utilities usage was relatively easier, more efficient, and provides insight through visualisation compare to the numerical method. Therefore, in this project, the author has utilised a new graphical method named Superimposed Mass and Energy Curve (SMEC) to perform the process integration to a given case study to minimise the water and energy consumption. Besides, through research, this method was also applicable to wide range of system such as mass transfer-based, non-mass transfer-based system and complex design problems with multiple pinches. The SMEC was an improved graphical method which adapted from few of the research papers, where the source and demand allocation curve was superimposed into the heat surplus diagram with constraints of six design heuristics. A great achievement has been reach through this method in the author’s case study where large percentage of utilities, which were 31.17 % of freshwater and wastewater, 65.55 % of heat utilities and 100 % of cold utilities have been reduced compare to the original case.

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LIST OF SYMBOLS / ABBREVIATIONS

C	concentration, ppm
C_p	specific heat capacity, J/(kg·K)
F	flowrate, kg/s
ΔH	enthalpy change, kW
Δm	mass loading, ppm
Q_{Cmin}	minimum cooling energy, kW
Q_{Hmin}	minimum heating energy, kW
T_{in}	inlet temperature, ^{o}C
T_{out}	outlet temperature, ^{o}C
EMD	energy match diagram
FW	freshwater
HCC	heat composite curve
MTB	mass transfer base
NMTB	non-mass transfer base
SDCC	source demand composite curve
SDAC	source demand allocation curve
SMEC	superimposed mass and energy curve
WW	wastewater

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CHAPTER 1

INTRODUCTION

1.1 Background

Process utilities especially water and energy are among the most important resources used in the process industries. As the price of crude oil increased significantly nowadays and the scarcities of water sources, the optimum consumption of both process utilities has become the most critical issue in process industries (Bogataj and Bagajewicz, 2008).

In certain processes, large amount of energy consumption to be needed to heat up or cool down the water. For example, in petrochemical plants, significant amount of energy and water are required in heating and cooling of process streams in order to meet process operating conditions (Bagajewicz *et al.*, 2002). In food manufacturing industries, large amount of energy and water are required for the washing operations and sterilisation processes. As consequence, water and energy management need to be considered simultaneously when both the quantity and temperature of water are important (Bogataj and Bagajewicz, 2008).

Past decades, there were different methods based on conceptual design or mathematical programming, have been developed for energy and water minimization. The most widely and famous used technology was the well-known Pinch Technology (Linnhoff et al., 1982). However, there are some drawbacks from this method such as only energy was concerned in the research, non-optimal solution achieved or limited by multi-contaminant problems (Bogataj & Bagajewicz, 2008). Thus, mathematical programming techniques were developed to overcome the drawbacks. Still, the techniques mentioned previously were limited to only mass-transfer based systems. In addition, the research in simultaneously minimisation of energy and water was still in the developing stage and hence more researches were needed.

In this project, a new method called Superimposed Mass and Energy Curves (SMEC) proposed by Wan Alwi *et al.* (2010) was used to solve the energy and mass utilised problem. This SMEC method provides a simple and interactive visualisation tool to target the minimisation of water and energy usage. It is also offers graphical insights for network design where it can be apply to both flowrate deficit and mass load deficit cases. In this method, energy match diagram is superimposed into the same graph with the source and demand composite curves on a plot of flowrate versus mass load/temperature.

1.2 Problem Statement

Process utilities including heat and water are very important resources in process industry. Over the last ten years, many researchers come out with the technique to minimise heat and water consumption. Separate reduction of heat and water may result in extra utilities as well as heat exchanger. In this study, the author focus on application a case study on new development method that can reduce the water and heat simultaneously to achieve the minimum utility consumption.

Give a set of water and heat-using systems which involve the mass transfer-based water using, it is desired to reduce the water and energy consumption using a user-friendly visualisation tool i.e. graphical technique based on pinch analysis concepts and heuristics.

1.3 Objective

The main objective of this project is to simultaneously minimise the water and energy consumption on a given case study by using a new graphical approach method named Superimposed Mass and Energy Curves (SMEC) developed by Wan Alwi *et al.* (2010).

The new SMEC graphical method provides a good insight between the water and energy where the temperature effect on the source and demand water in the case study can be seen immediately (Wan Alwi *et al.*, 2010). This cannot be achieved by the graphical approach technique proposed by Savulescu at al. (2005a) and Savulescu *et al.* (2005b). Therefore, as an extension for this study, the new SMEC method is used in this project for approach of the water and energy design target.

1.4 Significant of Research

In previous studies, simultaneously minimisation of water and energy has been approached by various methods such as conceptual graphical methods and mathematical modelling methods. However, there are some research gap still exist in those methods (Wan Alwi *et al.*, 2010). Hence, in this work, a new SMEC graphical method which combined the water and energy targeting will be used to fill up those research gaps in previous studies.

1.5 Scope of Study

The scope of study in this project is to graphically determine the minimum flowrate of fresh water usage and waste water discharge by using the Superimposed Mass and Energy Curves (SMEC) from the case study in Ataei and Yoo (2009). Besides, this project also targets the minimum hot and cold utilities requirements from the SMEC.

In this project, a case study studied by Ataei and Yoo (2009) was chosen. Ataei and Yoo (2009) applied a new mathematical method called “Non-isothermal Mixing” point identification in their paper. In this problem, one contaminant was considered instead of all three contaminants from the case study where no water flowrate change but with heat loss inside unit operations.

Table 1.1: The Water Using Operation Data (Ataei & Yoo, 2009)

Operation	Contaminant		Temperature		Limiting Water Flowrate, *F* (kg/s)
	Inlet (ppm)	Outlet (ppm)	Inlet (°C)	Outlet (°C)	
1	0	100	0	90	7.56
2	50	125	50	85	3.88
3	50	150	50	50	8.64

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In past recent years, a new research direction where the minimisation of water and energy consumption targets simultaneously has drawn attention of many of the researchers in the process integration field. The researchers were basically approach the research by conceptual graphical design methods, mathematical programming techniques or both.

Among the methods, conceptual graphical methods were typically easier to apply and master, most importantly, as a visualisation tools for the network design and pinch targeting. Whereas in mathematical programming methods, despite it provides great accuracy in global optimality, high effectiveness in computational dimensionality and complex network can be handling easily, however, less engineering practitioners are familiar with these methods mainly due to the difficulty to master the technique and to set up the problem models.

In this chapter, the previous studies and the development of the various methods of pinch analysis on the minimisation of energy and water were reviewed. In section 2.2 reviews the concept of process integration and pinch analysis. Section 2.3 covers the application of pinch analysis for energy reduction. The application of pinch analysis on the water will be reviewed in section 2.4. Lastly, section 2.5 reviews the application of pinch analysis simultaneously on water and energy.

2.2 Process Integration and Pinch Analysis

Process integration is a holistic approach to process design, retrofitting, and operation which emphasizes the unity of the process (El-Halwagi, 1997). Process integration is a special pathway for researchers to fundamentally understand the global insights of the process, methodically determine the process achievable performance targets, and by making systematically decisions, lead to the realization of these targets (El-Halwagi, 2006).

El-Halwagi (2006) concluded that Process integration involves following steps:

1. Task identification: Indentify the goal of the task and the achievable of the task.
2. Targeting: the identification of performance benchmarks ahead of detailed design.
3. Generation of Alternatives (Synthesis): Numbers of solutions are suggested to reach the target.
4. Selection of Alternative (Synthesis): Optimum solution is chosen among the suggested alternatives.
5. Analysis of Selected Alternative: Employ process analysis to evaluate the chosen alternative.

There have been numerous studies on the two main commodities utilities in the typical process field: energy and water. Energy integration is the understanding of the energy utilisation by systematic methodology and this understanding is employed in identifying the energy targets and optimizing heat recovery in energy utility systems. Mass integration, on the other hand, is the understanding of the global flow of water by systematic methodology and this understanding is employed in identifying mass performance targets and optimizing the generation and routing of species throughout the process (El-Halwagi, 2006).

Pinch analysis was firstly introduced by Linhoff and Vredeveld (1984). It is one of the most widely used and practical tools to apply the process integration in the energy and mass based process field. It allows researchers investigate the energy and mass flows within a process where the most economical ways of maximise heat recovery and minimise the utilities demand can be identified systematically (Natural Resources Canada [NRCAN], 2003).

Over the years, there have been numerous of pinch analysis studies successfully applied to the minimisation of energy consumption in various process field such as petrochemicals and pulp and paper industry. Pinch analysis allows the minimisation of utilities not only in energy but also in other sources such as water and hydrogen. Most recently, the application of pinch analysis has been extended to the optimisation of water and simultaneously energy and mass consumption where spectacular results have been achieved (NRCAN, 2003).

2.3 Application of Pinch on Energy

2.3.1 Review of Energy Pinch Targeting Methodology

2.3.1.1 Numerical Approach

Over twenty years ago, first numerical method called Problem Table Analysis (PTA) was introduced by the Linnhoff and Flower (1978). It was the first numerical method which was based on the pinch analysis. Table of hot and cold streams in the PTA perform the heat cascade analysis. The results of heat cascade analysis allow the determination of heat transfer between the hot and cold streams. Nowadays, PTA is typically used to determine the energy targets and to locate the pinch point prior to the drawing of the composite curves (CCs) proposed by Linnhoff *et al.* (1983).

Over the years of developing in numerical approaches, a new targeting method for the retrofit of heat exchanger networks was proposed by Van Reisen *et al.* (1997). The concept of zoning in grassroots design was applied in this technique with the combination of targeting and retrofit design method. The result from this technique takes the consideration of three aspects: saving, area investment and structural modification. Hence, the structural targeting retrofit method gives not only the utilities but including three aspects mentioned above. The definition of structural unities in the network is the most crucial step in this proposed method.

Kralj *et al.* (2002) proposed a new heat integration method which involves three steps:

1. Retrofit of the individual processes
2. Analysis of efficient transfer of waste heat between:
   - existing non-retrofitted processes
   - existing non-retrofitted and efficiently retrofitted processes
   - efficient retrofits and
3. Simultaneous integration between some non-retrofitted and some retrofitted existing processes using mixed integer non-linear programming (MINLP).

