Pinch Analysis and Solar Thermal Heat Integration in a Sugar Industry using Hint Software

A Major Thesis Submitted in Partial Fulfilment of the requirements
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NIRMAL PRATAP SINGH
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Under the Guidance of

Dr. J.P KESARI

Department of Mechanical Engineering,
DELHI TECHNOLOGICAL UNIVERSITY,
Shahbad Daulatpur, Main Bawana Road, Delhi-110042

DECLARATION

I hereby declare that the work which being presented in the major thesis entitled **"Pinch Analysis and Solar Thermal Heat Integration in a Sugar Industry using Hint Software"** in the partial fulfilment for the award of the degree of Master of Technology in **"Thermal Engineering"** submitted to Delhi Technological University (Formerly Delhi College of Engineering), is an authentic record of my own work carried out under the supervision of **Dr. J. P. KESARI,** Department of Mechanical Engineering, Delhi Technological University (Formerly Delhi College of Engineering). I have not submitted the matter of this dissertation for the award of any other Degree or Diploma or any other purpose what so ever.

Place: DELHI	NIRMAL PRATAP SINGH
Date: 30.07.2019	Roll No. 2K15/THE/08

CERTIFICATE

This is to certify that **NIRMAL PRATAP SINGH**, (Roll no. **2K15/THE/08**), student of M.Tech., THERMAL ENGINEERING, Delhi Technological University, has submitted the dissertation titled **“Pinch Analysis and Solar Thermal Heat Integration in a Sugar Industry using Hint Software”** under my guidance towards the partial fulfilment of the requirements for the award of the degree of Master of Technology under my guidance and supervision.

DR. J. P. KESARI
Department of Mechanical Engineering
Delhi Technological University
Delhi-110042

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NIRMAL PRATAP SINGH
(2K15/THE/08)

ABSTRACT

The rising cost of energy and environmental concerns have led the Sugar industry to search for techniques of reducing energy consumption in operations. In this paper, pinch analysis was applied to a typical Sugar Industry process to target for the energy requirements of the process. Hint software was used for the analysis. At the chosen ΔT_{min} of 10˚C, the minimum cooling and heating utility requirements of the industry is studied and were determined as being 46594 kW and 3258 kW respectively, with a pinch temperature at 113˚C. The hot utility requirements for the company before (traditional) and after pinch analysis approach were found to be 45574 KW and 3258 kW respectively, while the cold utility requirements were 102393 kW and 46594 kW, respectively, which presented an energy saving potential of 62,9 %.

Further the study tackles the integration of the thermo-solar technology in a heating requirement of stream sited in a climatic zone where diffuse irradiation is substantial. The Area requirement of solar collector, saving of oil equivalent and reduction of carbon in environment is studied.

Key words: Pin Analysis, Hot Composite, Cold Composite, Pinch Point optimization, Energy Recovery

Scientific field:

Technical science, Mechanical engineering, Thermal engineering

Narrow scientific field: Thermal Engineering

CONTENTS

Subscripts

HEN	Heat Exchange Network
TAC	Total Annual Cost
CC	Composite Curve
GCC	Grand Composite Curve
MER	Maximum Energy Recovery
ORC	Organic Rankine cycles
PFD	Process flow diagrams
PTC	Parabolic trough collector
LFR	Linear Fresnel Reflector
PDR	The Parabolic Dish Reflector
HTF	Heat transfer fluids
DNI	Direct Normal Irradiance
LTC	Low temperature collectors
MTC	Medium temperature collectors
HTC	High temperature collectors
ETC	Evacuated Tube Collectors
FPC	Flat Plate Collector
GHI	Global Horizontal Irradiation

LIST OF FIGURES

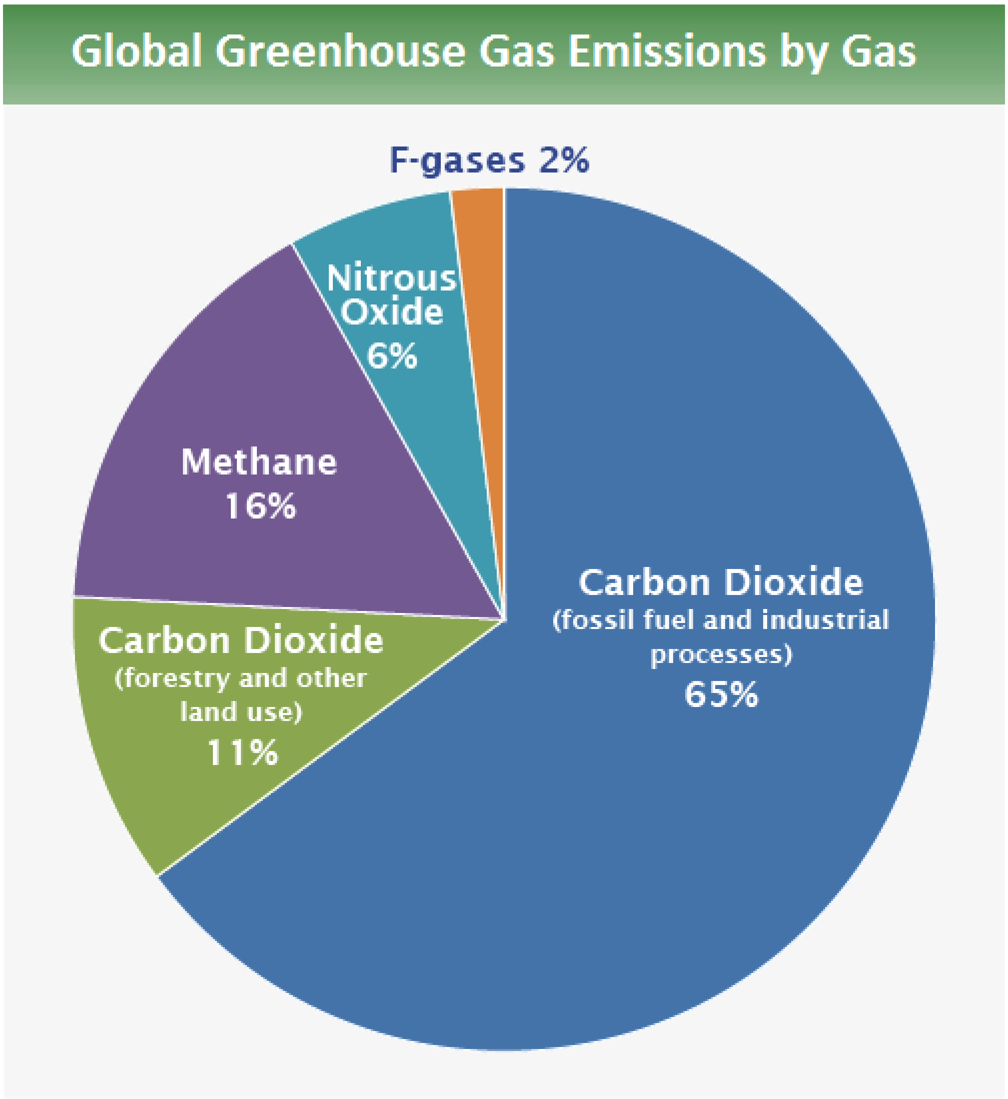
NOMENCLATURES

ΔH	*enthalpy change rate*	*kWh/m2/day*
I_{day}	*Solar irradiance*	*KW*
Ns	*Number of sunny days in a year*	*day*
tf	*Tilt factor of the solar collector*	
η	*Efficiency of solar collectors*	
Ta	*Ambient temperature*	^{o}C
$Tavg$	*Average operating temperature*	^{o}C
m	*mass flow rate*	*kg/s*
Cp	*Heat capacity at constant pressure*	*kJ/kg·K*
ΔT	*the temperature change in the stream*	^{o}C
CP	*the heat capacity flowrate (=mCp)*	*kJ/K*
$qprocess$	*the thermal energy requirement*	*kJ/ton*
P	*Mass flow rate*	*kg/s*
Ac	*Collector Area*	*m2*
$\eta combustion$	*combustion efficiency*	
kf	*fuel equivalent energy factor*	
toe	*tonne of oil equivalent*	
Cf	*fuel equivalent carbon dioxide emission factor*	*kg*
i	*fractional interest rate per year*	
n	*number of years*	
Ai	*heat transfer area*	m^{2}
Hi	*Enthalpy change*	*KW*
ΔT_{LMi}	*Log mean temperature difference*	^{o}C
N	*Number of enthalpy intervals*	
$umin$	*minimum number of units*	
N_S	*total number of streams*	
T_S	*supply temperature*	^{o}C
T_T	*target temperature*	^{o}C
a,b,c	*Cost law constant*	

CHAPTER 1

1.1 INTRODUCTION

Fossil Fuel utilized in the enterprises are the primary wellspring of CO2. The key ozone harming substances transmitted by human exercises are:



Refer Source: IPCC-2014

Figure 1.1 : Global Green House Emission by Gases

Global greenhouse gas emissions can also be broken down by the economic activities that lead to their production.

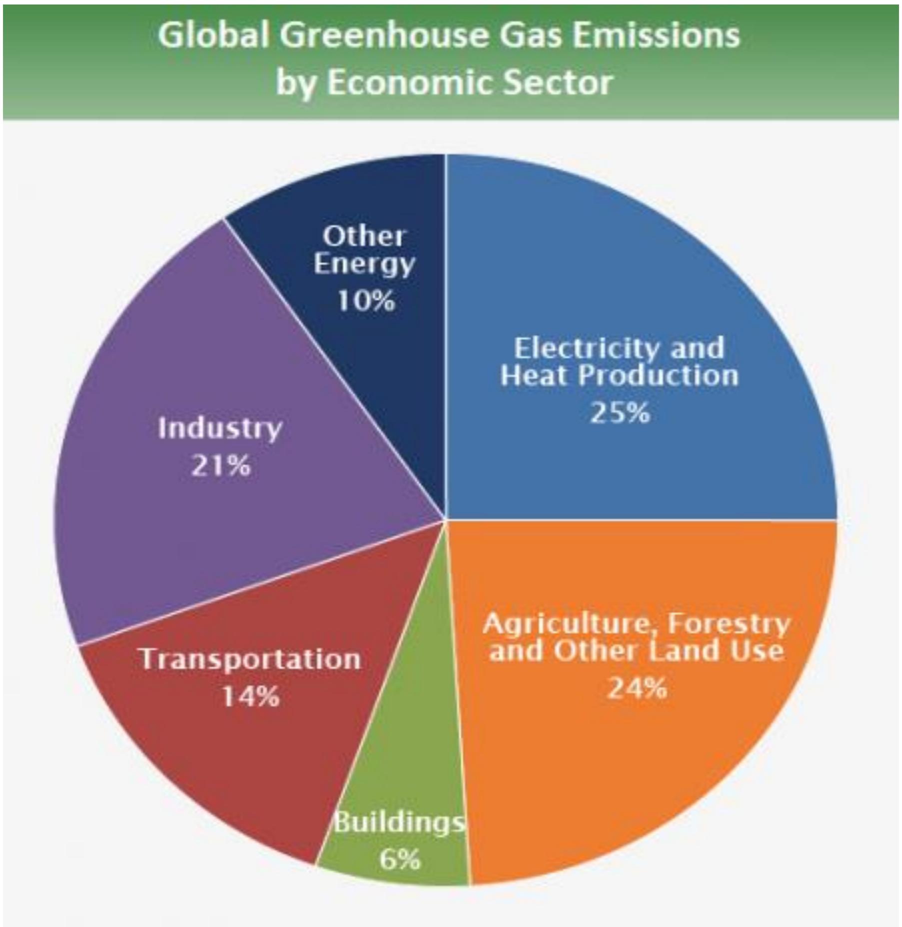


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Figure 1.2 Global Green House Gas Emission by Economic Sector

Industry is responsible for 21% of the world's direct CO2 emissions. The distribution of emissions between sectors is shown in Figure. Ozone depleting substance outflows from industry essentially include petroleum derivatives consumed at industry.

Note that industry also uses electricity generated by power plants so in fact its total contribution is larger than shown in the figure. Measures for reducing CO2 emissions in industry in a global perspective include energy efficiency measures. However, due to the ever increasing cost of energy a study of the efficient use of energy set in a financial context is becoming increasingly important.

Some potential measures for industrial energy efficiency improvement are -

- Cost-effective, currently available technology that can save primary energy supply to industry (economic potential);
- Energy efficiency measures that can potentially save money for industry
- Low cost measures such as energy management offer significant scope for savings
- Improvements in electrical and mechanical equipment like motors, drives, boilers, and compressed air plants can save.
- Process-specific savings represent the largest potential for savings.

Given this huge potential in process specific savings energy efficiency should be high on every industry's agenda in order to cut costs and/or emissions.

The sugar industry uses significant amounts of energy. The sugar mill demands a huge amount of energy for sugar production, especially heat. Heat is a primary energy that is used for several processes including sugarcane trunk from sugarcane, making sugar cane juice, boiling juice and crystallization until sugar.

Processes to produce granulated sugar includes juice extraction, clarification process, preheat and evaporation, syrup treatment, crystallization, centrifugalization and drying. Each process consumes a huge amount of both thermal and electrical energy, especially the juice extraction.

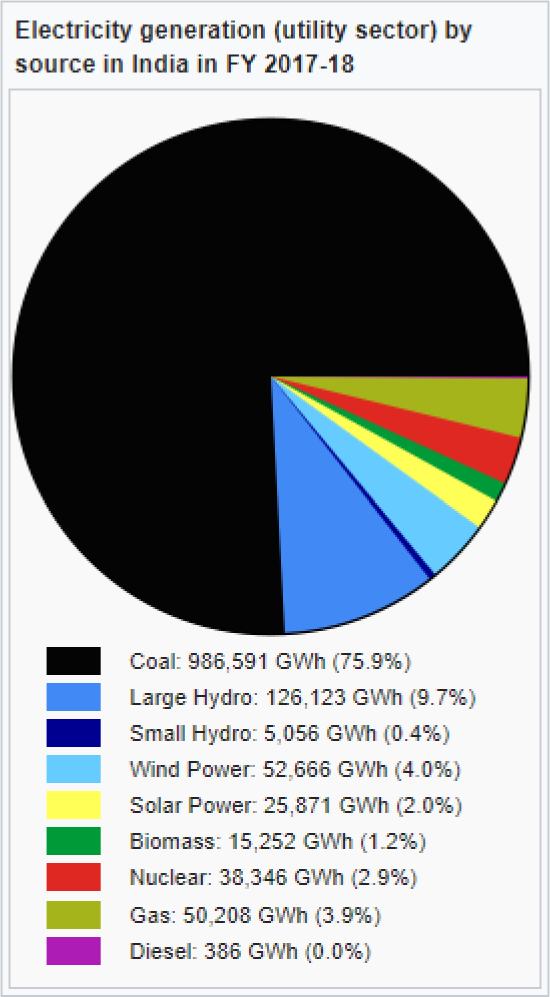
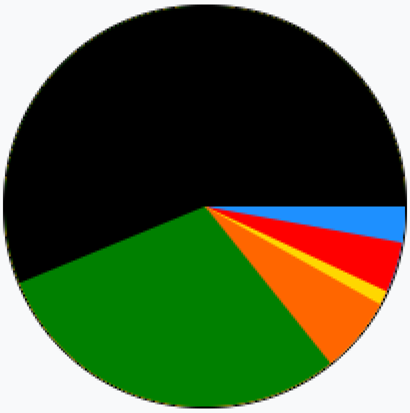


Figure 1.3 Electricity Generation by Sources in India in FY 2017-18

The sources of energy in India are electricity (refer figure), generated from mainly Coal (75.9 %) and hydro energy (10.1%), and thermal energy from geothermal sources. Energy from burning from coal produces a lot of CO2 emission. Furthermore, India is currently concerned about the maximum emissions allowed by the Kyoto Protocol and if it does not reduce its emissions, industries may have to start paying for their carbon emissions and that will reduce India’s appeal for investors in heavy industry and also incur extra costs for current industry. Therefore it becomes necessary for India to control its CO2 Emission at greater extent.

By Promoting energy efficiency contributes to increased available energy supply (in fact by reducing demand) and thus is a clear indirect benefit to India’s economy.



India: Total primary energy use of 753.7 Mtoe (excluding traditional biomass use) in the calendar year 2017[4]

⬛ 424.0 Mtoe Coal (56.26%)
🟩 222.1 Mtoe Petroleum & other liquids (29.47%)
🟧 46.6 Mtoe Natural gas (6.18%)
🟨 8.5 Mtoe Nuclear (1.13%)
🟥 30.7 Mtoe Hydroelectricity (4.07%)
🟦 21.8 Mtoe Other renewables (2.89%)

1.2 Objective of the Thesis

The Sugar industry is a significant consumer of energy. In addition to conventional Observations and analysis to estimate potential energy savings, pinch analysis is used to analyse the heating and cooling demands of an industrial process. It has been successfully applied to a number of process industries where energy costs represent a significant proportion of the total production cost. This study will analyse energy saving potential and apply pinch technology to a Sugar Production process to :

(a) To Calculate the Minimum Hot Utility, Cold Utility requirement, Pinch Temperature, Minimum number of Heat Exchanger required, Maximum Energy Recovery in the process
(b) To study the Pinch Method , application of Pinch Analysis in Sugar Industry, Hint Software and its application in Process Heat Integration, Solar thermal Heat Integration.

(c) To Estimate the Solar Collector’s Area, Annual Fuel Oil Savings, Carbon Savings,

(d) To analyse Variation of Pinch Temperature with DTmin, Variation of the energy requirements with DTmin, Variation of Capital Cost with DTmin

(e) To find the Capital Cost, Operating Cost and Total Cost of the Project.

CHAPTER 2

2.1 Literature Review

Matsuda et al [1] applied the total site approach using a "Total Site Profile (TSP) analysis" (based on pinch technology) to a large scale steel plant. Despite the very high efficiency of the individual process systems of the plant, that there would be a huge energy saving potential by adopting this approach. It became apparent that the available pinch technology tools and techniques lend themselves very well to the analysis of a steel plant. The heat (thermal energy) under 300 ^{o}C has previously not been well utilized in steel plants. But TSP analysis was able to identify the distribution and the quantity of such heat, from which energy saving plans could be developed.

Mirzakhani et al [2] attempted to focus on development of a rapid approach for benchmarking of an existing cement plant with respect to energy consumption, and subsequently estimating an achievable scope for energy saving. To realize this goal, five different pyro-process units were simulated and then targeted using Pinch Analysis approach. Having done this conceptual analysis, the obtained results were mathematically correlated to shape a benchmarking model. The resulting model was also validated, in terms of accuracy, and was applied to other cement plants and showed an energy saving potential of up to 24%.

Custódio et al [3] addressed the application of a detailed Pinch Analysis modelling technique, developed in Excel/VBA, for a multipurpose refinery batch plant. This application was focused on developing a tool that enables a quick analysis of Heat Integration to improve the energy-efficiency by rescheduling the operations. The developed tool was used with a real case study process data of a vegetable oil's refining plant. Several scenarios of re-scheduling were used to still accomplish the demand from the downstream plant production. This study show that a reduction of about 15 % in both utilities consumption can be achieved by some scenarios compared to the current vegetable refining scheduling. Also the results show that the integrated approach leads to better synchronization between production plant and the utility system. Thereby, the integrated approach leads to significant reduction in energy costs and gas emissions, showing advantages for future improvements based on rescheduling and indirect/direct heat exchange opportunities. Also the results of this work indicate a great potential of the use of HENs in real Batch Process systems for refining vegetable oils and present an important enhancement on the industrial plant thermal energy efficiency.

Gadalla et al [4] developed a general retrofit methodology for crude refineries, accounting for the changes to the process operation of the integrated systems. The major contribution of the new methodology relies on the emphasis of process operation changes rather than topology modifications. The new method utilises a recent new graphical method specifically to describe typical heat exchanger networks and retrofit the existing installations for better energy efficiency. The graphical representation of exchanger network has been applied to locate the Network Pinch and identify the pinched matches. With a set of process operation parameters translating the interaction between the background process and the network, heat recovery is improved and the Network Pinch is overcome. Procedures for both diagnosing an existing process and proposing potential process changes have been presented. A case study has been considered for two applications, one to maximise heat recovery opportunities and the other is to remove the Network Pinch. Substantial energy savings have been obtained without any network topology modifications. Retrofit implications have been evaluated in terms of capital investment of additional areas to existing exchanger matches. The retrofit solution proposed by the new methodology is yet attractive compared with literature solutions. An illustrative example showed that process changes overcome the Network Pinch and energy recovery was increased by 14% beyond the maximum level achieved for the existing process conditions. Capital investments imposed were minor compared with substantial energy cost savings.

Gai et al [5] proposed an improved phenol and ammonia recovery process that the sour water stripper and the solvent recovery system are thermal integrated based on the conventional wastewater treatment process. Therein, the ammonia-rich gas drawn from the middle of sour water stripper, as a heat source, is exchanged with the reboiler of the solvent distillation column and the solvent stripper. The results showed that the operating cost is about 34 % less than that of the conventional process, and the TAC (Total Annual Cost) can be decreased by about 30.8 %. The proposed process of phenols and ammonia recovery for the coal gasification wastewater is proven to be an effective and economical process with a good application prospect.

Shahruddin et al [6] studied the simulations for 4 components distillation column sequences. By using the pinch analysis, the energy saving for all sequences (except for direct-indirect) were enhanced. Therefore, it was suggested that the use of pinch analysis has a potential to further enhanced the energy saving in any distillation column sequence and works very well with driving force method for optimal sequence design with percentage saving of 4.85% (heating load), 9.01% (heating load) and 6.31% (total load). From the grid diagram suggested, the energy requirement for cooling has been reduced to 0.277 MJ/h.

Diban and Foo [7] proposed an extended Automated Targeting Model which allows area and total cost targeting for a heating medium system, which is a special case of HEN. The proposed method allowed the lowest total annualised cost of the system that includes the regeneration cost of heating medium to be determined by identifying the optimum DTmin. The result obtained for the industrial case study in scenario was evident where the current solution was found to be superior to the result calculated through graphical approach. Besides, with the implementation of pipe and fitting losses in scenario, a better solution was achieved as the actual pressure loss was found to be lower than previously assumed. The application of process integration for the industrial case study showed reduction of total annualised cost by 19% compared to the conventional design. In both hypothetical and industrial case study, the optimum solution found that the highest temperature of the heating medium is preferable when the inlet temperature of the heating medium is varied.

Tibasiima and Okullo [8] Pinch analysis was applied to a typical Ugandan based brewery process to target for the energy requirements of the process. Hint software was used for the analysis. At the chosen ∆Tmin of 10˚C, the minimum cooling and heating utility requirements of the brewery studied were determined as being 4862.21 kW and 8294.21 kW respectively, with a pinch temperature at 68˚C. It was observed that using the technique, 1806.59 kW of energy could be recovered through process to process heat exchange which presented an energy saving potential of 21.5%. It was recommended that results from this study could be used in the design or retrofit of a heat exchanger network of a brewery for improved energy efficiency. Considerations can also be made for other values of ∆Tmin.

Yoon et al [9] studied, a heat exchanger network (HEN) for an industrial ethylbenzene plant which was retrofitted by pinch analysis. In the ethylbenzene process, ethylbenzene is produced by alkylation of ethylene and benzene, and the whole product is used to produce styrene monomer. From the real operating data, a HEN of the ethylbenzene process was extracted.

Analysis of the HEN reveals that the current process was operated efficiently, but there was a possibility to improve the heat exchange in light removal columns. After analysis, an alternative HEN is proposed to save the energy. The alternative HEN was achieved by adding a new heat exchanger and changing operating conditions. It reduces the annual energy cost by 5.6%. In order to achieve it, the capital investment is necessary but the annual cost saving will be enough to recover the cost in less than one year.

Khorshidi et al [10] investigated the opportunities to increase process energy efficiency at the distillation unit of Shiraz oil refinery by the use of the pinch technology. By extracting all the required data from the refinery's flow sheets they realized that in study they would deal with a threshold problem which had not need any utilities. Then by conducting the pinch analysis and range targeting several new HENs were designed with respect to operating conditions and various $\Delta Tmin$. Accrdingly, they found that increasing $\Delta Tmin$ capital cost decreases and operating cost increased. In the regions where energy prices are rather low, $\Delta Tmin$ could be set higher since by doing so capital cost declines. However, in investigation the optimal value of $\Delta Tmin$ was found to be 22.3 °C and based on energy consumption this design was affordable. There will be 5 percent reduction in annual total cost of HEN. 5 percent of the total cost makes a lot of difference and shows how powerful and effective the pinch analysis could be.

Matija & Otma [11] showed that the application of pinch technology would make it possible to reduce the demand for cooling water and medium pressure steam. With the problem table algorithm, data were quickly extracted from the flowsheet and were analyzed for energy saving. From the thermodynamic point of view the process requires only cooling utilities and does not need any heating utilities. This case study corresponds to that of a threshold case where only cold utility is needed. The nitrous gas stream was used for heat transfer with ammonia without any additional heating stream. The total number of exchangers was one less than in the original case and three of them had to be redesigned. The final result is reduction of energy costs with the payback time of 14.5 months.

Wang et al [12] started a case study of total process energy-integration in a commercial ammonia plant was performed using a modified pinch analysis. Several tools, including Grid Diagram, Composite Curve (CC), Grand Composite Curve (GCC), Balanced Grand Composite Curve (BGCC) and Splitting Grand Composite Curve (SGCC), were adapted in the diagnosis of process energy-utilizing. It was shown that the utility loads calculated by operating pinch calculation (OPC) were very close to those in the existing process, and that the method could be used to describe the heat-flow profile of the plant. Some inefficient energy use in the plant was observed in the calculation. The design pinch calculation (DPC) revealed that 1150 kg/h of fuel gas (natural gas) and 1322 t/h of cooling water could be saved through optimizing the temperature difference contribution value (ΔTc) of heat transfer in each stream for an existing ammonia plant. And a proposal for energy saving was presented. The energy-integration technology showed great promise in the retrofit of large-scale complex process.

Walmsley et al [13] observed Milk powder production and found that it was highly energy intensive and can benefit from the application of Pinch analysis techniques to develop better methods for integrating the process. Process stream data was extracted from an industrial plant and Pinch analysis applied to calculate utility and heat recovery targets. Some of process data was also varied, within small ranges that do not harm product quality or violate environmental regulation, to minimise utility use targets. Using the Pinch design method and the targets as a guide, Maximum Energy Recovery (MER) networks are developed for two cases, where the condenser in the evaporator section of the plant may be directly or indirectly integrating into the reminder of the process. The two MER networks were compared to two heat exchanger network structures commonly found in industry. Results showed that there is potential to increase specific heat recovery by over 30%, while reducing total cost by almost 10%, in the best case. To achieve maximum energy recovery, spray dryer exhaust air heat recovery was necessary and should be matched to preheat the dryer inlet air stream.

Miah et al [14] applied heat integration in diverse production lines by a combination of direct and indirect heat exchanges at a confectionery factory. The whole procedure comprised of four stages; process zoning and data extraction, streams zonal analysis, intra-zonal integration, and inter-zonal integration. By adopting an integrated approach, the framework seeks to maximise heat recovery for the total factory, as opposed to solely for targeted areas which focus either on direct or indirect heat integration. The introduction of exclusion thresholds followed by a grading system ensures streams are investigated further based on the energy costs avoided and heat duty. The application at a confectionery factory had demonstrated the usage of the procedural tool in evaluating both direct and indirect heat integration opportunities in a consolidated attempt at different scales of a factory. In this case study, five heat integration options were developed that can deliver between 3.77% and 5.72% energy reduction at a factory level with a total investment of £321,328 and a cost saving between £48,884 and

£104,661 resulting in a payback of the cost of the changes between 3.07 and 6.57 years. The proposed framework offers a comprehensive and practical tool for the application of a Pinch-based approach to energy saving in industry.

Oslen et al [15] showed how energy conversion units such as heat pumps, combined heat and power systems or Organic Rankine cycles (ORC) can be optimally integrated into a process. An ORC converts low temperature waste heat (e.g. 100-200°C) into electricity. However, the integration of an ORC requires a sound conceptual design to ensure proper integration. In this paper the importance and application of pinch analysis for integrating an ORC was presented. Pinch analysis plays a significant role in the development of a sound conceptual design as it identifies and quantifies the amount of waste heat as well as allows the determination of the streams most suitable for the ORC. The so called grand composite curve was used for the integration of an
ORC to ensure the proper placement when considering the entire process. A properly integrated ORC that uses waste heat as a heat source must operate below the pinch point, i.e. the ORC takes heat from below the pinch point and converts a part of it to electricity and rejects the remaining heat to the environment. This methodology stresses improving the overall process energetic efficiency first through heat recovery before using (real) waste heat in an ORC. A novel industrial case study was presented to illustrate proper ORC integration showing the benefit energetically but limited financially under the given process and economic.

Olsen & Wellig [16] had determined and tested a case study that demonstrates the analysis approach for integrating a mechanical vapour recompression (MVR) unit operation within a process containing an evaporator. In addition, the analysis approached for a batch process using the separate design type was shown. The use of conventional, resequencing and repipe design type assumptions was elaborated in how to determine a cost optimal heat exchanger network (HEN) through the maximizing of the common area over all time slices during the targeting stage. Finally, the PinCH software has shown to successfully support the analysis of an energy conversion unit (ECU) integration and separate design type batch analysis for direct heat integration studies.

Tokos et al [17] analysed the possibilities of heat integration, and combined electricity, heating, and cooling production in a beverage plant by application of mathematical programming optimization models. The mathematical model for the heat integration of batch processes was slightly modified in order to correspond to industrial circumstances. Two matches were predicted in the brewhouse by this model. The first one was between waste vapour from wort boiling and adjunct mash heating processes. The second match integrates the heat released at wort clarification with the mash heating process. The resulting savings on utilities would be significant, however, only the first match was acceptable to the company. The second match supplies only part of the heat required by the mash heating process and was, therefore, rejected. A simplified mixed integer linear programming (MILP) model was developed for the feasibility analysis and selection of the optimal system for combined electricity, heating, and cooling production in the plant with significant seasonal variations in demand. The set of alternatives included steam and gas turbines at three pressure levels, and a tri-generation system with a back-pressure steam turbine. The option of heat production increase above the company's demand was optimized. The optimal polygeneration system for the brewery was selected according to the economic criteria considering the company's constraints. The cogeneration system with a back-pressure steam turbine at a pressure level of 42.4 bar has the highest net present value. Heat production would be increased during the heating season by 50%. Electricity production would cover 42% of the current Brewery's consumption. The net present value is positive and the payback period is 3.2 years. The disadvantage of this solution is that the plant would become dependent on external consumers of surplus heat energy.

Walmsley et al [18] applied total Site Heat Integration approach in conjunction with a detailed process and utility model, to develop an innovative ultra-low energy milk powder plant design. The basis for the analysis was a state-of-the-art modern milk powder plant that requires 5265 MJ/tp of fuel and 210.5 kWh/tp (58.5 MJe/tp) of electricity. The model of the modern milk powder plant was validated against industrial data and changes to process and/or utility systems are targeted and implemented into the model to understand the impacts on thermal and electrical demands and emissions. Results showed that seven significant changes are beneficial: (1) pre-concentration of milk to 30% using reverse osmosis, (2) a twostage intermediate concentrate (30%) homogenisation to enable high solids (60%) spray drying, (3) an ultra-low energy Mechanical Vapour Recompression evaporator system, (4) spray dryer exhaust heat recovery, (5) condensing economiser for the boiler, (6) upgrade and integration of chiller condenser heat with hot water utility systems, and (7) recycling of air in the building ventilation system. These changes were estimated to reduce thermal energy use by 51.5%, electricity use by 19.0%, and emissions by 48.6% compared to a modern milk powder plant.

2.2 Research Gap

1. Very less research has been carried out in Heat Integration by using Pinch Technology in Sugar Industry to minimize the energy consumption.
2. There is wide scope for Heat Integration through Pinch method and also integrating Solar Energy with the existing network.
3. Retrofitting of a network can be quite an expensive for a project therefore using pinch method to for every new project can be beneficial.
4. The same methodologies can be extended aggressively for other industries as well since it’s use is not widespread across industries.