MINLP algorithm can be applied to the simultaneous integration between processes, non-retrofitted or/and retrofitted processes.

Years later, a new targeting method has been proposed by Kralj *et al.* (2005) which extended from heat integration method in Kralj *et al.* (2002) between processes using another three possible steps:

1. Internal integration of individual processes;
2. Analysis of possible heat transfer between internally nonintegrated and integrated processes;
3. Simultaneous external heat integration between the internally nonintegrated and the best internally integrated processes using the mixed integer nonlinear programming (MINLP).

Four existing complex processes which using pinch analysis and MINLP has been applied with this new targeting method. Maximise the annual profit of integration between processes and retrofits were the main objectives of this approach.

Salama (2005), on the other hand, has developed an improved algorithm based on PTA named as the simple problem table algorithm (SPTA). Which is similar to the PTA, SPTA also used to generate the grand composite curve (GCC) to determine heat energy targets (hot and cold utilities and pinch temperature), but SPTA eliminates the lumping stage exists in the PTA. This approach proposed was different from the conventional PTA, where the optimal positioned CCs was determined first before the determination of energy targets, pinch location and lastly GCC.

Year later, Salama (2006) proposed a simple and direct numerical technique, which based on geometric approach, to determine the optimal heat targets. The based geometric approach was the horizontal shifting of the cold composite curve (CC) where the hot composite curve remains stationary. The proposed numerical technique was conceptually deviates from the PTA and SPTA due to the technique based on the geometric approach not the heat cascade analysis using temperature subintervals.

2.3.1.2 Graphical Approach

The first intend of targeting the energy pinch point by graphical method was conducted by Linnhoff *et al.* (1983). The composite curves (CC) introduced was the plot of temperature versus enthalpy (T-H) which graphically represent the profiles of heat sources (hot composite curve) and heat demands (cold composite curve) in a certain energy based process. Figure 2.1 shows the example of a composite curves proposed by the authors.

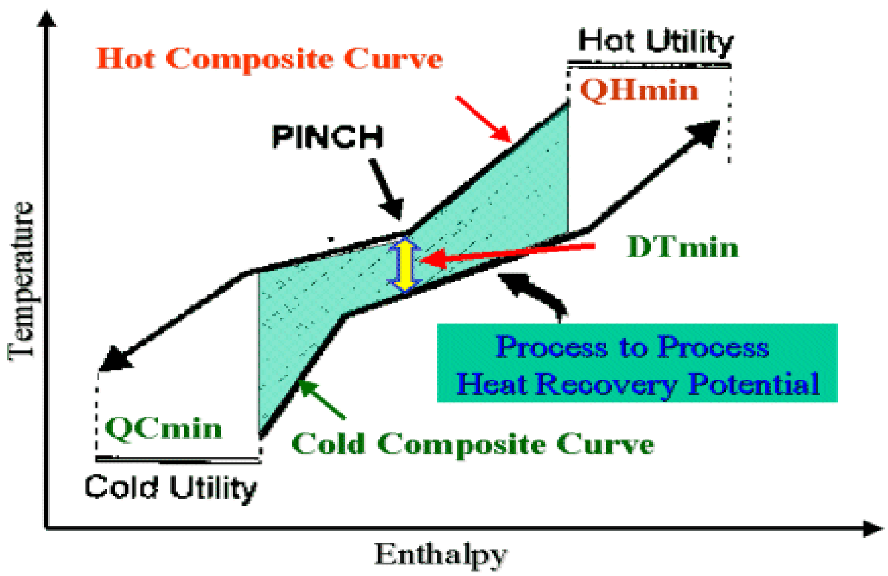

Figure 2.1: Example of Composite Curves

From the figure above, the overlap area (green shaded area) in between the hot and cold composite curves represent the potential of maximum amount of heat recovery possible in the process. The “overshoot” of the cold composite curve, is the amount of external heat required from the utilities which is Q_{Hmin} in the figure above. On the other hand, the “overshoot” of the hot composite curve is the amount of external cooling required from the utilities, which is Q_{Cmin}. The pinch temperature is the closest point of two curves. A minimum temperature difference, ΔT_{min} is the minimum temperature for heat exchange, to target the external heating and cooling utilities.

A new graphical targeting methodology has been proposed by Bandyopadhyay *et al.* (1998) to solve the problem of the pinch in distillation column. The column grand composite curve (CGCC) which is the T-H diagram of a distillation column at practical near-minimum thermodynamic condition (PNMTC) is a useful technique for the targeting of energy pinch. In this paper, the proposed feed stage correction (FSC) rigorously considers the mass and enthalpy balance at feed stage to make sure that the CGCC is identical for the top-down approach or the bottom-up approach in the distillation column. The paper has further discussed the effect of FSC on the targets for energy conservation by reflux modification, feed conditioning, and introduction of side reboilers/condensers.

Anantharaman *et al.* (2006) on the other hand, utilise process simulation tools to develop an energy integration strategy to define the interaction between various subsystems in a certain plant. In addition, a graphical technique also proposed to explore the possible schemes and help the engineer to easily interpret the results from the simulation to improve the energy efficiency. This graphical method is nearly similar to the pinch analysis composite curve (CC), which is named as Energy Level Composite Curve (ELCC). ELCC offers the reduction of pinch analysis case when dealing with heat transfer. Since pressure, temperature, and composition changes were taken in consideration in this method, therefore, wide range of energy utilised chemical plants can be applied.

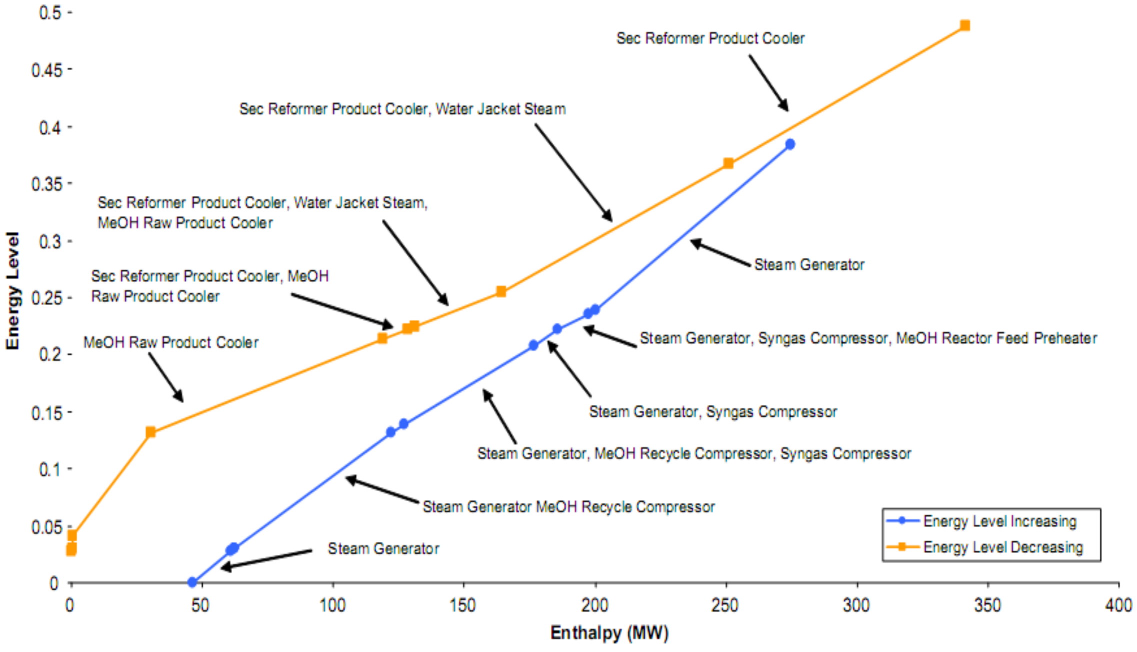

Figure 2.2: Example of Energy Level Composite Curve (ELCC)

As discussed in numerical approach in section 2.3.1.1, Salama (2009), has also gave his contribution in the research of graphical approach on energy targeting method. The new technique developed called enthalpy flowrate technique used stream cumulative enthalpy flowrate as independent variable to construct the HEN composite curves. Complement grand composite curve (CGCC) was a new developed curve from the proposed enthalpy flowrate technique. CGCC can be considered as a tool for (a) presentation of the temperature differential distribution between the composite curves (CCs), (b) estimation of heat exchanger area, and (c) facilitation of heat exchanger area estimation in multiple-utility targeting. HEN designer that targeting the energy pinch can have full range of information on composite curve and presentation of GCC and CGCC plotted in a graph, by using the technique of cumulative enthalpy flowrate proposed.

Nordman and Berntsson (2009a; 2009b) presented a new theory and concept of a graphical method for HEN retrofit. New insights on the complexity and possible solutions of different retrofit alternatives were introduced. In this paper, they concluded that the closer the pinch to the existing heaters or coolers, the higher the potential for the cost-effective retrofit to perform.

2.3.1.3 Research Gap on Energy Pinch

Pinch analysis on energy integration has been introduced at 1970's. Since the introduced of pinch analysis, various authors were mainly focus in the research in this field and various method such as mathematical approach and graphical approach have been well developed.

Mathematical approaches provide great accuracy and global optimal solution to the system, however, the mathematical modelling was hardly to accomplish for the researchers as tedious iteration need to be done. However, graphical approaches provide great visualisation and insight to the system. The researchers prefer graphical approaches technique as it is typically easier to apply and understand it.

2.4 Application of Pinch Analysis on Water

Apart from energy targeting method, minimising the mass consumption using pinch analysis is another focus of study among the researchers. Mass such as water, chemicals and gas is another commodity utility used in most chemical plants. Water pinch analysis approach comprises two distinct stages, targeting followed by design. In this section, the review on the development of targeting mass in pinch analysis is conducted.

2.4.1 Review of Water Pinch Targeting Methodology

2.4.1.1 Numerical Approach

Sorin and Bédard (1999) established the Evolutionary Table to numerically determine the fresh water and wastewater targets. This paper has further developed the two approaches proposed earlier by Wang and Smith (1994) and Dhole *et al.* (1996). However, the targeting approach introduced by Dhole *et al.* (1996) could result in a number of “local” pinch points, but Wang and Smith (1994) define just one pinch point. However, the method fails to locate pinch point correctly when multiple pinch points exist in water using processes, as mentioned by Hallale (2002).