CHAPTER 3

3.1 Pinch Analysis

Energy efficiency can be improved by a number of ways. To estimate the most efficient use of energy the main pillars are to study energy management, energy conversion, energy recovery, and process integration. Energy management is the most straightforward way of decreasing energy use. Simple things such as turning off lights when not necessary and generally being aware of use of energy are ways of energy management. Energy conversion involves examining the selection of a fuel as an energy source (electricity, heat, coal etc.) and the most efficient use of that fuel for an application. Energy recovery aims to minimize losses and waste energy. Various ways can be considered for energy recovery. Commonly implemented measures include increasing insulation, preventing friction and recuperating heat by heat exchanging. For fluids, indirect heat exchangers are most common whereas heat pumps are often used for air. Process integration is a way to quantify the maximum energy recovery potential for an industrial process. For this thesis the most relevant points to consider are energy management and energy recovery (process integration).

3.2 Pinch Analysis: Introduction of basic concepts

Pinch analysis (process integration) is a methodology for minimizing energy consumption of chemical processes by calculating thermodynamically feasible and minimum energy targets and achieving them by optimizing heat recovery systems, energy supply methods and process operating conditions. It is also known as pinch technology or process integration or heat integration.It is based on thermodynamic principles (mainly the 2nd law) and on the fact that different processes in an industrial plant require different temperature and pressure. It is a tool for heat exchanger network design and the investigation of heat and power utility options. [19]

The process data is represented as a set of energy flows, or streams, as a function of heat load against temperature. These data are combined for all the streams in the plant to give composite curves, one for all hot streams (releasing heat) and one for all cold streams (requiring heat).

The point of closest approach between the hot and cold composite curves is the pinch temperature and is where the heat exchanger network design is the most constrained.Hence, by finding this point and starting design there, the energy targets can be achieved using heat exchangers to recover heat between hot and cold streams. In practice, during the pinch analysis, often cross-pinch exchanges of heat are found between a stream with its temperature above the pinch and one below the pinch. Removal of those exchanges by alternative matching enables the process reach its energy target. The main advantage of process integration is to consider a system as a whole (i.e. integrated or holistic approach) in order to improve its design and/or operation. In contrast, an analytical approach would attempt to improve or optimize process units separately without necessarily taking advantage of potential interactions among them.

Typically, process integration techniques are employed at the beginning of a project (e.g. a new plant or green field design) to screen out promising options to optimize the design. Increasingly however, they are used for analysing an existing plant (as is the case in this project). The optimal solution for a retrofit is not the same as for green field design. For retrofit of heat exchanger networks there are no “perfect” methods (for larger networks) and for a given level of increased heat recovery a retrofit design which modifies as few units as possible is usually the most cost effective solution.

3.4 Objectives of Pinch Analysis

To understand the basics of pinch technology there are a few important concepts that must be defined:

- Hot/cold streams;
- Heat exchangers, hot utility and cold utility;
- ΔTmin;
- Composite curves;
- Pinch Point;
- Interval temperatures;
- Grand composite curve.

A hot stream implies a cooling demand. Similarly, a cold stream requires heating in order for its temperature to be changed from the initial to a target value. A cold stream implies a heating demand.

There are three types of heat exchangers under consideration: An internal heat exchanger placed between two process streams, heaters that add heat to the process from an external heat source. A hot utility is an external heat source and a cold utility is an external cooling system. The minimum temp. of approach, (ΔTmin), is the lowest temperature difference between the hot stream and the cold stream that can be accepted in a heat exchanger . By reducing ΔTmin the running costs decreases, since less fuel is needed and cooling water. On the other hand, we increase our capital costs, since the increase in heat exchanger area needed is larger in the internal heat exchanger, due to the lesser driving force, than the decrease in the cooler and the heater.

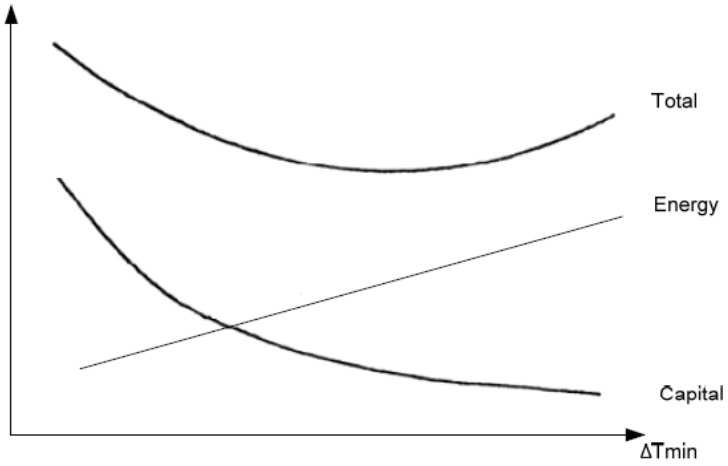


Figure 3.1 Annual costs as functions of minimum temperature approach

3.5 Composite Curves

Composite curves are useful to establish energy targets for multi-stream systems. The hot composite curve is constructed by finding total heat content of all the hot streams existing over any given temperature range. The cold composite curve is constructed correspondingly. When there is overlapping of the two curves, internal heat exchanging is possible; heat can be transferred from the hot to the cold streams.When there is no overlapping of the two curves, external heating or cooling must be used.

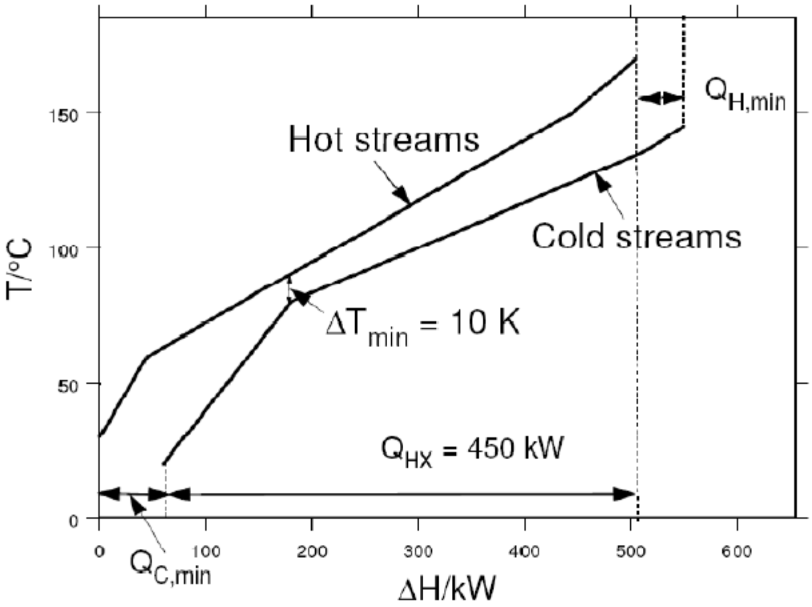


Figure 3.2 The Composite curves, ΔTmin=10K

The *pinch temperature* in general the minimum allowable temperature difference between hot and cold streams (ΔTmin) occurs at one point only. This point is called the pinch. The pinch point divides a process into heat source and heat sink. To cool above the pinch means that heat is extracted from a system, which has a deficit of heat. The same amount of heat must therefore be added with the external heater. To heat below the pinch means that heat is added to a system that already has an excess of heat.The same amount of heat must therefore be cooled with external coolers.

When all the streams are defined they can be divided into interval temperatures. All hot stream temperatures are decreased by Tmin /2 and all cold stream temperatures are increased by Tmin/2. The Tmin is the minimum temperature difference allowed between streams that exchange heat.

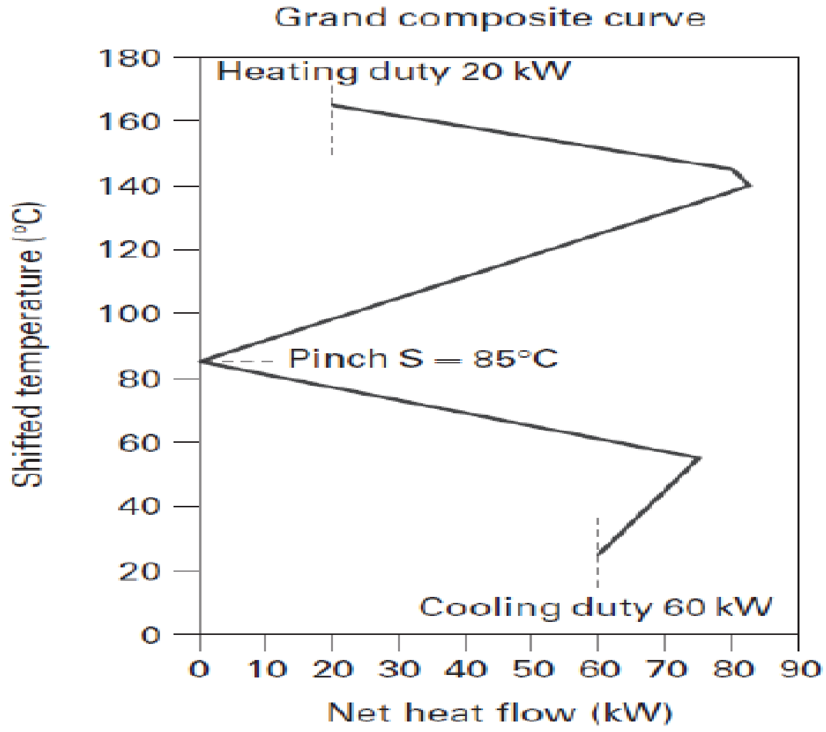


Figure 3.3. A typical Grand Composite Curve (GCC)

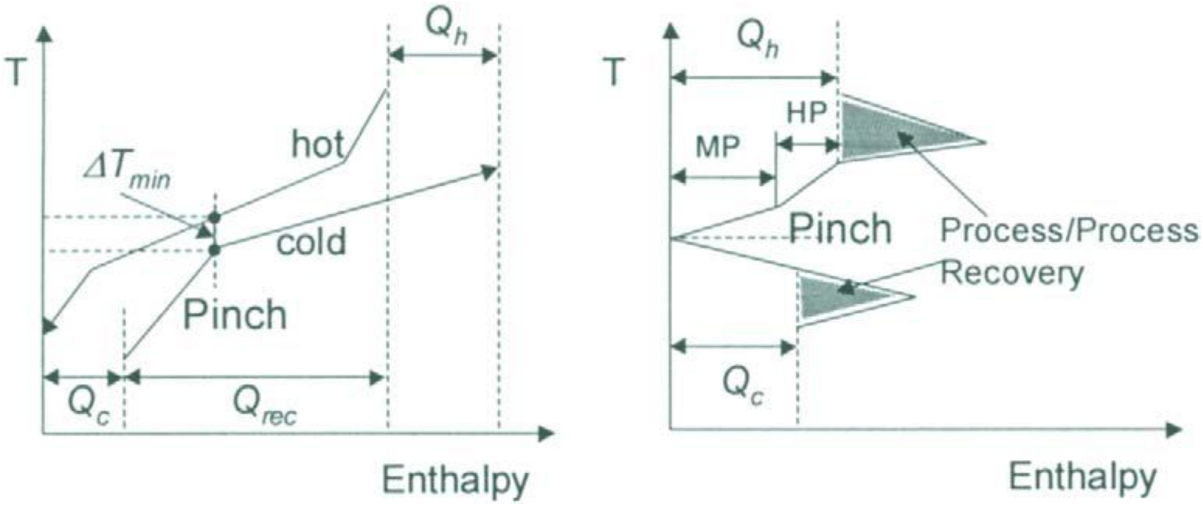


Figure 3.4 The Composite curve & Grand Composite Curve (GCC)

Thus, three golden rules can be identified (Kemp 2007):

- No heat transfer to be done through the pinch;
- No cooling with external coolers above the pinch;
- No heating with external heaters below the pinch.

A violation of these rules is referred to as a *pinch violation*.

So called *interval temperatures* are obtained by subtracting ½ΔTmin from the hot stream temperatures and adding ½ΔTmin to the cold stream1temperatures.In interval temperatures, the minimum approach temperature difference will then be zero. If there is an excess of heat in a given temperature interval, this can of course be used to cover a deficit in a lower temperature interval, since the hot streams in this interval are hot enough to supply a deficit in the cold streams in lower temperature intervals.

Pinch Analysis was performed using the following key hypotheses:

- Thermal losses during heat transfer were neglected.
- The process streams physical properties were constant at the given process temperatures.

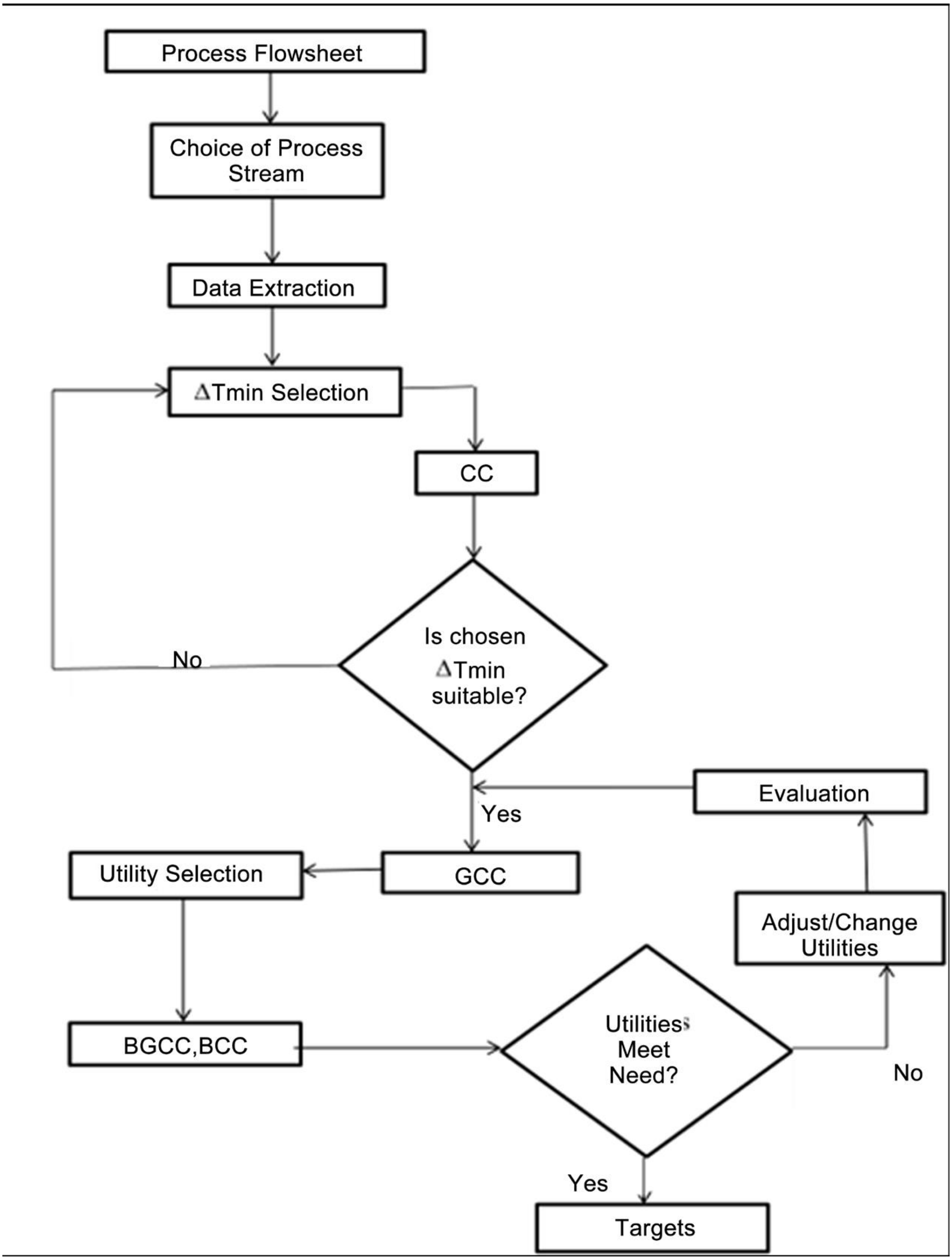


Figure 3.5 Energy Targeting Process Flow Chart

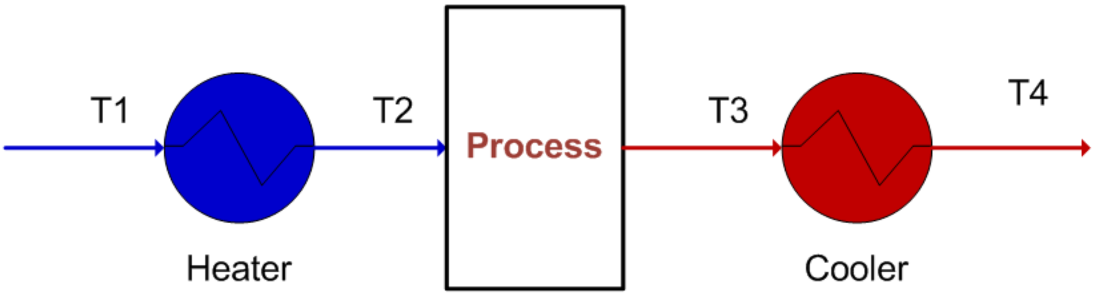
3.6 Steps of Pinch Analysis

The1basic1steps1of1any1Pinch1problems1are:

1. Recognition of1Hot Stream, Cold1Stream, and1Utility1Streams1in1a process
2. Thermal1Data1Extraction
3. Selection of DTmin.
4. Development of1Composite1Curves and1Grand1Composite1Curve
5. Minimum1Energy1Cost1Targets1Calculations
6. HEN1Capital1Cost1Targets1Estimation
7. Optimum1DTmin Value1Calculation
8. Energy Cost1and1Capital1Cost1Trade-Off
9. Design of HEN

Finding Hot Stream, Cold Stream, and1Utility1Streams1in1the1Process

Data1Extraction



Stream	Stream type	Supply Temperature (°C)	Target Temperature (°C)	Duty (kW)	CP (kW/°C)
1	Hot	200	100	2000	20
2	Hot	150	60	3600	40
3	Cold	80	120	3200	80
4	Cold	50	220	2550	15

Figure 3.6 Thermal Data Extraction

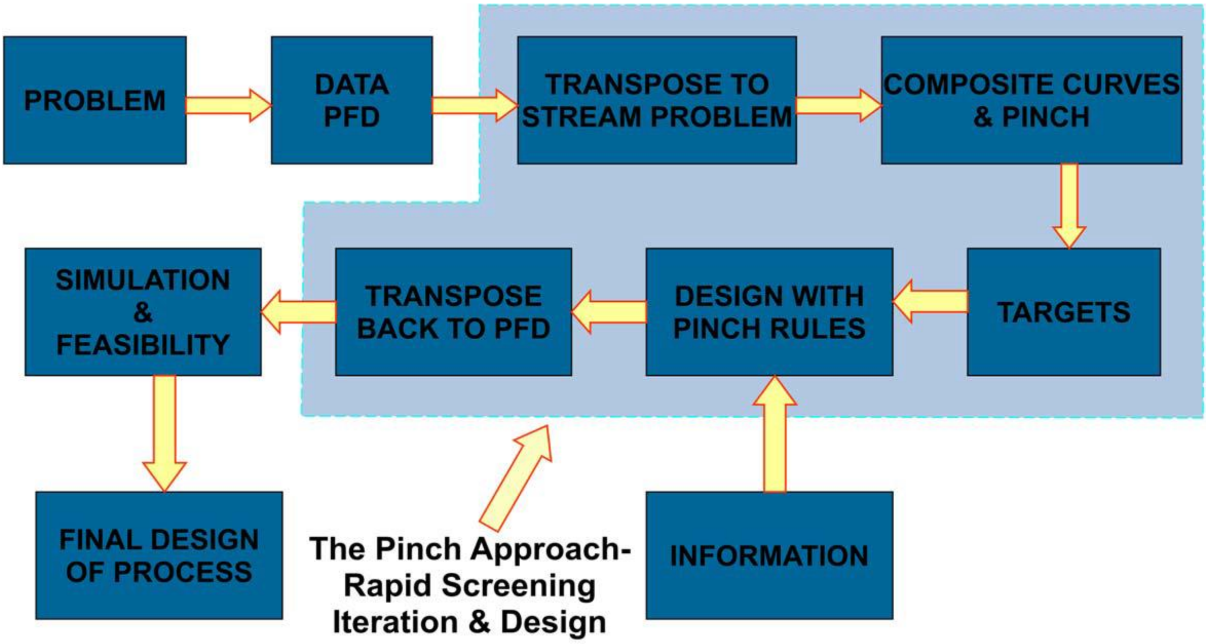


Figure 3.7 Pinch Methodology Flowchart
(Source: NPTEL)

$$\Delta H = m*Cp*\Delta T = CP*\Delta T$$

Where,

ΔH = Rate of change of enthalpy

m =mass1flow1rate1

Cp1= heat1capacity1rate

ΔT = Temperature1change1in1the1stream, and

CP = mCp = the1heat1capacity1flowrate

Additionally, the following information must be collected on utilities and existing heat exchangers

- Heat1exchanger1area1 (m2)
- Heat1transfer1coefficient1 (h) for1cold1and1hot1sides1of 1heat1exchangers1 (kW /m2 OC).
- Utilities1available1in1the1process1 (water1temperature, steam pressure levels, etc

After completing the data extraction part, the next phase is the creation of hot and cold composite curves. Composite Curves are temperature-enthalpy (T-H) profiles of heat available in the process (through the “hot composite curve”) and heat demands in the process (through the “cold composite curve”) with the help of graphical representations. For integration instead of dealing with individual streams an overview of the processis needed. Composite curves are the second step for the integration process. To figure out the heat availability and demand in the process one has to capture the essence of heat load (hot as well as cold streams) integration and heat flow. In other words one should search for a frame work under which integration of heat energy can be performed.

Representation of Process Stream data

Fig.3.7 shows the representation of hot and cold streams graphically. Hot streams are conventionally drawn from left to right with arrow head pointing to right. Near the supply temperature a text box having the stream No. is placed and supply temperature is written. Near the arrow head the target temperature is written. The CP value of the stream is also indicated. Cold streams are drawn from right to left with arrow head pointing left. A text box containing the stream number is placed at the supply temperature end. Supply temperature is written near the box and the target temperature is written at the other extreme end having arrow head. The CP value is also indicated for the stream.Cold and hot streams with hot pinch and cold pinch values written in both the sides of a vertical line. The CP values of different streams are written near to the stream at one end and the ΔH values in other end. For hot streams ΔH values are –ve and for cold stream it is +ve.

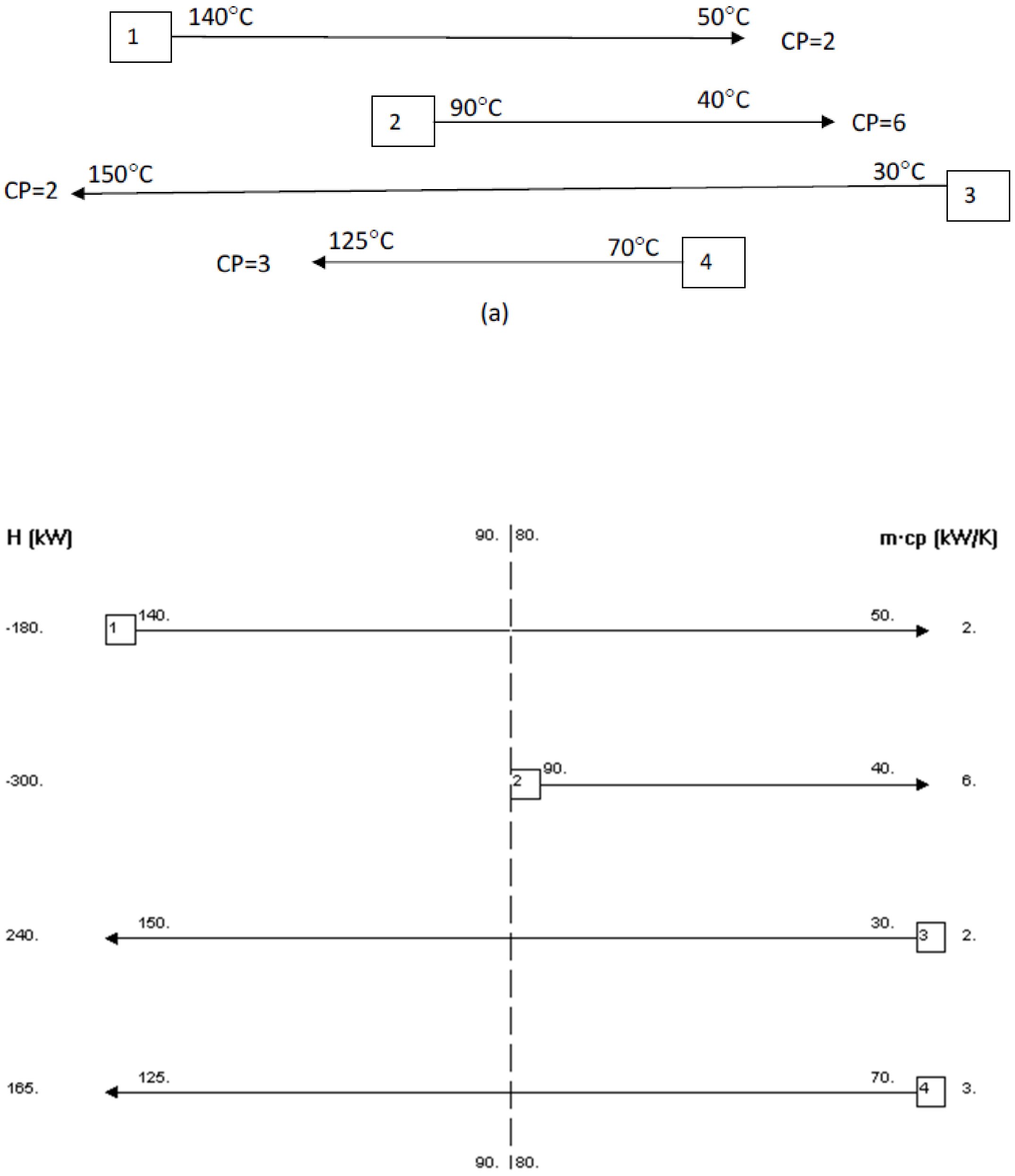


Figure 3.8 Graphical Representation of process streams

Formulation of equation

Cost targeting

The cost targeting is divided into two parts:

a) Capital cost Targeting and
b) Operating cost targeting.

The cost of a heat exchanger depends primarily on1its material of1construction, pressure rating and the type of exchanger itself. Cost of single heat exchanger with surface area A can be found out using simple relationship: -

Capital cost of exchanger = a + b Ac

a, b and c are the cost law constants that vary according to the material of construction, pressure rating and the type of the heat exchanger.

for using above equation to find the capital cost of a heat exchanger network, consisting of many heat exchangers, the simplest assumption of equal area for all the exchangers is used.

Network capital cost = N [a + b (A Network / N) ^{c}]

Here, N = the number of units/shells

As mentioned earlier, cost is involved at two places in any Heat exchanger network synthesis problem: -
a) Capital cost of the heat exchangers, heaters and coolers
b) Utility costs

Total Annual Cost (TAC) = Annualized capital cost + Annual utility cost

Annual capital cost = (capital cost) $*\left(\frac{i*(i+1)^n}{(i+1)^n-1}\right)$

Where,
i = fraction of interest rate (yearly)

n = number of years (useful life of exchanger in years)

Calculation of capital cost target is done based on following relationship:

Capital Cost of Heat Exchanger ($) = 30,000 + 400 (A) $^{0.9}$

AREA TARGETING

Area targeting is a vital component in the determination of the HEN capital cost and thus plays an important role in capital energy trade off to determine the optimum ΔTmin. The inherent concept of area targeting is discussed below:

$$A\mathrm{i} = \frac{\Delta \mathrm{Hi}}{U\mathrm{i} * \Delta \mathrm{TLMi}}$$

Where;

Ai is heat transfer area required in ith enthalpy interval for heat transfer of amount ΔHi

Hi is the Enthalpy change over ith enthalpy interval

Ui is the Overall heat transfer coefficient in ith enthalpy interval

ΔT_{LMi} is LMTD of ith interval

N is Number of enthalpy intervals

However, to compute ΔT_{LMi} all the four temperatures (Hot stream inlet and outlet and cold stream inlet & outlet) should be known

The total heat transfer area of the network is:

$$A = \sum_{i=1}^{N} Ai = \sum_{i=1}^{N} \frac{\Delta Hi}{Ui * \Delta TLMi}$$

If overall heat transfer coefficient of all the enthalpy intervals is same and is denoted by U, then the total heat transfer area of the network is given by:

$$A = \sum_{i=1}^{N} A\mathrm{i} = \frac{1}{U} \sum_{i=1}^{N} \frac{\Delta \mathrm{Hi}}{\Delta \mathrm{TLMi}}$$

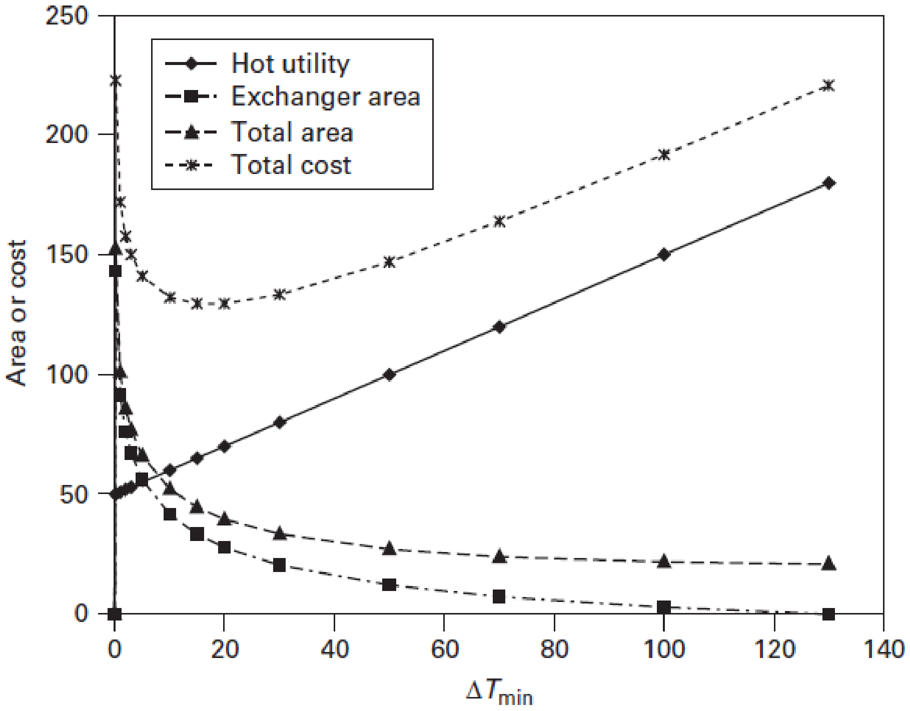


Figure 6.1 Variation of Utility use, exchanger area and cost variation with ΔTmin

We have seen that hot and cold utility requirements increases if the values of ΔTmin is higher and it therefore seems that we need a ΔTmin as minimum as possible, to get the higher energy efficiency. However, there is a twist; lower value of ΔTmin results in larger and more costly heat exchangers. Which means, the heat exchanger area is essentially inversely proportional to the temp. difference. Therfore, low values of ΔTmin can lead to very large and costly exchangers, as capital cost is closely related to area. Obviously a low ΔTmin value gives a low ΔT_{LM}. Clearly, it will be important to choose the right value of ΔTmin for our targeting and network design.

Algorithm for Area Targeting

The area targeting for heat exchanger networks can be divided into two major sections: -

a) Area targeting with equal heat transfer coefficients
b) Area targeting with unequal heat transfer coefficients

No. of units target

The fixed cost of a heat exchanger network (HEN) depends upon the number of heat exchanger it employs. Thus, there exists a possibility that a HEN with minimum no. of heat exchanger will cost less.Thus there exists a strong incentive to reduce the number of heat exchangers (matches between hot and cold streams) in a HEN.
The first step required for this process for itsinitiation is to identify the number of heat exchangers a HEN will require from the number of Hot, Cold and Utility streams it handles.