Nonetheless, Manan *et al.* (2004) established a revolutionary water and wastewater targets technique named as Water Cascade Analysis (WCA). As similar to the characteristic of problem table analysis (PTA) in grand composite curves (GCC), WCA was developed towards to the water surplus diagram in water pinch analysis. WCA offers a quick and accurate yield of water targets and pinch point for a water network without the tedious interactive steps. Therefore, the design and retrofit of a water recovery network can be performed easily with this method. Besides, WCA was applicable to the wide range of water using operations compare to the previous proposed method.

Aly *et al.* (2005) introduced the load problem table (LPT) which was another numerical approach to establish the wastewater minimization problem and synthesis of water reuse networks. This technique was adapted from load interval diagram (LID) by El-Halwagi and Almutlaq (2004) for material reuse and recycling. The LPT was almost similar with the Problem Table Algorithm (PTA) used in heat integration. Mass Transfer Based (MTB) and Non Mass Transfer Based (NMTB) operations were applicable to this technique and good insight in network design was provided.

Nevertheless, Foo *et al.* (2006) established an algebraic technique which consists of two approach tools to rigorously targets the basic frameworks which were minimum usage of fresh resources and waste discharge, maximise the direct resources reuse in a mass utilised network. First tool was the graphical approach called property surplus diagram to perform the basic frameworks as mentioned above. Besides, pinch location also can be determined in this graphical tool. Next, the Cascade Analysis (PCA) technique was established. PCA offers a simple technique to obtain fresh and waste water targets and material allocation targets without the tedious iterative steps. Additionally, to achieve various targets, a network design technique also presented in this paper to synthesis a maximum resource recovery (MRR) network.

2.4.1.2 Graphical Approach for Water Reduction

A first graphical method of targeting for maximisation water recovery network in a wide range of processes was first introduced by Wang and Smith (1994). The method was based on concept of limiting water profile where maximum inlet and outlet concentration to be considered during the approach. Using the graph of limiting water profile, pinch location was obtained to target the minimum fresh and wastewater flowrates prior to the network design. The proposed method can be addressed to both single and multiple contaminants problem. However, the method was only applicable to mass-transfer based operations.

Dhole *et al.* (1996) discovered limitation from Wang and Smith (1994) work where modelling the mass transfer operations in some unit operations were hard to accomplished. Therefore, water source and demand composite curves proposed to overcome this limitation. They also suggested process changes such as mixing and bypassing to further reduce the fresh water consumption. Meanwhile, Polley and Polley (2000) later demonstrated that unless the correct stream mixing system was identified, the apparent targets generated by Dhole's technique (Dhole *et al.*, 1996) could be substantially higher than the true minimum fresh water and wastewater targets.

Hallale (2002) suggested a graphical procedure for targeting the fresh water and wastewater minimisation. The method was based on water composite curves and water surplus diagram. This approach had similar representation to the water source and demand composite curves introduced by Dhole *et al.* (1996). Graphical tools presented provide valuable insights that cannot be obtained from a purely mathematical approach. The advantage of this method was applicable to wide range of water using operations such as MTB and NMTB. Nevertheless, this new work has the ability to handle all mixing possibilities and yet still result the unique pinch and water reuse target.

El-Halwagi *et al.* (2003) introduced the source and demand composite curves (SDCC). The SDCC was a plot of cumulative mass load versus cumulative flow rate. This method can be used to establish the minimum fresh water and wastewater flow rates targets for both mass transfer-based and non-mass transfer-based operations. In addition, SDCC was applied for matching and allocation of mass load and flow rates of each source and demand. Pinch point obtained in SDCC divides the curve into above and below pinch regions for the matching process to be performed.

Nevertheless, concept of selection of external mass separating agents (MSAs) using the grand composite curve (GCC) in mass exchange network synthesis (MENS) was established by Fraser *et al.* (2005). This developed concept was superior to the method proposed previously. Alternative external MSAs or minimum flowrate for each MSA can be chosen systematically through this concept. According to Fraser *et al.* (2005), lowest cost per unit mass of MSA does not represent the cheapest, whereas permissible concentration change also was the issue that has to be considered. The paper also demonstrates the important role of composition levels of the MSAs to the target compositions of the rich streams and to the capital cost implications of the resulting mass transfer driving forces.

2.4.1.3 Research Gap on Water Pinch

The research on the targeting of mass such as water has been well developed in recent pass years. However, the research on targeting for other mass substances such as solvents and chemical substances remains a wide gap in the research field. In the SMEC method proposed by Wan Alwi *et al.* (2010), targeting and design of mass on the chemical substances has well developed as ammonia was used in the study.

2.5 Application of Pinch Analysis Simultaneously on Water and Energy

2.5.1 Water and Energy Pinch Targeting and Network Design Methodology

A new approach of simultaneously optimisation of energy and water consumption was introduced by Bagajewicz *et al.* (2002). This approach was the improvement in the design network of water utilisation process plant where minimum freshwater and minimum utility consumption were featured. A single pollutant case was studied in this paper, where a numerical technique of linear programming formulation and heat transshipment model was applied. The first step of the approach was the solving of the LP model to obtain the minimum water usage and target values of minimum utility heating amount. Next, a MILP was proposed to consider the non-isothermal mixing where the necessary information for the construction of water reuse structure and corresponding heat exchanger network.

Savulescu *et al.* (2005a; 2005b) established a new systematic design methodology for the problem of simultaneous energy and water minimisation. Taking the consideration of water network mixing possibilities and water contamination, the design of a water system for maximum energy recovery can be achieved by this method. First stage in this method was the determination of the various options in water system with minimum water and energy consumption. In second stage, heat exchanger network design was performed. In this method, the complexity of the stream distribution can be reduced which implied to a better heat exchanger network design. However, since the approach cannot observe immediately temperature effect, hence, there were some drawbacks in this technique. In addition, since the energy minimisation graphical method only focused in this method, therefore the design of water minimisation network need to be constructed manually.

Zhelev (2005) proposed a paper with the objective of management energy and water, which are two important resources in process industry. A method of design procedure with the consideration of simultaneous heat and mass transfer which based on the concepts of pinch analysis was proposed. Two procedures with targeting of maximum flue gas energy recovery and minimum temperature of cooling water proposed provide guidance for the system design and operation. Through this design method, water conservation can be achieved by the minimisation the losses of water evaporation.

On the other hand, Leewongtanawit and Kim (2008) developed a simultaneous design technique which provides a general design framework for the water and energy combined system. This approach is based on the mathematical optimisation where MINLP model was formulated. Besides, the proposed method was applicable to the multi contamination system. In this paper, the authors systematically investigated the design interactions between two subsystems and its economic trade-offs, in addition, stream merging and generation of separate systems have also taken into the focus in this technique. Hence, a cost-effective and environmental-benign design of heat-integrated water systems has been developed in this paper.

Bogataj and Bagajewicz (2008) presented a new superstructure for HEN synthesis which was an approach for the simultaneous synthesis and optimisation of heat integrated water network. Proposed method is based on the MINLP model. Due to the various optimal solutions from the non-linear and non-convex equations and constraints in the MINLP model, hence an efficient initialisation to search for the global or good local optimal solution was needed. Therefore, using this developed technique, the problems related to the initialisation were solved efficiently. Besides, the sizes of the problems were considerably reduced by this technique.

Meanwhile, Liao *et al.* (2008) considered that to design the energy efficient water utilisation systems, the split of water operations was a major role in the total utility cost. Hence, they proposed a detailed procedure for the network design which was based on the MINLP model. The concept was to treat the direct and indirect heat transfer separately, hence the target for fresh water and energy consumption could be obtained. This method provided a low complexity approach to the network design, although local but not global optimum solutions could be obtained. However, the approach was applicable to single contaminant and MTB problems only.

Lastly, a revolutionary technique called simultaneous water and energy (SWE) was proposed by Manan *et al.* (2009). This was a method which included numerical and graphical approach. This technique included three major steps; setting the minimum water and wastewater targets, design of minimum water utilisation network, and lastly, heat recovery network design. An important plot called heat surplus diagram (temperature versus stream flowrate) provided a good insight to the stream matching procedure and the relationship between the sources and demands in certain energy and water network. This was a very important approach to the development of the simultaneous energy and water targeting and network design field where it is applicable to MTB and NMTB water-using operations.

2.5.2 Research Gap of Water and Energy Pinch Targeting and Network Design Methodology

There were number of issues still remain unsolved in the previous studies to the simultaneous minimisation of water and energy.

1. Design of system network was still remain as a research gap for those researchers since the targeting approach methods were only well developed in previous studies.

2. Mathematical approach provides a great accuracy and global optimal solution to the system approach. However, the mathematical modelling was hardly to accomplish for the researchers as tedious iteration need to be done.

3. Targeting and design network in water and gas has successfully been done by Wan Alwi and Manan (2008) and Wan Alwi *et al.* (2009). However, targeting and design network in energy and water approach has no work to be done yet.

CHAPTER 3

METHODOLOGY

3.1 Introduction

The methodology applied in this project to obtain the target of the water and energy pinch is discussed in step-wise procedure in this chapter. The newly developed graphical method named as Superimposed Mass and Energy Curves (SMEC) for the simultaneously approach of energy and water targets is discussed in detail. SMEC method was proposed by Wan Alwi *et al.* (2010) where the sources and demands curves (El-Halwagi *et al.*, 2003) and heat surplus diagram (Manan *et al.*, 2009) were superimposed into a plot of cumulative flowrate versus cumulative mass loading/ temperature.

SMEC allows to target the minimum freshwater required in a water using system and crucial for network design by taking into the account of energy limitations. It is an efficient visualisation graphical tool which provides good insight to the simultaneous minimisation of energy and water. In addition, the SMEC method is applicable to the mass transfer based (MTB), non-mass transfer based (NMTB) problems as well as all types of mass besides from water such as solvents and chemical substances. In this chapter, the assumptions made in construction of SMEC were discussed in section 4.2. Section 4.3 discussed the detailed procedures to construct SMEC.