$u\text{min} = N - 1$

Where $u$min = minimum number of units (including heaters and coolers) and
NS = total number of streams (utilities are also included)

Temperature-Enthalpy Diagram

For integration of energy two parameters are most important, amount of energy (given by enthalpy change, ΔH and direction of energy flow covered by second law of thermodynamics and conserved through maintaining the temperature (T) level sacrosanct. Thus, integration and transfer of energy can be implemented through two parameters namely ΔH and T. The above parameters are shown as two axes of a quadrant below as a 2D representation of a process which can be handled graphically. The plot, as shown in Fig.3.8, Is called temp. enthalpy diagram:

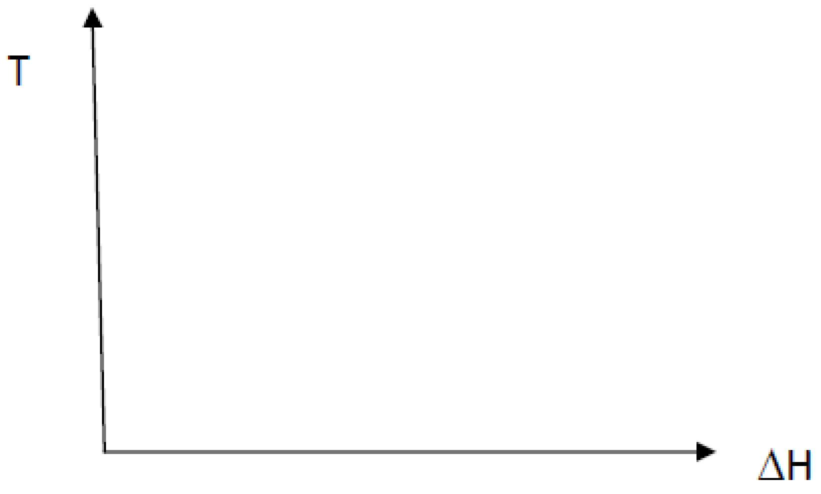


Figure 6.2 Temperature vs enthalpy representation of heat integration

6.5 Heat Integration

The heat value Q of a stream (kW) is commonly called its enthalpy H. Furthermore, the differential heat flow dQ, when added to a process stream, will increase its enthalpy (H) by CP dT, where:
CP is heat capacity flowrate (kW/K) (mass flow W (kg/s) x specific heat CP (kJ/kgK)), and
dT is the differential temperature change

Thus, for a stream requiring heating ("cold" stream) from a "supply temperature" (T_S) to a "target temperature" (T_T), the total heat added will be equal to the stream enthalpy change
(ΔH) and will be equal to:

$$\Delta H = Q = \int_{Ts}^{Tt} CpDT$$

Eq. 3.1 is valid when CP= f (T). In most of the cases CP is a function of T and is given by:

Heat capacity flowrate $CP = c_0 + c_1T + c_2T_2 + c_3T_3$ …
And thus, ΔH becomes,
Enthalpy change $\Delta H = c_0T + (c_1T_2/2) + (c_2T_3/3) + (c_3T_4/4)$ …

The above integration makes ΔH as a nonlinear function of T as shown in Fig.3.9. The non-linear temperature –enthalpy behaviour can be represented by a series of linear segments. Such situations are tackled by methods given in section 3.2.

Figure 6.3 Non-linear representation of a stream.

However, if the value of CP remains constant in the range of investigated temperatures (i.e. Ts to T_T) it can be taken out of the integral sign and thus,

$$H_T - H_S = \Delta H = Q = Cp\int_{Ts}^{Tt} DT = Cp\,(T_T - Ts)$$

Where HS and HT are enthalpy of the stream taken at TS and TT temperatures w.r.t. a common a common reference enthalpy (Ho) based on the reference temperature, say 0^{o}C. While dealing with differential enthalpies like (H_T - H_S) the reference enthalpy Ho cancels out.

$$(T_T - Ts) = \Delta T = \frac{1}{CP}\,(H_T - H_S) \text{ ....} (3.5)$$

The Eq.3.5 resembles with the famous equation of straight line y = mx + c. where c =0
Where ΔT/ΔH = 1/CP the slope of the straight line

Thus a hot stream which undergoes a temperature change from T_S to T_T and having a constant heat capacity flowrate as CP can be represented by a straight line in Temperature-enthalpy diagram given in Fig.3.10.

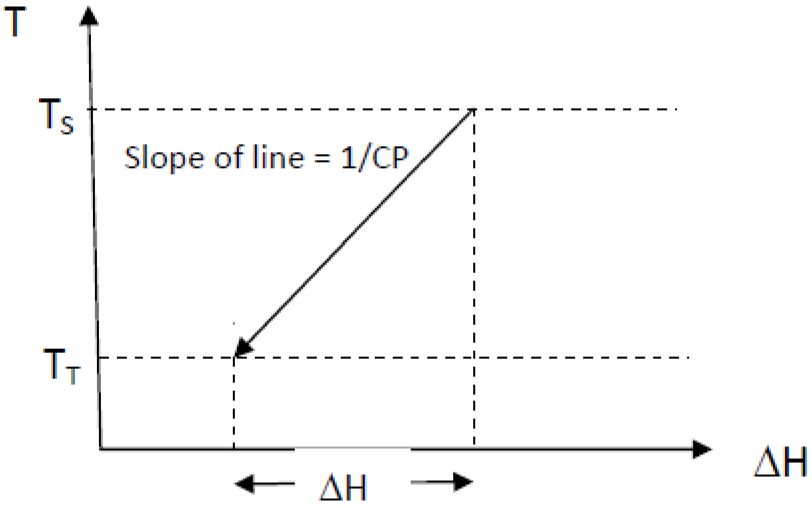


Figure 6.4 Representation of a hot stream in a T-H diagram

It should be noted that whereas, T is treated as an absolute quantity, ΔH is treated as a differential quantity. Due to the differential nature of ΔH it is not dependent on the reference temperature or in other terms any change in reference temperature to evaluate absolute values of H_T and H_S will not affect ΔH.

It will be seen later that the above concept is going to play a vital role in integration of heat loads.

Let's take a three Hot Stream Problem. Streams (Hot Stream-1, Hot Stream-2 and Hot Stream-3) operating under same temperature interval, T1 toT2 and having heat loads and CP values (within temperature interval of T1 to T2) as ΔH1 & CP1 , ΔH2 & CP2 and ΔH3 & CP3 respectively . Then,

$$(T_1 - T_2) = \Delta T = \frac{1}{CP1} \Delta H_1$$

$$(T_1 - T_2) = \Delta T = \frac{1}{CP2} \Delta H_2$$

$$(T_1 - T_2) = \Delta T = \frac{1}{CP3} \Delta H_3$$

By manipulating Eqs.3.6, 3.7 & 3.8 and adding one gets Eq.3.9,

$$(T_1 - T_2)\,(CP_1+CP_2+CP_3) = \Delta H_1 + \Delta H_2 + \Delta H_3$$

Or

$$\frac{\mathrm{T1-T2}}{\Delta\mathrm{H1} + \Delta\mathrm{H2} + \Delta\mathrm{H3}} = \frac{1}{CP1+CP2+CP3}$$

Thus slope of the composite line of all the three hot streams is

$$1/(CP1 + CP2 + CP3)$$

The above method can be generalized for n number of streams.

The Input Parameters for the Study

The following parameters are considered for the study of solar collectors as follows:

i. Solar Irradiance, *Iday* (kWh/m2/day)

ii. Total Count of sunny days in a year, *Ns*

iii. Solar collector tilt factor, *tf*

iv. Solar collector's efficiency, η

v. Atmospheric temperature, *Ta*

Thermal Energy Requirement Estimation

Heat demand of the process is estimated as per the following releationship, where, *qprocess*, as kJ/ton of product (MA Ramaswamy et al., 2012):

$$qprocess = P \times Cp \times (Tavg - Tin), \ (1)$$

Where *Cp* = the specific heat of water or air (kJ/kg/K) and *Tin* = the fluid inlet temperature.

Calculation of Collector Area

Since requirement of Hot Utility = 3258 KW (*qprocess)*

Cp for water = 4.18 KJ/Kg-K, *Tavg* = 250 ºC, *Tin* =25 ºC

Since Iday = 5.5 kWh/m2/day, Efficiency of solar collector = 0.3125 (Paraboloid Dish)

$Qc = Iday * \eta dish$

Annual Fuel Oil Savings

Annul fuel savings are estimated based on the amount of thermal energy (Qthermal in GJ) supplied by solar collectors as follows – [40]

Fuel oil savings (toe) = Qthermal / (kf× combustion),

Where ηcombustion is the combustion efficiency and kf is the fuel equivalent energy factor in GJ per ton (e.g., kf for fuel oil is 41.868 GJ).

(Considering ηcombustion = 0.15, total number of sunny days = 260, Qthermal = 3258 KW)

Carbon Savings

CO2 savings due to reduction of fuel oil use for process heating are estimated as follows (Carbon Trust, 2016):

Annual CO2 Savings (kgCO2) = Cf × Fuel oil savings (toe).

Here Cf is the fuel equivalent carbon dioxide emission factor in kg per ton of fuel [e.g., Cf for fuel oil is 3,232.7 kg of carbon dioxide [41]

Chapter 4

4.1 Sugar Industry Overview

A typical sugar production process involves sugar cane harvesting ,cane preparation ,juice extraction ,clarification ,filtration ,evaporation ,sugar boiling (crystallization), centrifugation and sugar drying . Figure 7 illustrates a simplified production process from sugar cane.

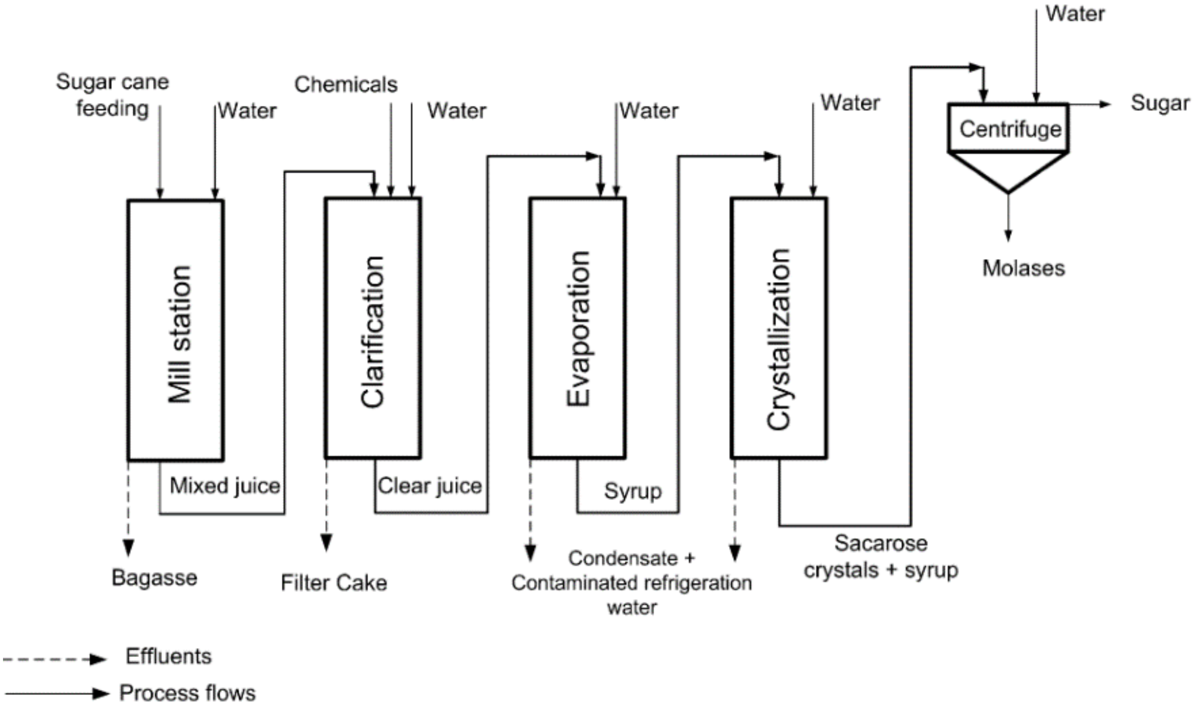


Figure 4.1 A simplified process of sugar production from sugar cane [20]

A brief description of a typical sugar process is made as follows:

4.1.1 Harvesting: Harvesting of sugar cane can be done either manually or mechanically . Sometimes , burning of sugar cane field is done before manual harvesting , in order to facilitate cutting the cane for field workers . Several countries (E.g. Cuba , Australia and Brazil) are shifting to green harvesting methods [21] as sugar cane field burning causes environmental pollution and loss of the cane straw which contains 30 % of the energy available in the sugar cane plant [22].

4.1.2 Cane preparation: The preparation of sugar cane is a very important step which affects the extraction of juice during milling. Since the sugar content of the sugar cane degrades , the cane needs to be delivered to the milling station in less than 24 hours after harvesting .Before the cane is transferred to the crushing section, it is usually washed to remove dirt that has been transported with the cane from the harvest field. Sugar cane plants use 32-316 litres of water per second and the waste water after the cane washing is either recycled or disposed [23].

4.1.3 Extraction: The next step is to chop up the washed cane in preparation for crushing. This step is skipped if the sugarcane was harvested by machines because it is usually the harvester that cuts the cane stalks into pieces. These chopped up cane stalks are then crushed and milled to extract the sugar juice. Bagasse is produced as a by-product which is usually sent to boilers for burning . [24].

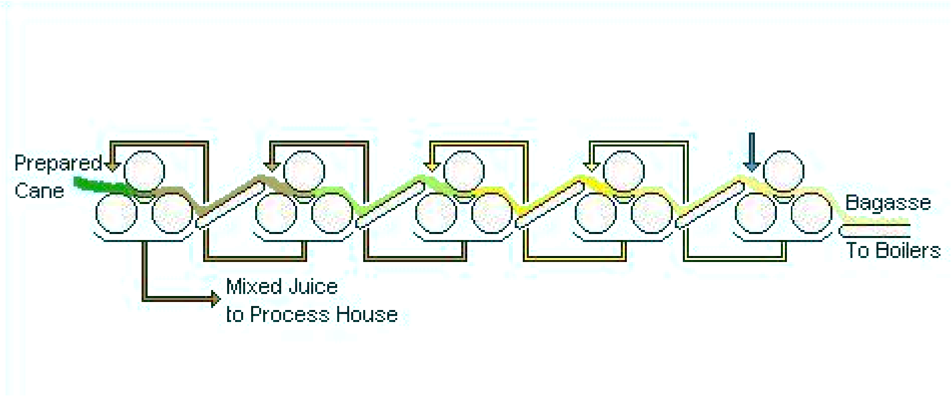


Figure 4.2 A simplified illustration of sugar extraction process [24]

4.1.4 Clarification : This involves separation of impurities from the juice by adding flocculants which will react with organic material and precipitation of non-sugar debris (mud) will follow . The clarification process gives clear juice to be sent to the evaporation process and mud which juice will be filtered further .

4.1.5 Filtration : This involves the filtration of the mud from the clarification process in order to separate suspended matter and insoluble salts formed (fine bagasse is entrained with these) from the juice.

4.1.6 Evaporation : The clear juice obtained from the filtration and clarification process will be concentrated to form syrup called molasses by heating it with a low pressure steam in sets of vessels called multiple effect evaporators .The use of multiple effect evaporation is a common practice in sugar mills (typical numbers of effects is quadruple). As can be seen from the stream lines of the single evaporator vessel primarily exhaust steam (in case of the first vessel) or vapour from previous vessel is fed to a certain vessel .

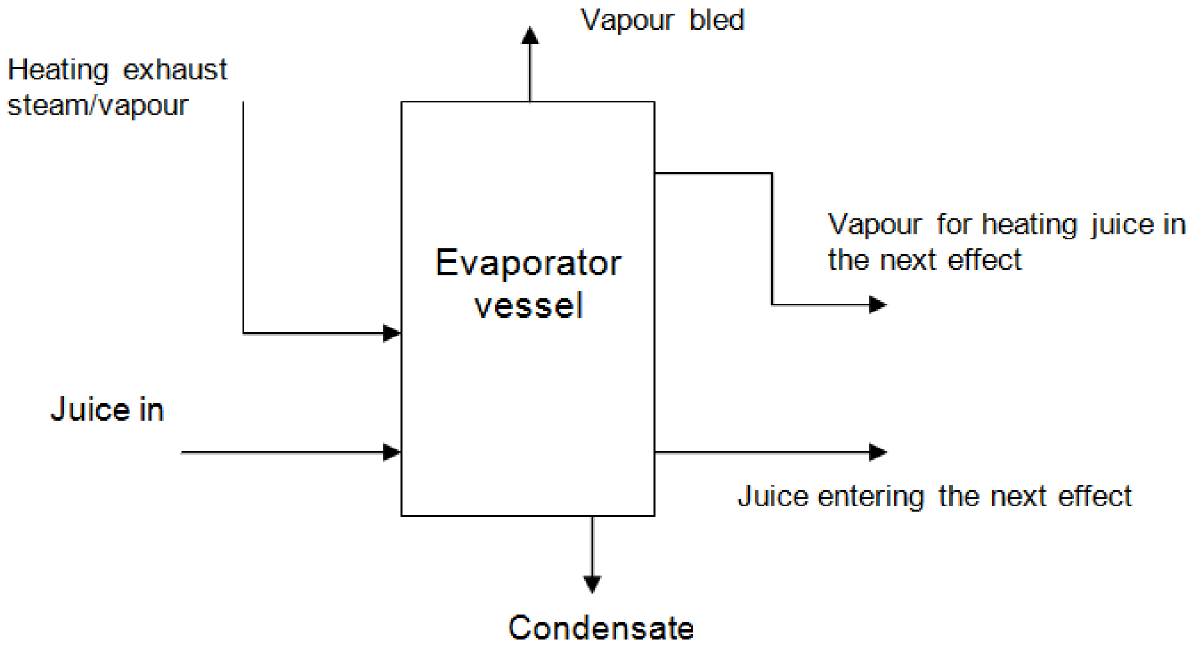


Figure 4.3 A single evaporator vessel

4.1.7 Crystallization (sugar boiling): This process involves formation of crystals from the syrup which usually takes place in simple effect vacuum pans.The steam for the sugar boiling is usually obtained from the vapour bled from multiple effect evaporators.

4.1.8 Centrifugation : This process separates the crystals from the molasses to get raw inedible sugar.Batch centrifuges are more common in traditional sugar mills but continuous centrifuges are also becoming widely used in newly built sugar mills .Usually in the conventional sugar mills , a set of centrifuges is driven by a system where hydraulic motors having adjustable pumps are driven by motors .

4.1.9 Drying: This is the last advance in the handling of crude sugar before it is packed. The drying procedure encourages appropriate capacity of the crude sugar and restrains smaller scale micro-organism development . Before drying , raw sugar has a water content ranging from 0.5-2% and after the drying process (by hot air) the water content can be decreased to 0.2 and 0.5%. Drying is done with air which is preheated with steam . The air should not be heated beyond 95°C-100 °C.

Chapter 5

5.1 Solar Energy for Process Heating

The problem with fossil fuel is not only that it is limited in nature but also the emission from it which produces Carbon-Di-oxide.CO_2 is one of the most important candidate responsible for Global Warming. It can be estimated that with the increasing concentration of CO_2 the earth can gets warmer by 1-5°C with the advent of the next century [25].The emission emanating from fossil fuels is also dangerous for human health as it causes the air pollution. So the need of hour is that we need to mainstream an energy resource which is not only abundant but also clean in nature. Solar energy has solution for both the concern.

The four commonly used CSP Technologies are parabolic trough collector (PTC), Linear Fresnel Reflector (LFR), Paraboloid Dish and Solar Power Tower (SPT) out of which the first two are belongs to line focus system and last two point focus systems. The PTCs are primarily used in industry since they are the most developed and cheap compared to other CSP Technologies [26]. However, its cost is still more expensive than that of the conventional fossil fuel power plants. Second most installed is SPT technology after PTC, and growing at faster rate among all CSPs technologies [27]. High efficiencies are obtained because the receiver operates at high temperatures and reduced losses. There is a lot of similarity between Linear Fresnel Reflectors and Parabolic Trough Collectors. The difference is the geometry of LFRs which is a long flat or slightly curved mirror placed for concentration of sunlight.

LFR has lower efficiency than other CSP Technologies. The concentration ratio in LFR is significantly lower than that of PTCs. But simplicity of LFR means that they are easy and cheaper to manufacture makes them advantageous over others in certain conditions [28]. The Parabolic Dish Reflector (PDR) or Dish Engine is a concave mirror, focuses the incoming sunlight onto a point receiver [29].Paraboloid Dish Systems give the highest efficiency among CSP Technologies.

5.2 Solar Thermal Technologies

There are four important Solar Thermal Technologies utilizing concentrated for generating energy used by industry. They are parabolic trough collectors, linear Fresnel reflector, power towers or central receiver systems, and dish/engine.

5.2.1 Parabolic Trough Collector (PTC)

PTCs is a proven technology used for process heating and other applications commercially around 90 % of the solar thermal power plants are based on parabolic trough systems. [CSP Today, 2013]

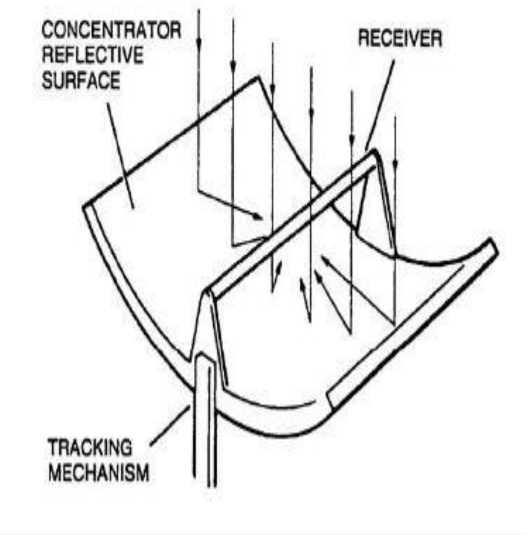


Figure 5.1 Parabolic trough system

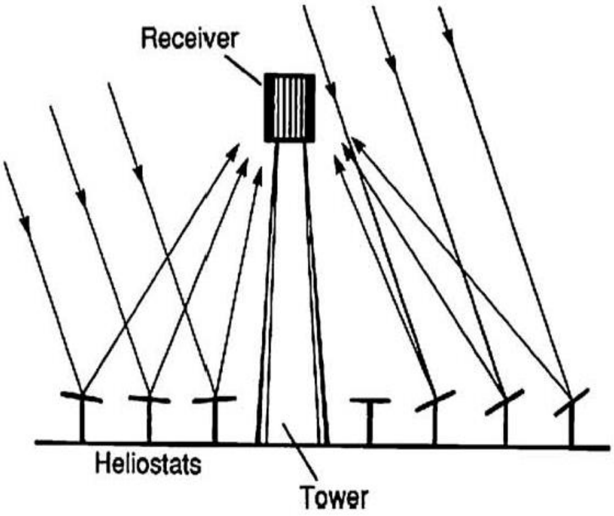


Figure 5.2 Central Receiver Tower System

The main components of PTCs are a parabolic reflecting plate, a transparent cover on reflecting plate and an observer, which passes heat energy to Heat transfer fluid (HTFs). The absorber is fixed permanently at the focus of the parabolic concentrator. The absorber tube is protected by the transparent cover from the heat losses. The Parabolic concentrator is settled on a fixed structure and the single-axis tracking mechanism follows the sun's trajectory. Every cross-section of a PTCs has a focal point. These focal point when joined makes a focal line (Fig.1). The solar Radiation that passes parallel to optical plane is reflected from the plate in such a way that it passes through the focal line

[30].PTC can concentrate direct sunlight to generate working temperatures up to400°C and achieve concentration ratios in the range of 30-100 [31].

5.2.2 Central receiver tower : The Solar power tower consists of a field of thousands of mirrors (heliostats) surrounding a tower which holds a heat transfer fluid to concentrate light on a central receiver atop a tower. An array of heliostats concentrate the sunlight onto a receiver settled at the top of a tower. Central Receiver tower is a point focus system. High efficiencies are obtained because the receiver operates at high temperatures and reduced losses. They provide better energy storage capability among CSP technologies. The individual inbuilt tracking mechanism keep the heliostat focused on tower and fluid is heated which runs a turbines. General concentration ratios ranges from 300 to 500 [32].

5.2.3 Linear Fresnel Reflector (LFR)

LFRs uses a long flat or nearly flat reflector and a receiver assemble which is fixed to some structure. The assembly may contain single linear receiver tube or multiple linear receiver tubes depending upon the size of the plant. The reflectors are placed at different angles to concentrate the incoming radiation on receiver tubes. Each line of reflectors has its own single-axis tracking system to concentrate the radiation correctly on the receiver. Due to its geometric properties the optical efficiency of LFR Field is always lower than that of PTCs Solar field. General concentration ratios is around 30 [33], which is low compared to other CSP technologies.

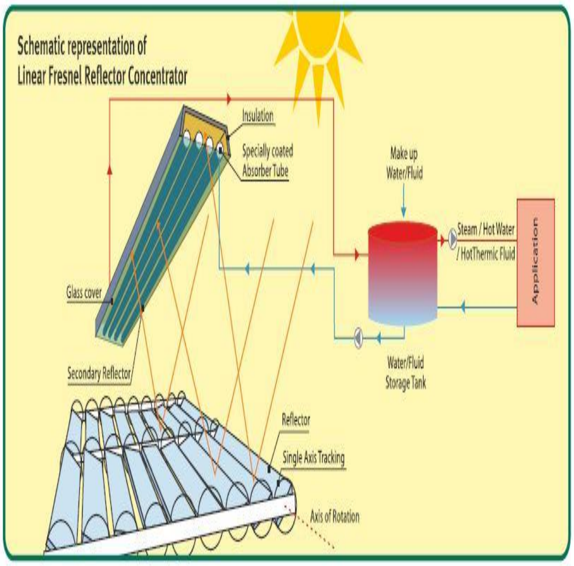


Figure 5.3 Schematic representation of Linear Parabolic Dish Reflector [9]

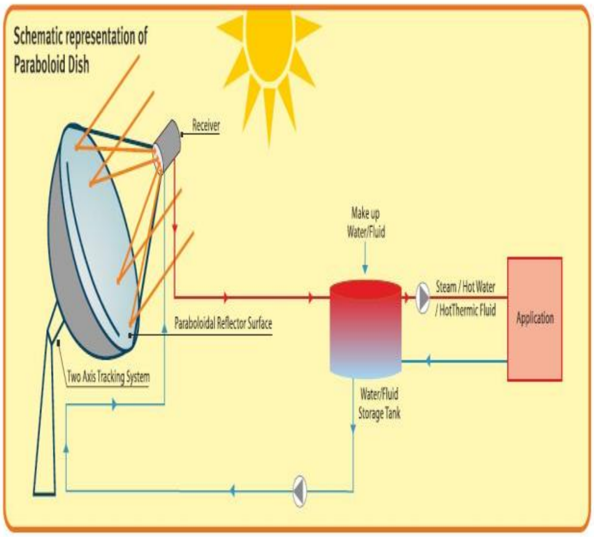


Figure 5.4 Schematic representation of Fresnel Reflector Concentrator [8].

5.2.4 The Parabolic Dish Reflector (PDR)

The four main units of PDR is concentrator , receiver, and Stirling engine and generator (Refer Fig.).The Stirling engine, receiver, and generator are enclosed in Power Conversion Unit (PCU). The concentrator (which is outside the PCU) focus the solar radiation into the cavity of the receiver. By concentrating the solar energy to actuate the Stirling engine the system produces the electricity. The Parabolic Dish Reflector system is integrated with the dual axis tracking system for tracking the solar radiation [34]. The advantage the system lies in the fact that the higher solar to electric efficiencies is achieved. As the ongoing research suggest the Dish Engine has the tremendous potential. The efficiency of 31.25% has been achieved with one PDR, which set the world record for the solar to electrical efficiency [35]. Since the PDR System uses 2-axis tracking mechanism, it capture the highest solar radiation among all CSP Technologies and optical efficiency can be as high as 94%. This lead to higher concentration ratio which is around 500 to 2000. The concern about using this technology is the high cost of mirrors. Some alternative method are being explored to use cheaper mirrors.

The PDR based Solar Industrial process heating system can be installed at automobile industrial plants with high DNI values to make automobile production more green and environment friendly. [36]

5.3 Heat transfer fluids (HTFs)

In CSP System the heat is collected from the receiver by a thermal energy carrier called heat transfer fluids (HTFs). The HTF can be taken directly to drive a turbine for production of power or, more often, be used in a heat exchanger to transfer its heat to an fluid known as the cycle fluid. Desired properties and characteristics of a HTF are: high boiling point, low melting point, and thermal stability, low vapor pressure (<1 atm) at high temperature, low viscosity, low corrosion with metal alloys used to contain the HTF.

The main HTFs based on type of material used are-[14]-(1) water/steam, (2) Organics, (3) molten-salts

5.3.1 Water or steam

The water or steam used as a Heat Transfer Fluid (HTF) of cycle removes the complexities from the system and enhance efficiency, with less cost of electricity production. It is used as both HTF and working fluid in the world’s largest CSP plant – the Ivanpah solar power facility. The principle issue with the water steam HTF is the shortage of water in desert area, and since for better Direct Normal Irradiance (DNI) throughout the year these CSP plants are mostly located in deserts, using water as a HTF poses serious challenges.

5.3.2 Organics

Organic materials are also used widely as HTFs in CSP systems. For example Therminol VP1 (Biphenyl/Diphenyloxide) is commonly used in commercial CSP systems. Biphenyl/Diphenyl oxide is a eutectic mixture of two very stable organic compounds; Biphenyl (C12H10) and Diphenyl oxide (C12H10O). The first solar thermal plant with this organic material as the HTF was commissioned in 2009 at Badajoz, Spain and was named as 'Alvarado 1'.

5.3.3 Molten-salts

The most widely used HTF is the Molten Salt. They possess excellent properties like high working temperature (more than 500°C) and heat capacity, low vapor pressure and corrosive property, and good thermal and physical properties at elevated temperatures, which are quite desirable for any HTF [15]. Currently the most common molten salt HTF and thermal energy storage media are a mixture of 60% $NaNO_3$ and 40% KNO_3.The first molten-salt as a HTF based power tower systems launched in 1984. They were THEMIS tower (2.5 MW) in France and Molten-salt Electric Experiment (1 MW) in the United States [37].

The main disadvantage of this salt mixture is the high melting point. The salt can freeze and block the pipeline during winter nights. In order to overcome this problem, auxiliary facilities need to be installed, which could increase the investment and operational costs.

5.4 Solar Collectors for Process Heating

Solar collectors can be mainly classified as Low Temp. Collectors (LTC), Medium Temp. Collector (MTCs) & High-Temp. Collectors (HTCs) with operating temperatures of less than 80°C, from 80°C–250°C, and greater than 250°C, respectively. The operating temperature decides the selection of the solar collector. Majority of the industrial operation needs thermal heating at temp. in the range of 40°C to 250°C. High-Temp. Collectors can produce heat up to 400°C.Dish collectors are considered among other

HTC technologies for processes that can generate temperatures greater than 150ºC. working fluids in these collectors. Dish collectors require high capital investment compared with FPCs and ETCs, but they can generate higher temperatures. The approximate plant life for an Flat Plate Collector, an Evacuated Tube Collector and a Dish Collector are around 20, 15 and 25 years, respectively.

Solar Collector Area Requirements for a Specific Process

The estimation of solar collector area is based on the requirement of thermal energy in an industrial process. The steps considered to estimate the collector area are shown in the following flowchart in Fig. 5.5.

Flowchart

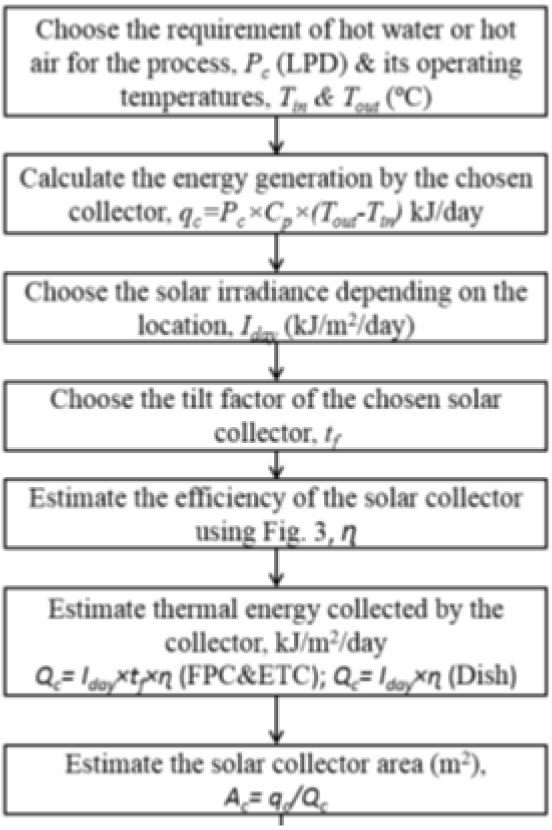


Figure 5.5 Solar Collector Area Requirements Flowchart for Process Heating

Solar Collectors Efficiency

The change of the thermal efficiencies of Flat Plate Collector, an Evacuated Tube Collector and a Dish Solar Collector with the operating temp. Of the working fluid is shown below in figure where *Top*= operating temperature and *Ta*=ambient temperature, respectively.