3.2 Assumptions Made in Construction of Superimposed Mass and Energy Curve (SMEC)

It is necessary to have some understanding of the interactions between water and energy systems before addressing the problem. There are eight assumptions that need to be made before the construction of SMEC. These assumptions are adapted from the Savulescu *et al.* (2005a) and applied into the approach using SMEC by Wan Alwi *et al.* (2010).

The assumptions made are listed as below:

1. In terms of operating data, each mass-using operation is specified by the maximum inlet and outlet concentrations of contaminant, contaminant mass to be transferred, and operating temperature.

2. Each mass-using operation is assumed to be isothermal and have a fixed value for supply temperature. In other words, the mass exchange units are assumed to be operating without heat losses or gains.

3. Single contaminants of single solvent operations are assumed.

4. The mass flowrate does not change through an operation, so there are no flowrate losses or gains.

5. A single source of fresh mass is assumed with a given temperature of $20^{o}C$.

6. No contaminant concentration constraints have been introduced for the discharge of effluent.

7. The discharge temperature which is $30^{o}C$ has been specified.

8. The system is assumed to be operating in steady state and continuously.

3.3 Targeting and Curves Design Procedure

In this section, the procedures and rules to construct the SMEC were discussed in detail. The first major procedure in this method is the data extraction step. Following by second major procedure, targeting and design of mass recovery network based on heat constraints which consists the construction of few curves for SMEC approach can be done.

3.3.1 Data Extraction

Extracting the stream data from the process flowsheet is absolutely a crucial part of pinch analysis. Tale 3.1 below shows the example of water using operation data from Savulescu *et al.*, (2005a).

Table 3.1: The Water Using Operation Data (Savulescu *et al.*, 2005a)

Operation	Contaminant		Temperature		Limiting Water Flowrate, *F* (kg/s)
	Inlet (ppm)	Outlet (ppm)	Inlet (°C)	Outlet (°C)	
1	0	100	40	40	20
2	50	100	100	100	100
3	50	800	75	75	40
4	40	800	50	50	10

It reveals the opportunity to reuse mass and heat and thus minimise the quantity of waste generated. Source and demand streams are the important data that need to be extracted for mass. Demand streams are actually the input flowrate to system whereas; output flowrate from the system can be classified as source streams. The crucial data for mass integration are as following:

1. Mass flowrate, *F* (kg/s) of the source and demand streams
2. Concentration, *C* (ppm) of each streams

3. Mass loading value, Δm by calculation using following formula:

$$\Delta m = F \times C \tag{3.1}$$

where
Δm = mass loading, mg/s
F = mass flowrate, kg/s
C = concentration, ppm

Similar to the mass data, heat data are also classified into the source and demand streams respectively. In this case, heat stream temperature will be classified as source stream since heat transfer from hot to cold stream, and therefore cold stream as demand stream. The data required for heat integration are listed as follow:

1. Flowrates of the hot and cold streams, F(kg/s)
2. Heat capacity for each hot and cold streams, Cp (kJ/kg·^{o}C)
3. Supply (T_{in}) and target (T_{out}) temperature for each stream, (^{o}C)

Table 3.2: Example of Extracted Source and Demand Data

	Flowrate, F (kg/s)	Contaminant (ppm)	Temperature (^{o}C)	Mass Loading (mg/s)	Cumulative Flowrate (kg/s)	Cumulative Mass Loading (mg/s)
Demand						
D1	20	0	40	0	20	0
D2	100	50	100	5000	120	5000
D3	40	50	75	2000	160	7000
D4	10	40	50	400	170	7400
Source						
S1	20	100	40	2000	20	2000
S2	100	100	100	10000	120	12000
S3	40	800	75	32000	160	44000
S4	10	800	50	8000	170	52000

3.3.2 Targeting of Heat and Mass Recovery Network Based on Heat Constraints

3.3.2.1 Construction of Source and Demand Composite (SDCC) and Energy Match Diagram (EMD)

The second procedure was to draw the source and demand composite curve (SDCC) as developed by El-Halwagi *et al.* (2003) according to the Table 3.2. SDCC is the plot of cumulative mass loading versus cumulative flowrates. Figure 3.1 below shows the example of SDCC.

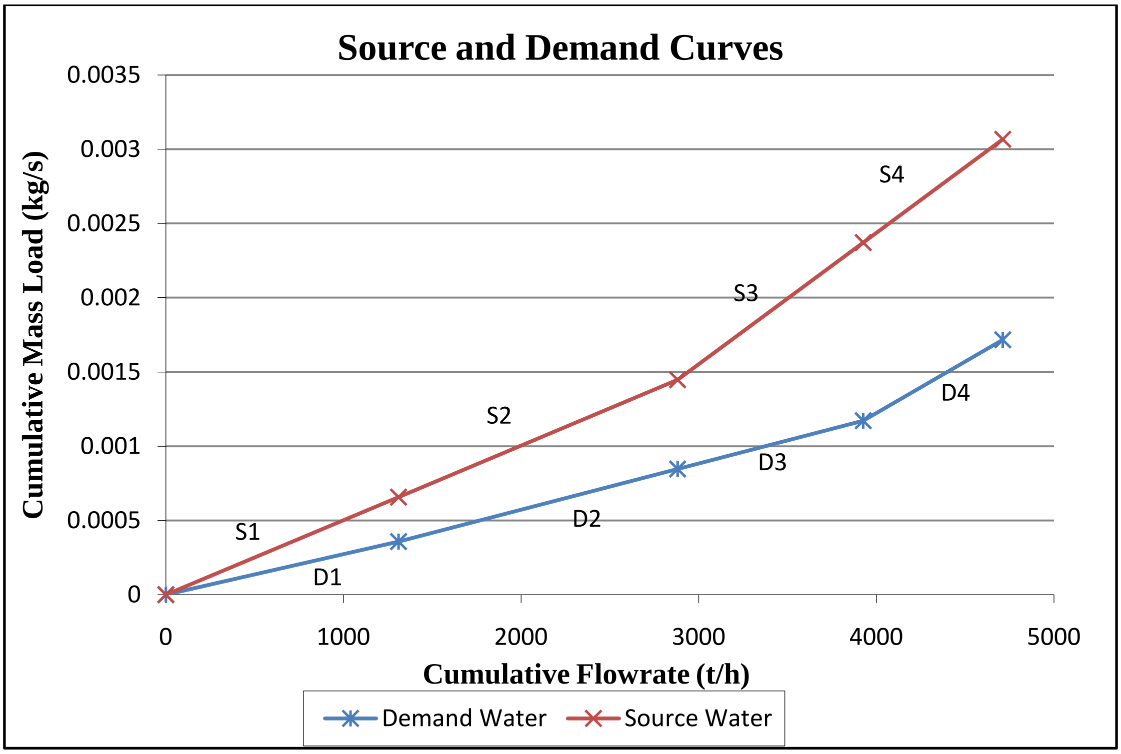

Figure 3.1: Example of Source and Demand Curves (SDCC)

From the Figure 3.1 above, by applying the concept of pinch analysis, the source water curve was then moved horizontally towards the demand water curve where its slopes remain the same until the point at which the source water curve was fully under the demand water curve. The point where both curves touch each other was obtained and called as water pinch point in the system. Figure 3.2 shows the results obtained in SDCC curve with the pinch point located at 100 ppm.

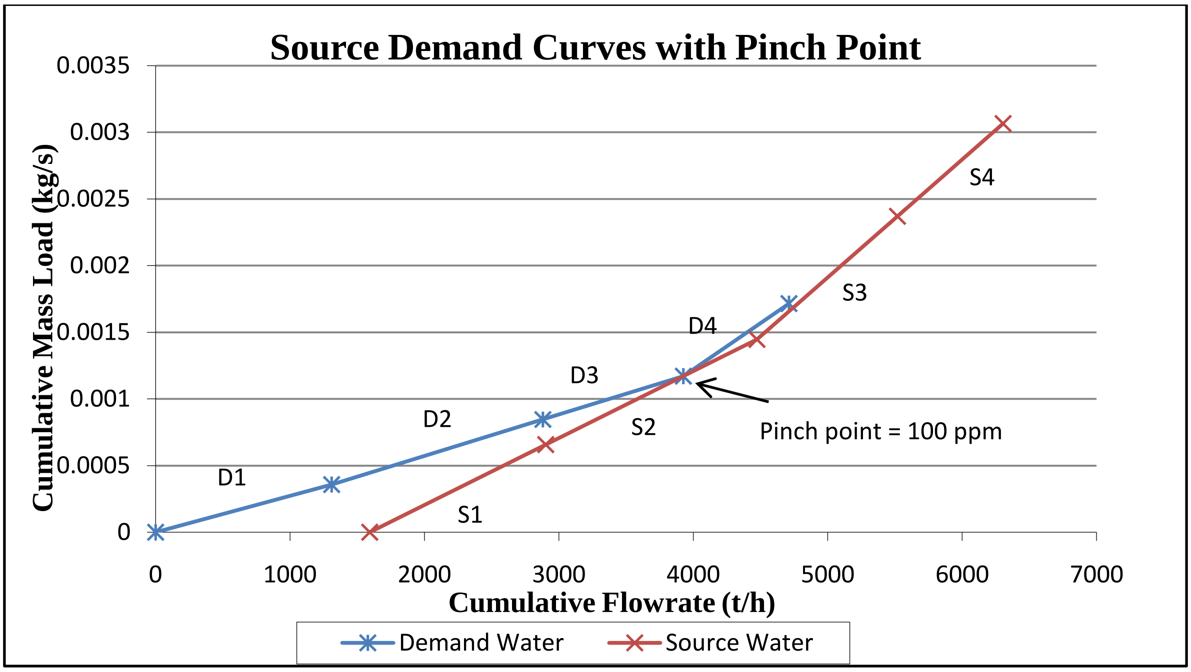

Figure 3.2: Example of Source and Demand Curves (SDCC) with Pinch Point

Next, the energy match diagram (EMD) or heat surplus diagram was drawn with temperature versus cumulative flowrate on the same graph as above. Constructing the EMD into the SDCC allows the researchers to observe the energy demands and stream matching scenarios during the design of water and energy recovery network (Manan *et al.*, 2009). The example of SDCC with EMD was shows in the Figure 3.3 below.