From the graph we can infer that the increase in temp. results in more heat losses and, hence, a loss in efficiency.Variation of a solar collector’s efficiency with process operating temperatures is shown in the figure below :

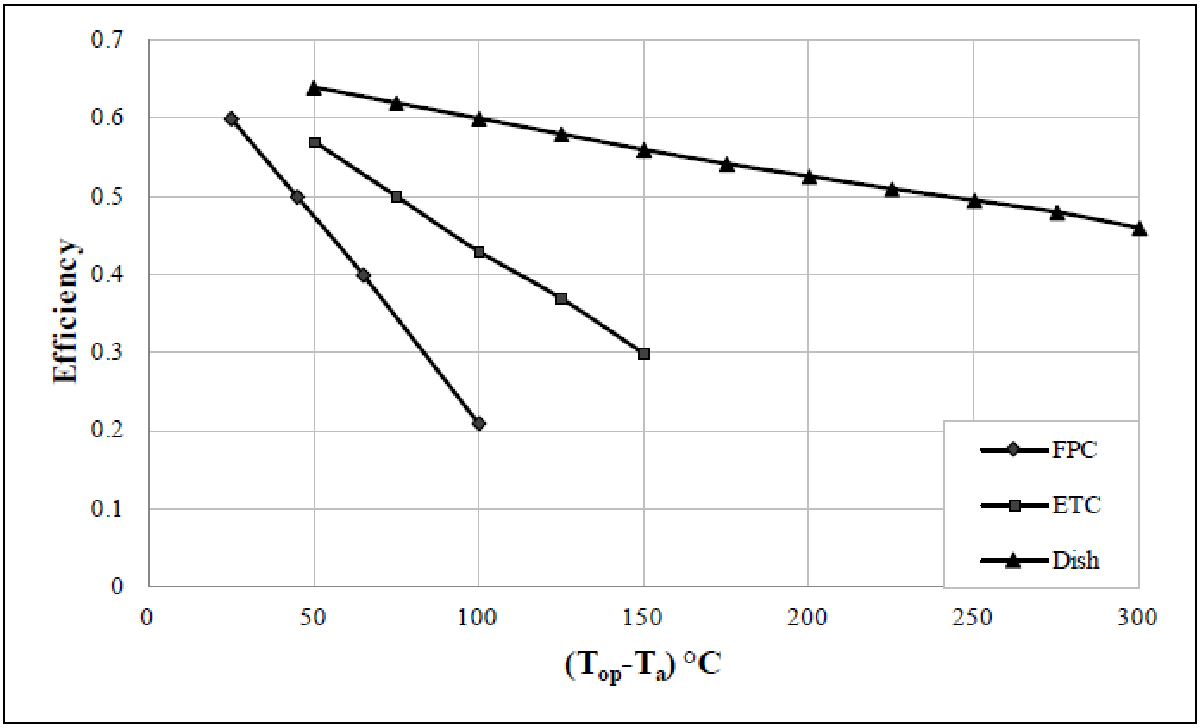


Figure 5.6 Variation of a solar collector's efficiency with process operating temperatures.

Assumptions

The assumptions for the solar collector use are as follows:

1. Direct Normal Irradiation (DNI) & Global Horizontal Irradiation (GHI) for India vary is taken as an average value of 5.5 kWh/m2/day. (NREL, 2015. India Solar Resource Maps & Data.)

2. Total count of sunny days (*Ns*) in a year is taken as 260. [38]

3. The tilt factor (*tf*) of both FPCs and ETCs is taken as 1.1

4. It is assumed that the thermal energy requirement of the industry are mostly met with fuel oil compared with coal and electricity. [39]

5. The capital costs of FPCs, ETCs and Dish collectors are considered as 178, 163 and 331, respectively (In US $/m2)

Chapter 6

Results and Discussions

Composite Curve

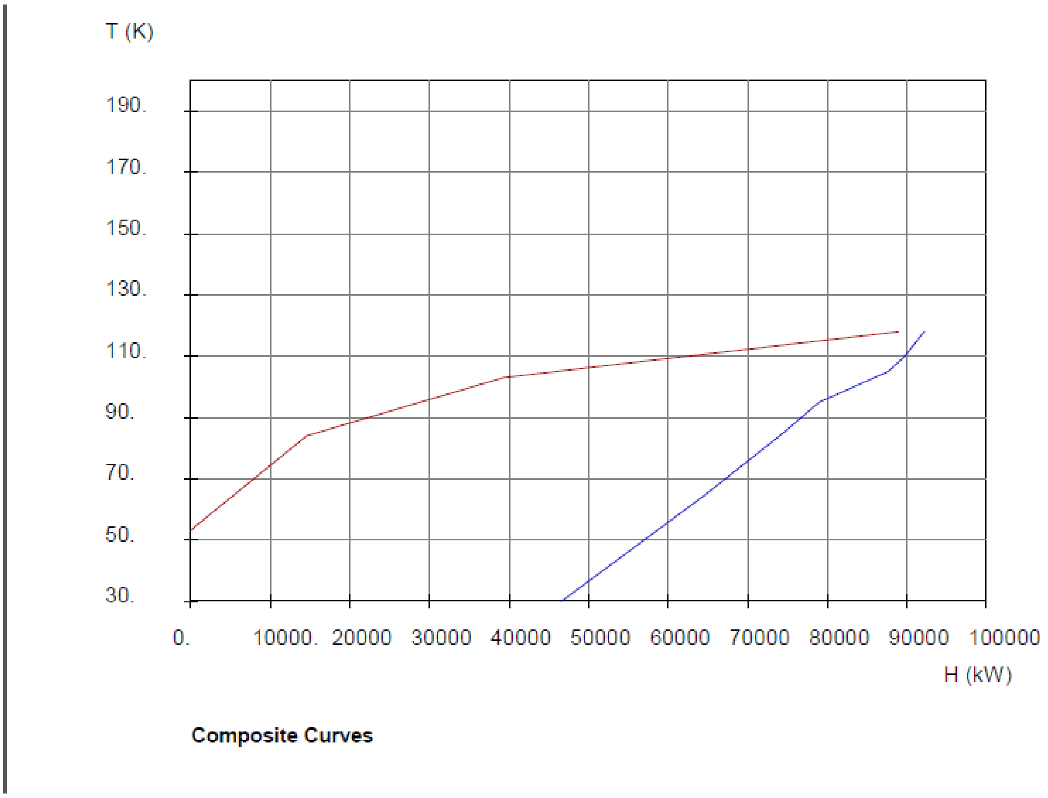


Figure 7.1 Composite curves (CC) for the process streams

The part of the hot streams CC that goes beyond the cold streams composite curve cannot be cooled by heat recovery.Therefore the minimum cold utility requirement was found to be 46594 kW. The part of the cold streams composite curve that goes beyond the hot streams composite curve cannot be heated by heat recovery. Therefore the minimum hot utility requirement was found to be 3258 kW. The point where the two curves are closest is the pinch point and the corresponding temperature is the pinch temperature. In our case, the pinch temperature was found to be 113 ºC.

Also it is established that the hot pinch temperature to be 118°C and the cold pinch temp. to be 108 ° C. The min. hot utility requirement, min. cold utility requirement and the pinch point temp. were calculated as 3258 kW, 46594 kW and 113 ˚C, respectively.

With ΔTmin = 10˚C, where there is an overlapping of the Hot composite curve and the cold composite curve, shows a possibility of process to process heat exchange. We predict the minimum energy requirements as 3258 kW and 46594 kW for the heating and cooling utilities respectively. The region of overlap indicates that the maximum energy recovery of 42316.6 kW that can be recovered in the process. This presents a potential reduction of 62.9% in the utility requirements as shown in Table below:

Utility	Current (kW)	Minimum (kW)	MER (kW)	% Recovery
Heating	45574.6	3258	42316.6	
Cooling	88910.6	46594	42316.6	
Total	134485.2	49852	84633.2	62.9 %

Grand Composite Curve

The Grand Composite curve in Figure plotted using net heat flow (utility requirement) and shifted temperatures shows a sharp pinch at 113˚C.This is the pinch temperature at which enthalpy is zero.It also gives the same results for the minimum utility requirements as the composite curves.

The values of net heat flow at the top and bottom end are the heat supplied to and removed from the cascade, and thus tell us the hot and cold utility targets. But not only does the GCC tell us how much net heating and cooling is required, it also tells us what temperatures it is needed at. There is no need to supply all the utility heating at the highest temperature interval; much of it can, if desired, be supplied at lower temperatures. The pinch is also easily visualised, being the point where net heat flow is 0 and the GCC touches the axis.

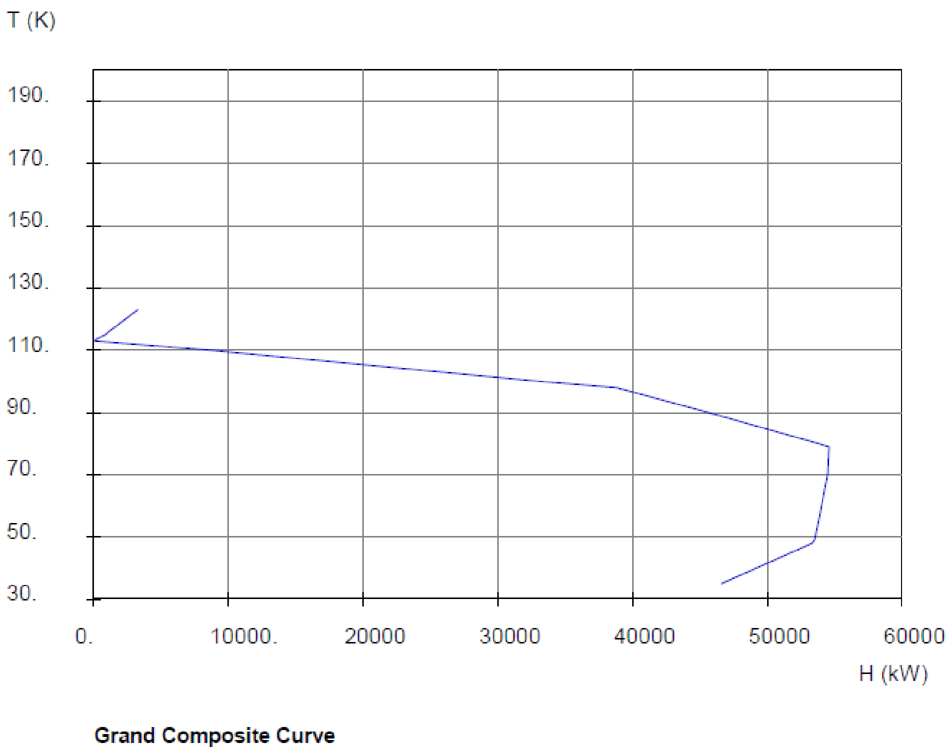


Figure 7.2 Grand composite curve (GCC).

Grid representation of Heat Exchanger Network

The grid is used to represent heat exchange network more conveniently. The important drawing rules of the grid representations are:

1. Hot streams (which require cooling) are drawn at the top showing left to right.
2. Cold streams (which require heating) are drawn at the bottom running from right to left.
3. A heat exchanger is represented by a vertical line joining two blank circles on the streams being matched. The heat exchanger load is conveniently written under the lower baling circle.
4. Heaters (H) and Coolers (C) can be represented in a circle inside written H or C on the stream being heated or cooled.
5. Temperatures are put on the grid as shown to allow easy check on the terminal approach temperature of each unit.

6. Hot streams are grouped together at the top and run left to right from their supply to target temperatures. Cold streams beneath run counter-current.
7. Pinch division is represented in the diagram by dividing the stream data at the appropriate temperatures, remembering to separate hot and cold streams by ΔTmin

The Grid representation for the given problem, which includes six hot (H1 to H6) and five cold (C1 to C5) streams are shown in Fig.

Grid representation of HEN

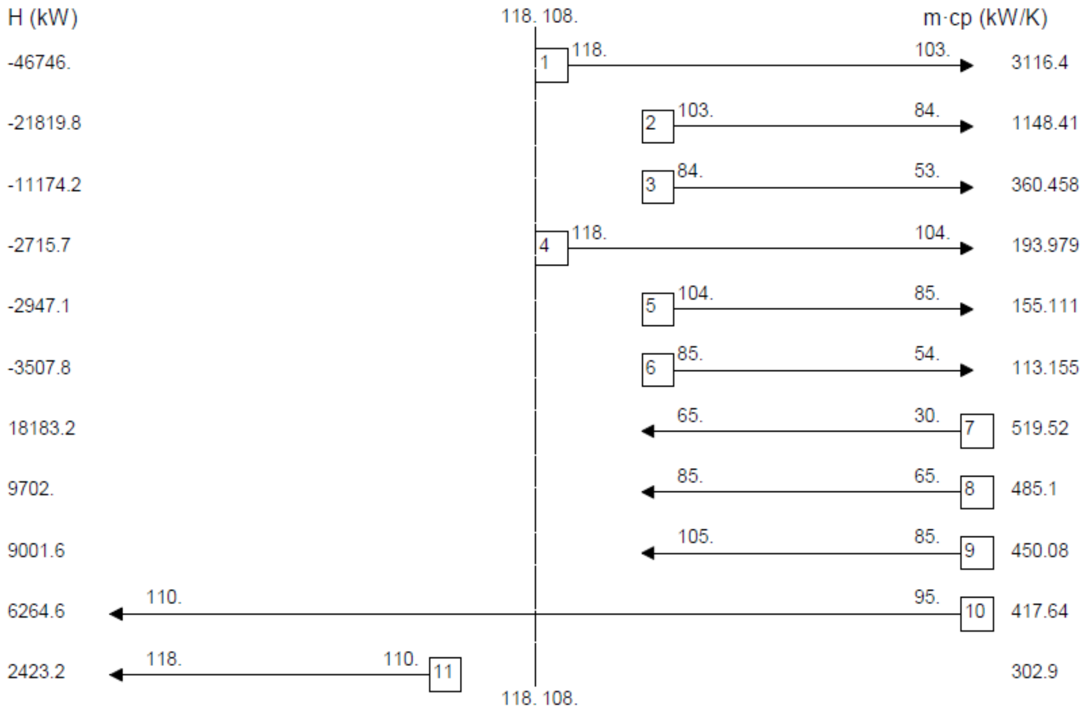
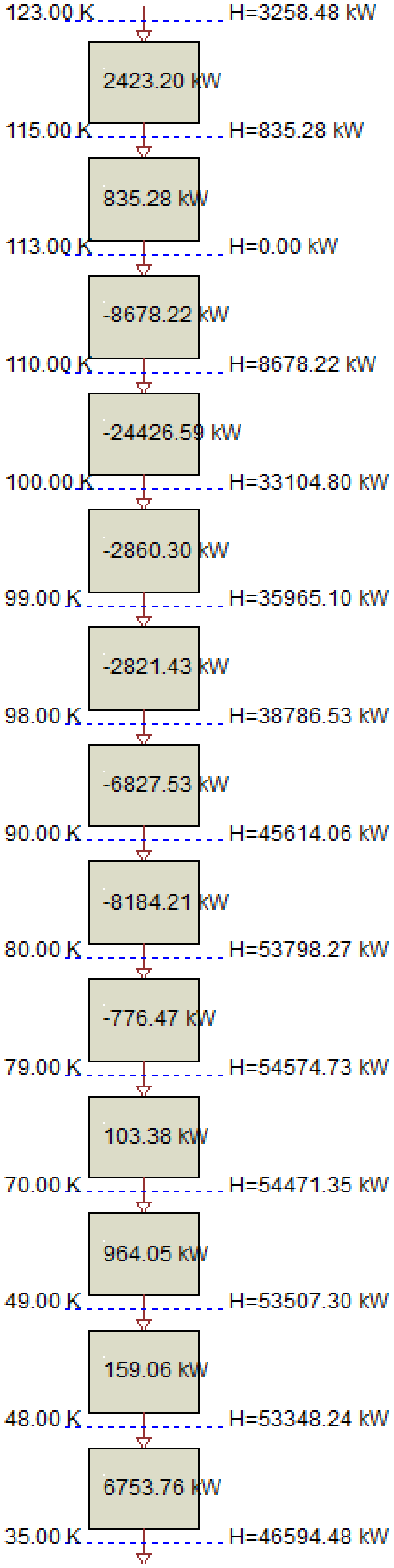
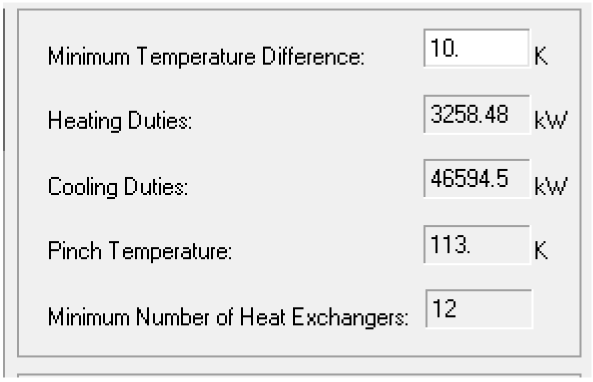


Figure 7.3 Grid representation of HEN

Cascade Diagram





Minimum Temperature Difference: 10. K

Heating Duties: 3258.48 kW

Cooling Duties: 46594.5 kW

Pinch Temperature: 113. K

Minimum Number of Heat Exchangers: 12

Minimum Number of Heat Exchanger

The fixed cost of a heat exchanger network (HEN) depends upon the number of heat exchanger it employs. Thus, there exists a possibility that a HEN with minimum no. of heat exchanger will cost less. Thus there exists a strong incentive to reduce the number of heat exchangers (matches between hot and cold streams) in a HEN. The first step required for this process for its initiation is to identify the number of heat exchangers a HEN will require from the number of Hot, Cold and Utility streams it handles.