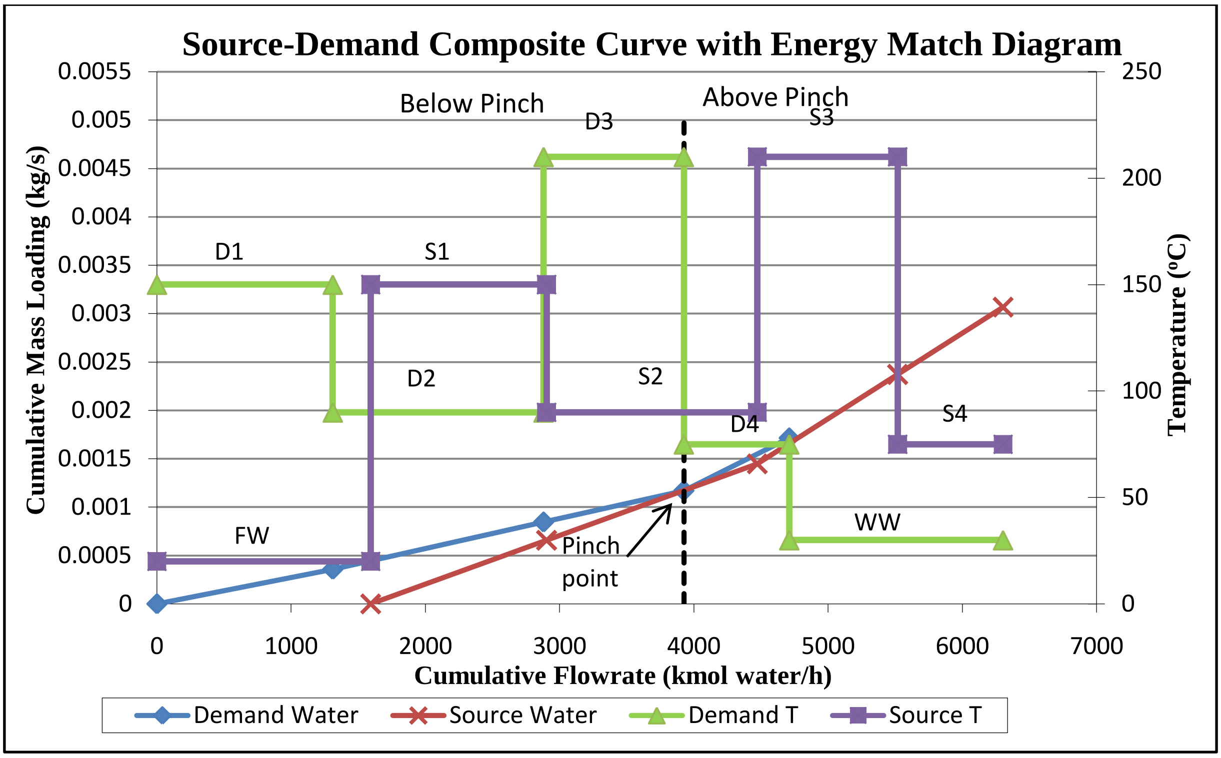

Figure 3.3: Example of Source Demand Curves with Energy Match Diagram

3.3.2.2 Constructing the Source and Demand Allocation Curve (SDAC)

Next, source and demand allocation curves (SDAC) were constructed based on EMD by the source-demand streams matching process. SDAC was the graphical way to present the results of stream matching processes or process integration in a certain system. There were five rules adapted from Alwi and Manan (2008) and Savulescu *et al.* (2005b) that need to be obeying in the stream matching processes in order to construction the SDAC. The five rules were:

Rule 1: Zero contaminant demands must be satisfied first if there are no zero mass load sources. The demand with concentration equal to 0 ppm has a value of zero mass loading, consequently sources with zero mass load need to fulfil this demand. If there are no other sources with zero mass load, fresh mass or freshwater (FW) which is mass load is equal to zero is needed to fulfil the demand.

Rule 2: All demand mass load and flowrate for below pinch region must be satisfied (Wan Alwi and Manan, 2008). Consequently, there is no waste mass available for below pinch region.

Rule 3: Connect the re-use mass source with the nearest temperature demand (Savulescu *et al.*, 2005b) but taking care of the mass load and flowrate constraint. For example, if there are two mass sources at 30 ^oC and 70 ^oC respectively and one demand at 35 ^oC, the mass source at 30^oC is chosen since it has closer temperature to the demand than the one at 70 ^oC.

Rule 4: For below pinch region, rule 1 to 3 can be used. After rule 1 to 3 have been used, guided by the rules introduced by Wan Alwi and Manan (2008), flowrate and mass load deficit rules can be used to satisfy other matches that cannot be matched in terms of nearest temperature due to mass load constraints.

Rule 5: For above pinch region, use rules 3 and 4 only if the sources concentration is below the demand concentration to ensure demand quantity are satisfied and demand quality is still preserved. Unmatched sources will be discharged as wastewater (WW).

Table 3.3: Example of Stream Matching/Process Integration Results

	Flowrate, F (kg/s)	Mass Loading (mg/s)	Temperature (^oC)		$F \cdot Cp$ kW/^oC	Cum. Flowrate (kg/s)	Cum. Mass Loading (mg/s)
			Inlet, Tin	Outlet, Tout			
FW-D1	20	0	20	40	84	7.56	0
FW-D2	50	0	20	100	210	9.50	0
FW-D3	20	0	20	75	84	11.44	0
S1-D3	20	2000	40	75	84	15.76	2000
S2-D4	10	4000	100	50	42	20.08	6000
S2-WW	40	10000	100	30	168	21.38	16000
S3-WW	40	32000	75	30	168	25.26	48000
S4-WW	10	8000	50	30	42	33.91	56000

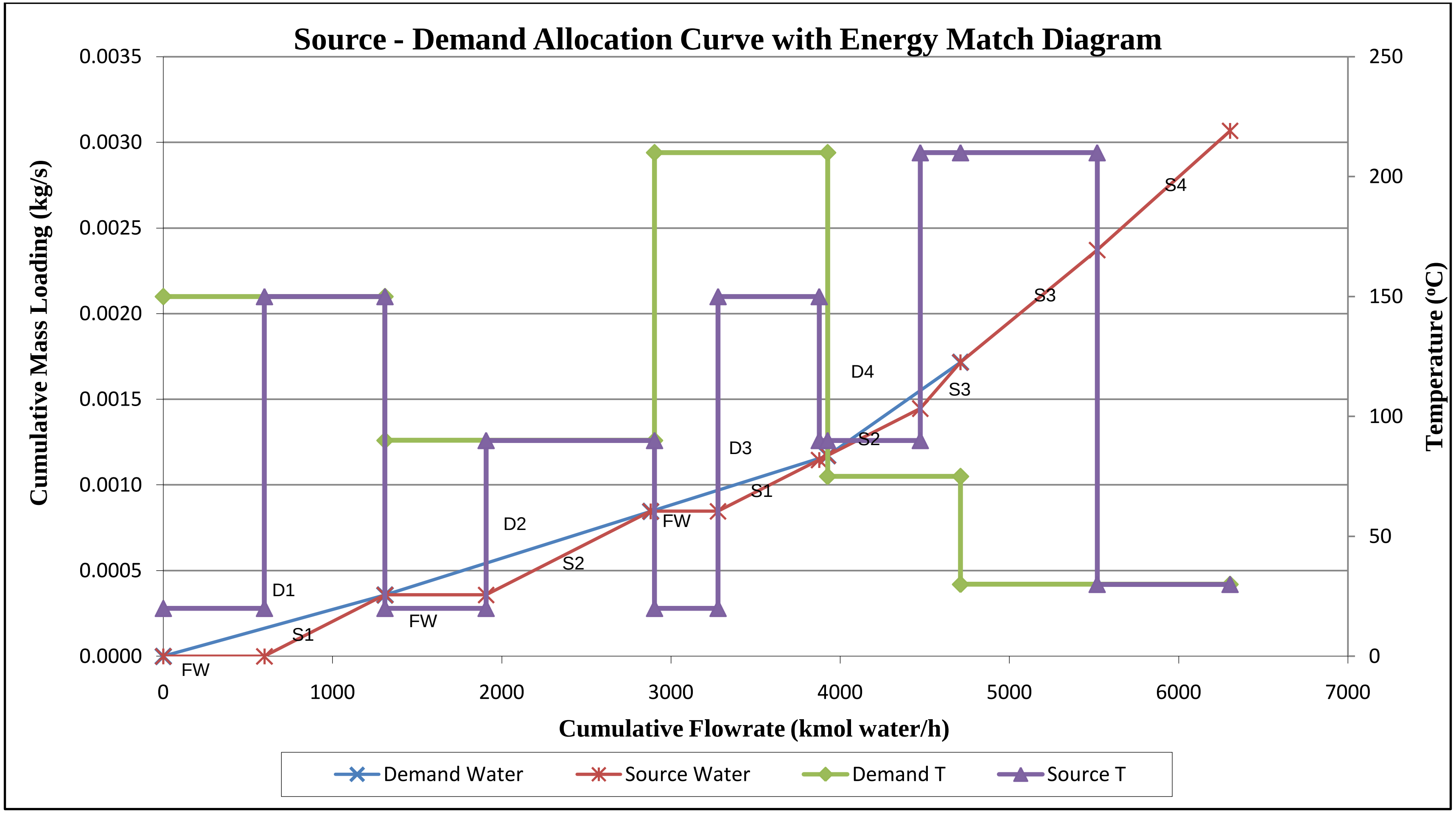

Figure 3.4: Example of Source Demand Allocation Curves (SDAC) with Energy Match Diagram (EMD)

3.3.3 Heat Data Extraction from EMD for Energy Targeting using Heat Composite Curve (HCC)

Lastly, heat data are extracted from the EMD. Notice that in EMD, the sections where demand temperature line located above the source temperature line indicate that heating is required for the streams. Vice versa, the sections where demand temperature line located below the source temperature line indicate cooling required for the streams.

Heat composite curve is then constructed to target the potential recoverable energy and minimum hot and cold utilities required in the system.

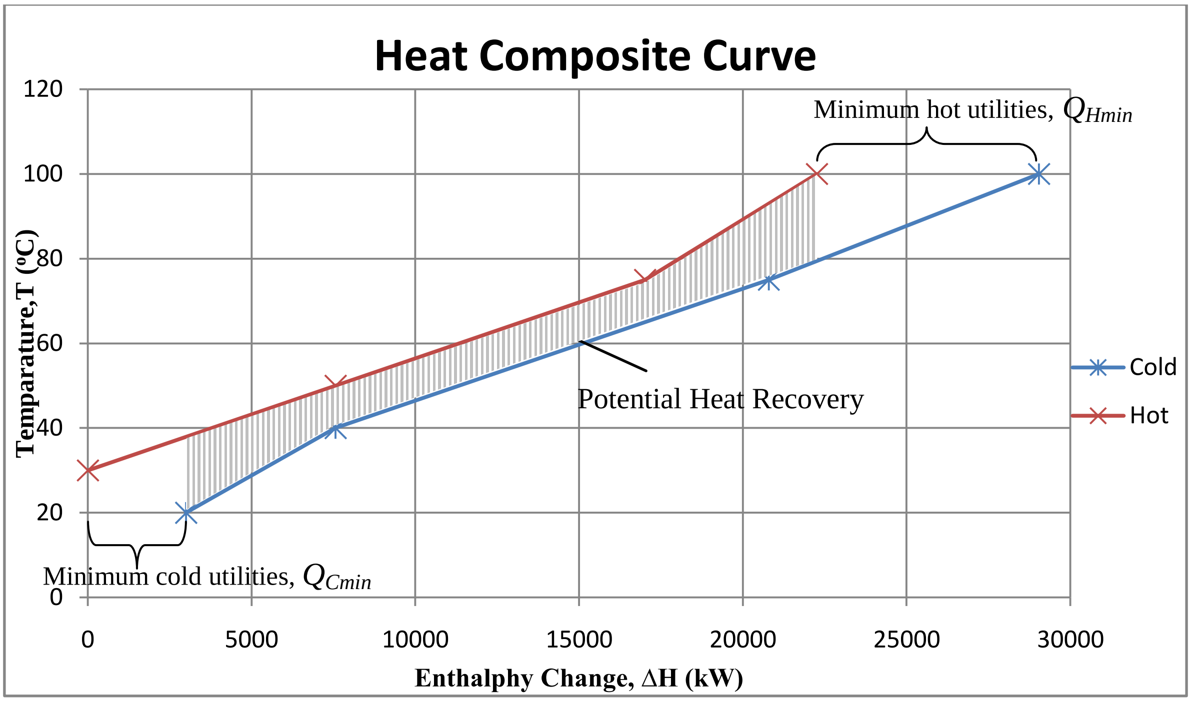

Figure 3.5: Example of Heat Composite Curve

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Data Extraction

In this project, a case from Ataei and Yoo (2009) was chosen to perform the Superimposed Mass and Energy Curve (SMEC) method. The water using operation system data obtained as shown in Table 4.1 below.

Table 4.1: Case Study - Water Using Operation Data (Ataei & Yoo, 2009)

Operation	Contaminant		Temperature		Limiting Water Flowrate, *F* (kg/s)
	Inlet (ppm)	Outlet (ppm)	Inlet (^{o}C)	Outlet (^{o}C)	
1	0	100	90	80	7.56
2	50	125	85	70	3.88
3	50	150	50	40	8.64

Applying the data extraction steps as introduced in Chapter 3 subsection 3.3.1, the required data for further study of SMEC method were calculated and tabulated as in Table 4.2 below. In the extracted table, demand is refer to the inlet whereas source denotes as outlet. Take note that the freshwater (FW) is assumed to be at 20^{o}C and discharge wastewater (WW) is at 30^{o}C.

Table 4.2: Extracted Source and Demand Data from the Case Study

	Flowrate, *F* (kg/s)	Contaminant (ppm)	Temperature (^{o}C)	Mass Loading (mg/s)	Cum. Flowrate (kg/s)	Cum. Mass Loading (mg/s)	Enthalpy Change, ΔH (kW)
Demand							
D1	7.56	0	90	0.00	7.56	0.00	2222.60
D2	3.88	50	85	194.04	11.44	194.04	1059.44
D3	8.64	50	50	432.17	20.08	626.21	1089.08
Source							
S1	7.56	100	80	755.99	7.56	755.99	-1587.57
S2	3.88	125	70	485.09	11.44	1241.08	-651.96
S3	8.64	150	40	1296.52	20.08	2537.60	-363.03

4.2 Targeting of Heat and Mass Recovery Network Based on Heat Constraints

4.2.1 Source and Demand Composite Curves (SDCC)

Figure 4.1 below shows the source and demand composite curve (SDCC) constructed based on the extracted data from the Table 4.2 above.

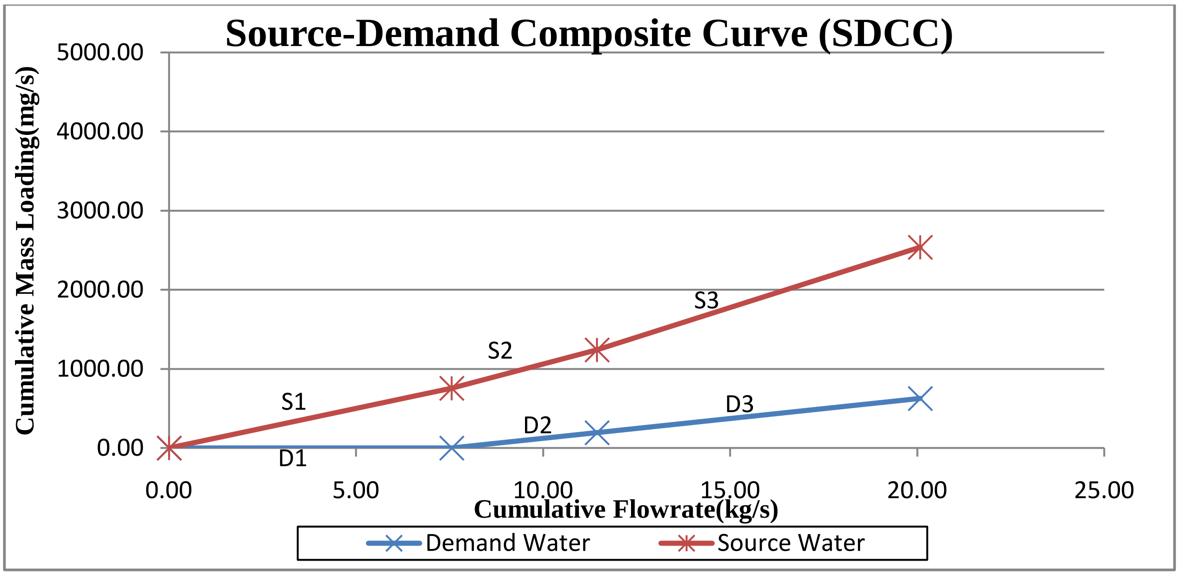

Figure 4.1: Source and Demand Composite Curve

From the Figure 4.1 above, the source curve was moved horizontally towards to the demand curve until a pinch point where it started to locate under the demand water curve. Figure 4.2 below shows the water pinch point was located at 100 ppm.

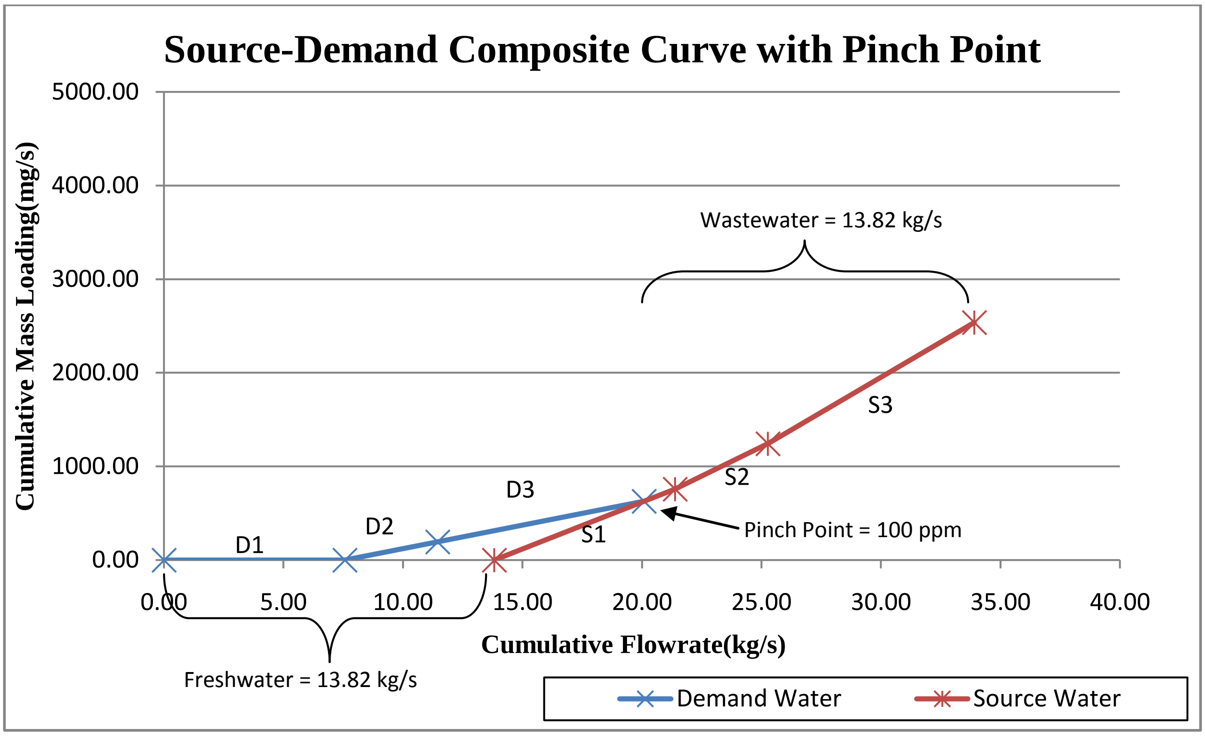

Figure 4.2: Source and Demand Composite Curve with Pinch Point

Meanwhile, the freshwater flowrate and wastewater flowrate can be determined from the Figure 4.2 as well. From the SDCC, 13.82 kg/s of freshwater and wastewater were obtained. These values were useful for the streams allocation of FW usage and WW discharge in the streams matching processes later. By this method, the flowrate of freshwater and wastewater have been reduced from 20.08 kg/s to 13.82 kg/s, or 31.18 % respectively compare to the original requirement in case study.

4.2.2 Energy Match Diagram (EMD) on Source and Demand Composite Curve (SDCC)

In this section, the energy match diagram (EMD) which was the plot of temperature versus cumulative flowrate was constructed into the SDCC secondary vertical axis as shown in Figure 4.3 below.

The area of rectangle formed where enclosed by the lines of source temperature and demand temperature represents the amount of heat surplus or hear deficit in the system by multiplying the area with water heat capacity, *Cp*. (Manan *et al.*, 2009)

From Figure 4.3 below, the area where enclosed by the demand temperature line located above of source temperature line, heating was required in the system. Vice versa, the area enclosed by source temperature line located at the demand temperature line, cooling was required in the system. From the figure, the heating amount required after this stage was 3582 kW and the cooling amount required was 1490 kW.

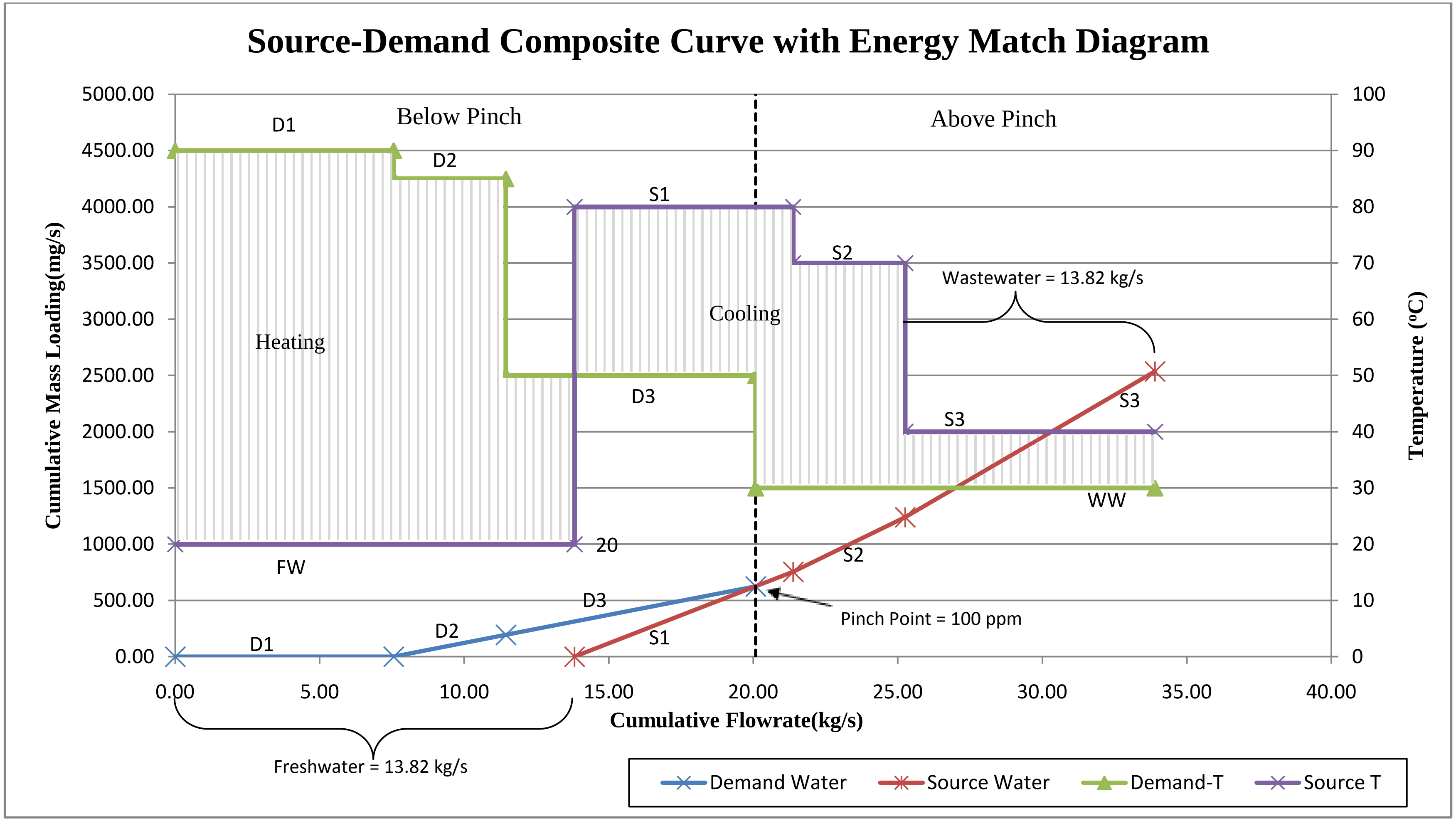

Figure 4.3: Source and Demand Composite Curve with Energy Match Diagram

4.2.3 Source and Demand Allocation Curve (SDAC)

As discussed in Chapter 3 section 3.3.2.2, there were five basic rules that need to be obeyed in order to construct the Source and Demand Allocation Curve (SDAC). These five rules provided a guideline to perform source and demand streams matching process or process integration for the minimisation of mass and energy in the system.

Firstly, by considered the first rule stated above, where zero contaminant demands must be satisfied in priority, therefore Demand 1 (D1) with the demands of zero contaminant was satisfied with freshwater (FW) with the flowrate of 7.56 kg/s. Hence, D1 with the zero mass loading requirement was satisfied.

Next, obeyed the second rule, Demand 2 (D2) and Demand 3 (D3) which were located at the below pinch region were chosen to be satisfied. D2 and D3 can only be satisfied with the Source 1 (S1) since it was the only source that located at the same below pinch region. By observed the EMD for S1 (80^{o}C), D1 (50^{o}C) and D2 (85^{o}C), according to third rule, S1 was chosen to feed into the D2 with flowrate of 1.94kg/s to satisfy the mass loading (194.04 mg/s) of the D2. Take note that this was a flowrate deficit case where the flowrate of D2 was not satisfied yet, therefore, the remaining requirement flowrate of D2 was fed with another 1.94 kg/s of FW.

On the other hand, the remaining demand streams (D3) was chosen to be satisfied. S1 was chosen to be fed into D3 since it was the only source available located at the below pinch region. Hence, in order to satisfy the mass loading of D3 (432.17 mg/s), 4.32 kg/s of S1 was fed into D3. Note again, this was another flowrate deficit case, therefore the remaining flowrate requirement was fed with FW with the flowrate of 4.32 kg/s.

Lastly, by obeyed the fifth rule, the unmatched and remaining sources streams were discharged as wastewater. Therefore, 1.38 kg/s of S1, 3.88 kg/s of S2 and 8.64 kg/s of S3 were discharged as wastewater. The results of streams matching were shown in the Table 4.3 below:

Table 4.3: Results of Source - Demand Streams Matching Process

	Flowrate, F (kg/s)	Mass Loading (mg/s)	Temperature (^oC)		$F \cdot Cp$ kW/^oC	Cum. Flowrate (kg/s)	Cum. Mass Loading (mg/s)
			Inlet, Tin	Outlet, Tout			
FW-D1	7.56	0	20	90	31.75	7.56	0
FW-D2	1.94	0	20	85	8.15	9.50	0
S1-D2	1.94	194.04	80	85	8.15	11.44	194.04
FW-D3	4.32	0	20	50	18.15	15.76	194.04
S1-D3	4.32	432.17	80	50	18.15	20.08	626.21
S1-WW	1.30	129.82	80	30	5.45	21.38	756.03
S2-WW	3.88	485.09	70	30	16.30	25.26	1241.12
S3-WW	8.64	1296.52	40	30	36.30	33.91	2537.64

The Source and Demand Allocation Curve, Figure 4.4 below graphically shows the results of streams matching and the EMD was constructed on order to provide a great insight to the energy demand in the between the streams (Manan *et al.*, 2009).

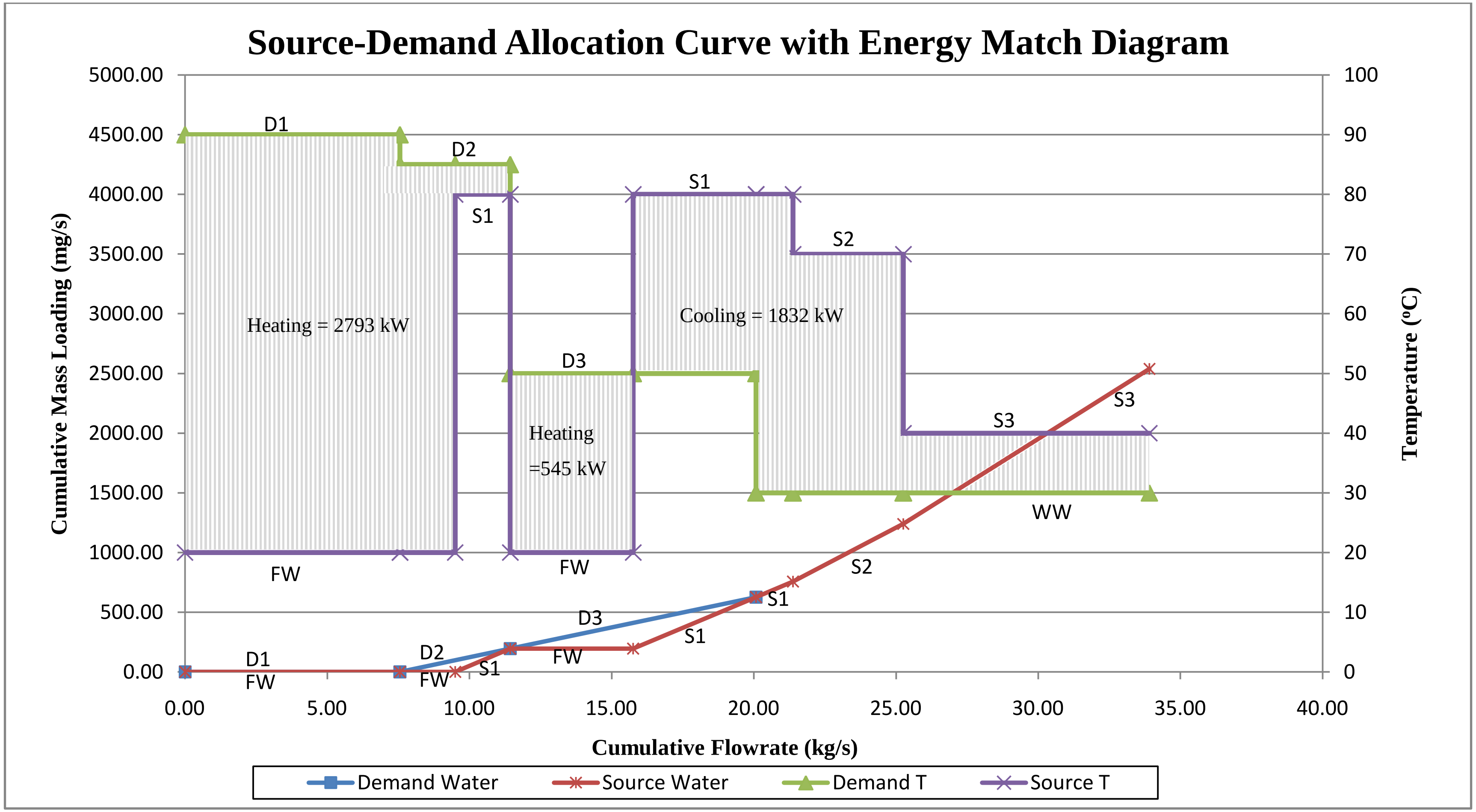

Figure 4.4: Source and Demand Allocation Curve with Energy Match Diagram

Notice that from the results obtained above, the total FW flowrate required to feed to S1 (7.56 kg/s), S2 (1.94 kg/s), and S3 (4.32 kg/s), and the total flowrate of WW discharged(1.38 kg/s of S1, 3.88 kg/s of S2 and 8.64 kg/s of S3), were equal to value of 13.82 kg/s respectively. Take note that these FW and WW flowrate were obtained in the SDCC curve as discussed early in section 4.2.1. Therefore, it proved that the streams matching process was correct and relevant to the SDCC obtained.

From Figure 4.4, the shaded area or the area enclosed by the demand temperature line and source temperature line shows the heating and cooling energy requirement for the system after the stream matching process. The total heating energy was 3337.32 kW and cooling energy was 1832 kW. Notice that at this stage, the energy required for the system for heating and cooling were solely produced by the extra utilities such as steam and cooling water. The total energy that can be recovered between the demand and source streams from the system will be discussed in next section.

4.2.4 Energy Recovery Targeting by Heat Composite Curve

According to the existing plant in this case study, the amount of heat required for the heating of freshwater from 20^{o}C to respective demands temperature requirement is 4371.12 kW. Whereas the amount of heat that need to be removed from the sources to the temperature of wastewater at 30^{o}C is 2602.56 kW. These amounts of heat can be reduced by the constructing of Heat Composite Curve (HCC) method (Linnhoff *et al.* 1983).

Through this HCC method, the energy supplied from extra utilities will be reduced significantly where the energy integration or energy targeting between the source and demand streams was performed in this stage. As discussed in Chapter 3 section 3.3.3, in order to construct the HCC, heat data must be extracted from the EMD in Figure 4.4 above. Table 4.4 below shows the extracted heat data from system. Heat capacity, C_P for water is assumed to be 4.2 kJ/kg^{o}C.

Table 4.4: Extracted Heat Data

	Flowrate, *F* (kg/s)	Temperature (^oC)		$F \cdot Cp$ kW/^oC	Enthalpy Change kW
		Inlet, Tin	Outlet, Tout		
FW-D1	7.56	20	90	31.75	2222.60
FW-D2	1.94	20	85	8.15	529.72
S1-D2	1.94	80	85	8.15	40.75
FW-D3	4.32	20	50	18.15	544.54
S1-D3	4.32	80	50	18.15	-544.54
S1-WW	1.3	80	30	5.45	-272.53
S2-WW	3.88	70	30	16.3	-651.96
S3-WW	8.64	40	30	36.3	-363.03

From the heat data in Table 4.4, HCC of the system can be constructed as shown in Figure 4.5 below. HCC constructed shows that after the energy targeting or energy integration process, the minimum heating utilities required were 1506 kW. On the other hand, the minimum cooling utilities shown zero in the HCC, which means no extra cooling utilities were required for cooling the streams after the energy targeting process. The shaded area represents the potential recoverable energy after the energy targeting process. The percentage of reduction in heating utilities compare to the existing system is 65.55 %. On the other hand, since there is no extra cooling utility after the integration, hence the percentage of reduction in cooling utilities is 100 %.

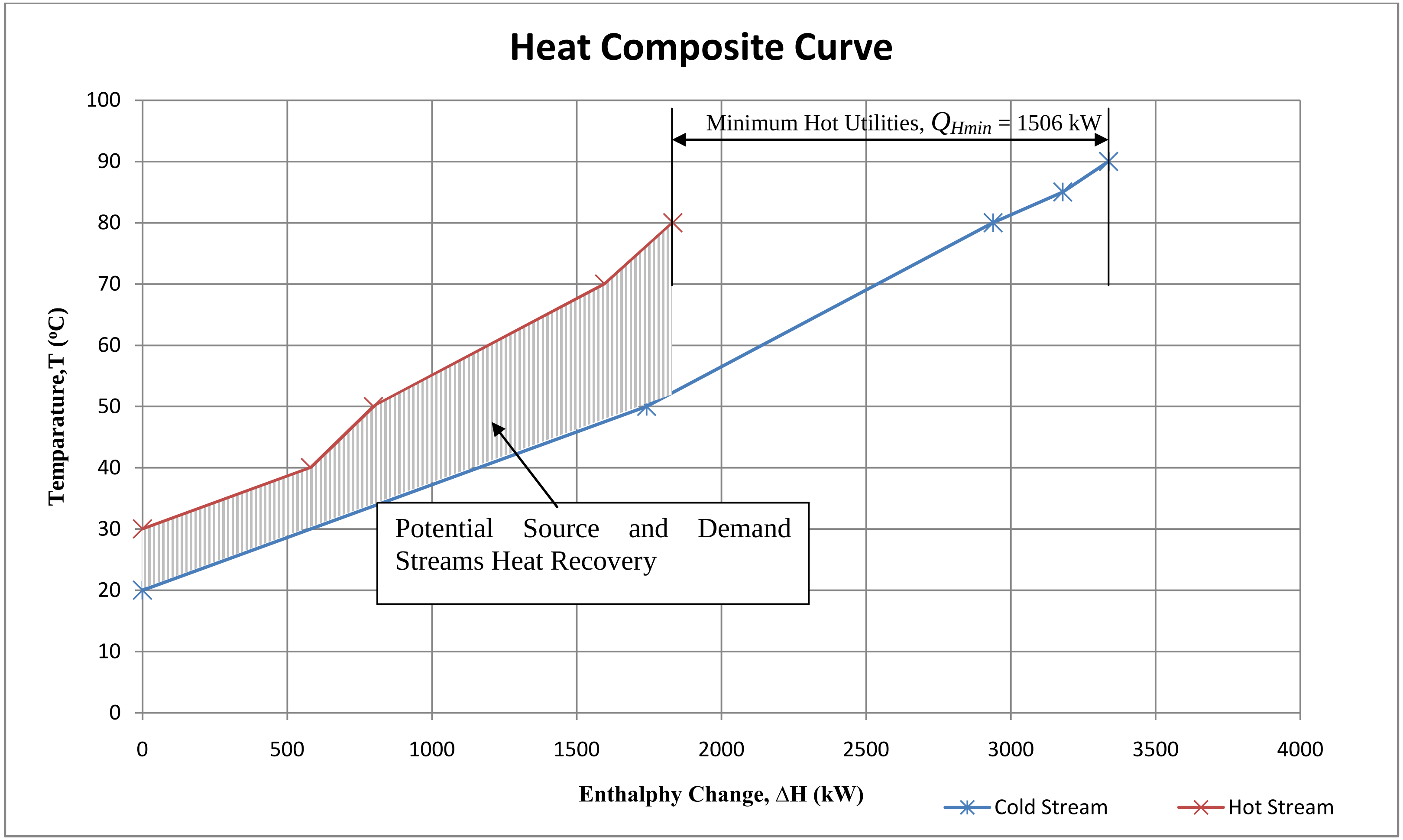

Figure 4.5: Heat Composite Curve

4.3 Summary of the Water and Energy Recovery

Table 4.5: Percentage of Reduction of Utilities after SMEC Method

Utilities	Existing Plant Requirement	After SMEC Minimisation	Percentage of Reduction %
Freshwater	20.08 kg/s	13.82 kg/s	31.18 %
Wastewater	20.08 kg/s	13.82 kg/s	31.18 %
Heating	4371.12 kW	1506 kW	65.55 %
Cooling	2602.56 kW	0 kW	100 %

The table above summarised the comparison of freshwater, wastewater, heating and cooling utilities usage before and after the SMEC method. By analysis on the results, it proved that the SMEC provides an efficient tool for the utilities recovery in a certain chemical plant. The percentage of reduction of all utilities in the system was significant which led to more cost saving in the chemical plant.

CHAPTER 5

CONCLUSION

The Superimposed Mass and Energy Curves (SMEC) method has been successfully applied into the water using operation case study. This method provides a good visualisation and user friendly tool for researchers to target the mass and energy utilisation. Besides, the research gap in the previous minimisation method such as poor insight through visualisation of system has been solved by this SMEC method. After applying the SMEC method, the water consumption has been reduced by 31.17 %, hot utilities by 65.55 % and cold utilities by 100 %. Before the SMEC method, the utilities in case study were solely produced by extra utilities. The great reduction of the utilities will lead to the saving of the plant operating cost. Therefore, a great achievement of minimisation of process utilities has been reach by the SMEC method in this project.

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APPENDICES

APPENDIX A: Case Study