$u_{\min} = N - 1$

Where $u_{\min}$ = minimum number of units (including heaters and coolers) and
N = total number of streams (including utilities).

In this case, Total streams are 11 and there are one hot utility and one cold utility,

which gives N = 13, therefore, $u_{\min} = N - 1 = 13 - 1 = 12$

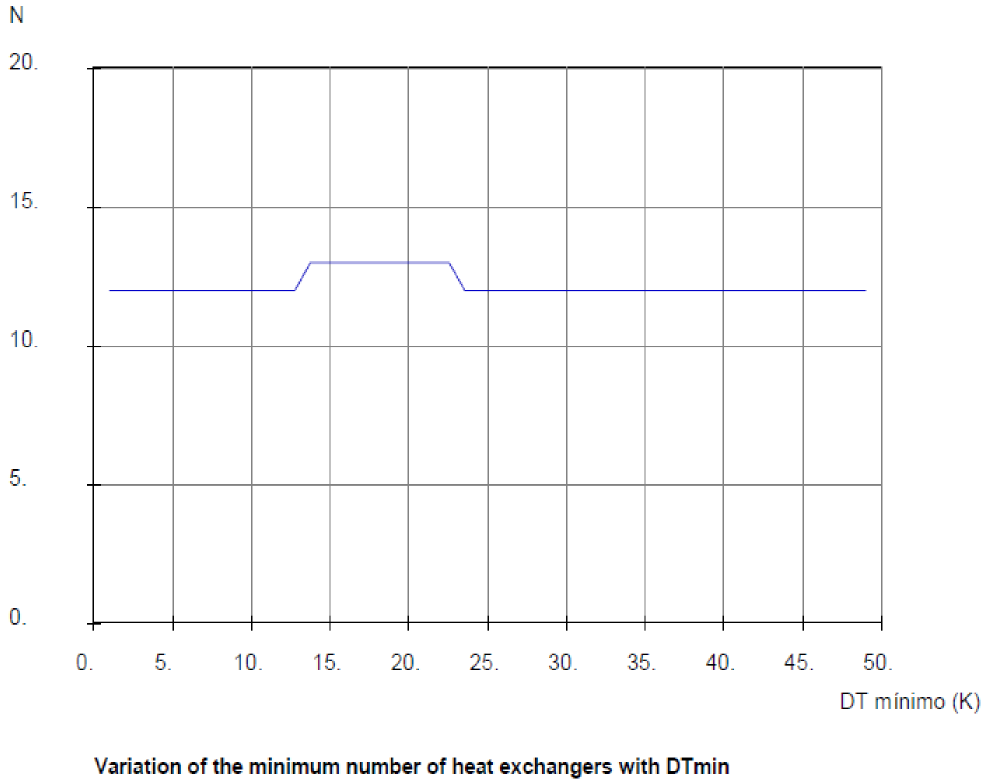
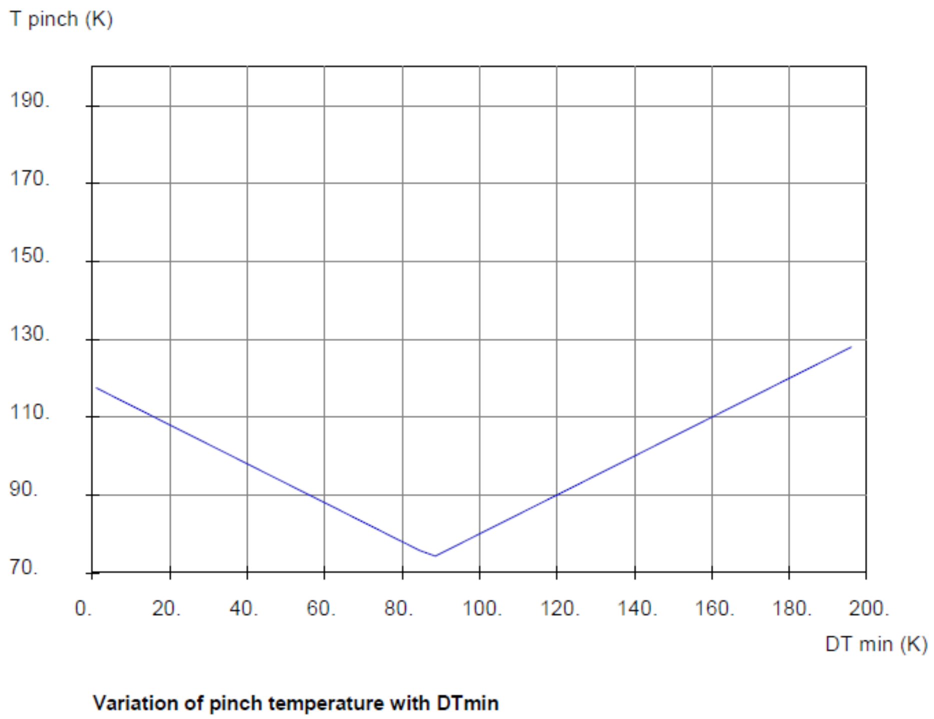


Figure 7.4 Variation of minimum number of Heat Exchanger with DTmin

Variation of Pinch Temperature with DT_{min}

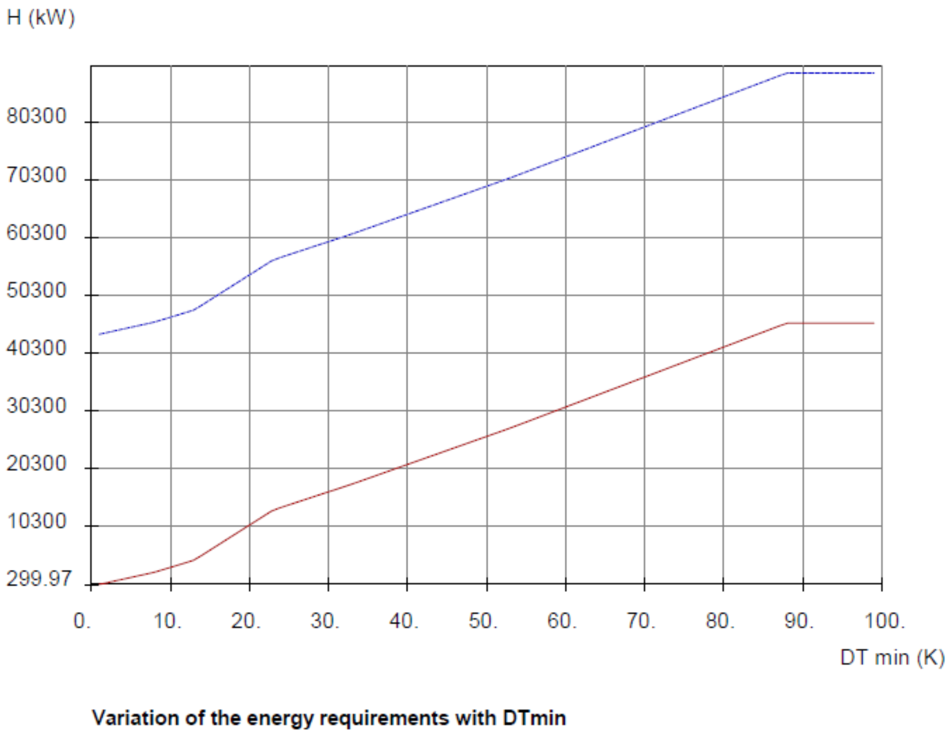
The temp. difference of 0°C is not practically possible because at this situation the net heat transfer will be zero and infinite surface is required for achieving this heat transfer. For a feasible solution the temp. difference is kept as 10°C (i.e. ΔTmin). After keeping the ΔTmin 10°C the Hot pinch is found at 118 °C and the Cold pinch is at 108 °C and the minimum Hot and Cold utility are at 3258 KW and 46594 KW respectively.



Variation of pinch temperature with DTmin

Figure 7.5 Variation of Pinch Temperature with DTmin

A plot of energy targets versus ΔTmin in figure shows that the possible range for the minimum temp. difference is from 0 < ΔTmin < 89˚C.

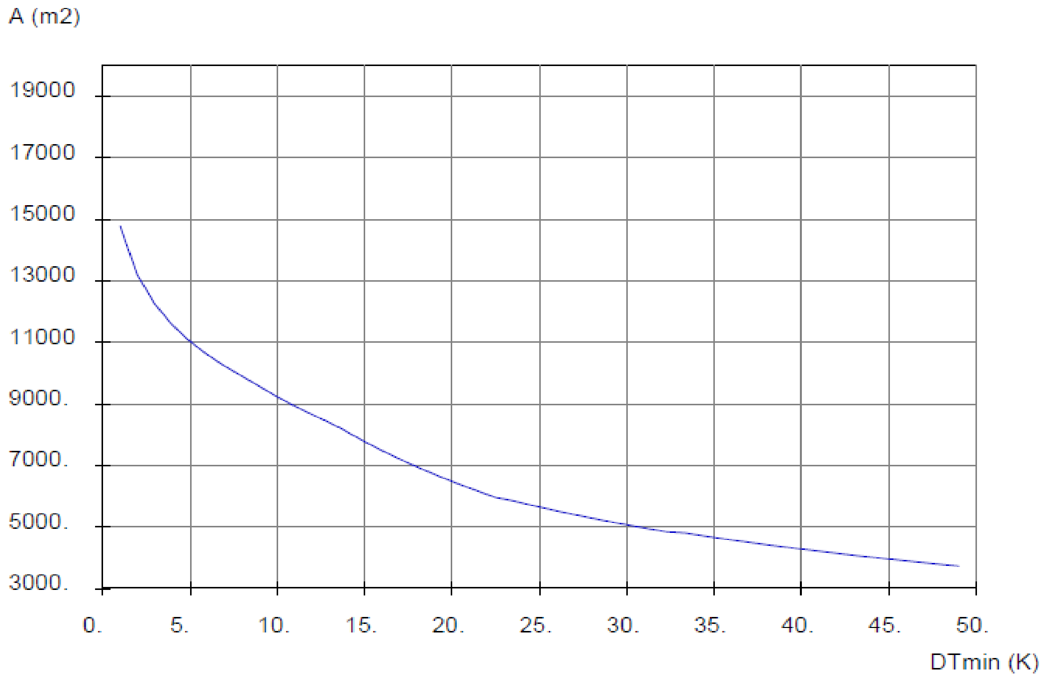


Variation of the energy requirements with DTmin

Figure 7.6 Variation of the energy requirements with DTmin

Minimum Exchanger Area with DT_{min}

Variation of Minimum Exchanger Area with DTmin shows that as ΔTmin increases, there is a reduction in the heat transferred within the system which requires a lower heat transfer area and therefore leading to a decrease in capital costs (if c < 1 in the cost equation Cost = a + bAc) as shown in Figure . Similarly, an increase in ΔTmin results in an increase in energy costs since there is greater external energy demand which manifest in an increase in the requirement for the additional heat transfer utilities.



Variation of the minumum exchanger area with DTmin

Figure 7.7 Variation of Minimum Exchanger Area with DTmin
]

Capital Cost Targeting for similar material of construction

The capital cost of a heat exchanger depends primarily on its material of construction, pressure rating and the type of exchanger itself. Variation of Capital Cost with DTmin suggest that as the DTmin increases there is reduction in Capital cost of the project. The capital cost decreases since there is decrease in minimum heat exchanger area with DTmin, implies that capital cost will also get reduced.

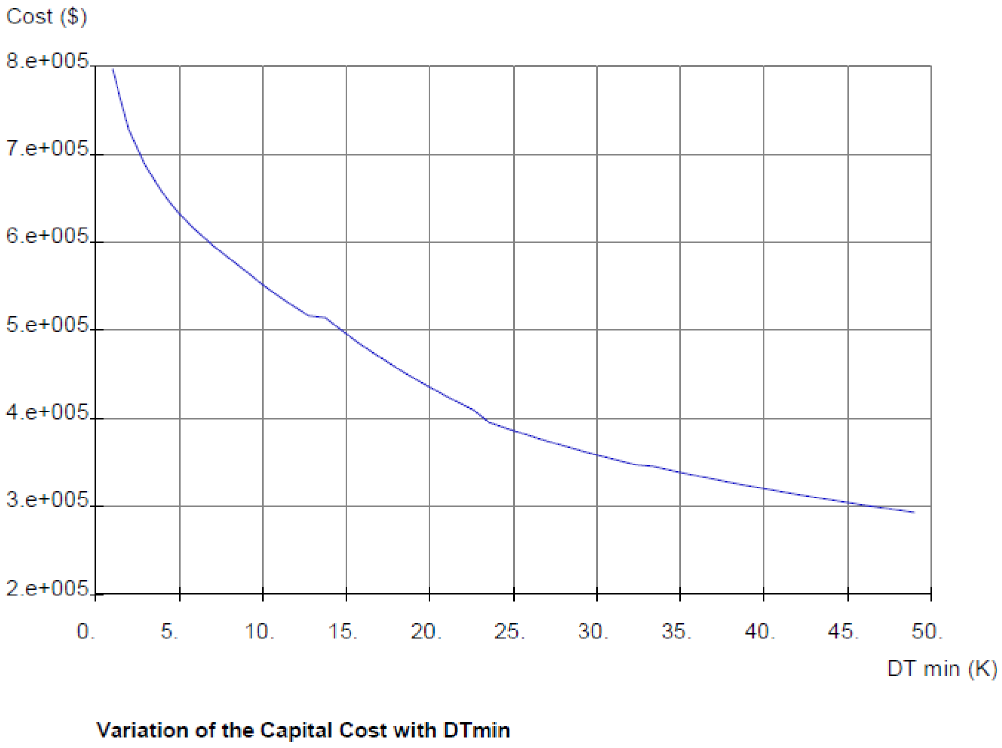


Figure 7.8 Variation of Capital Cost with DTmin

Operating cost targeting

Operating cost consists of the hot and cold utility cost.

For the present problem hot and cold utility are found as 3258 kW and 46594 kW, respectively.

The utility costs are:

Steam cost = 120 ($.kW-1.y-1)

Cooling water cost = 10 ($.kW-1.y-1)

Hot utility cost = 3258 * 120 = 3, 90,960 $.yr-1

Similarly,

Cold utility cost = 46594 * 10 = 4, 65,940 $.yr-1

Total Operating Cost = 390960 + 465940 = 8, 56,900 \$.yr-1

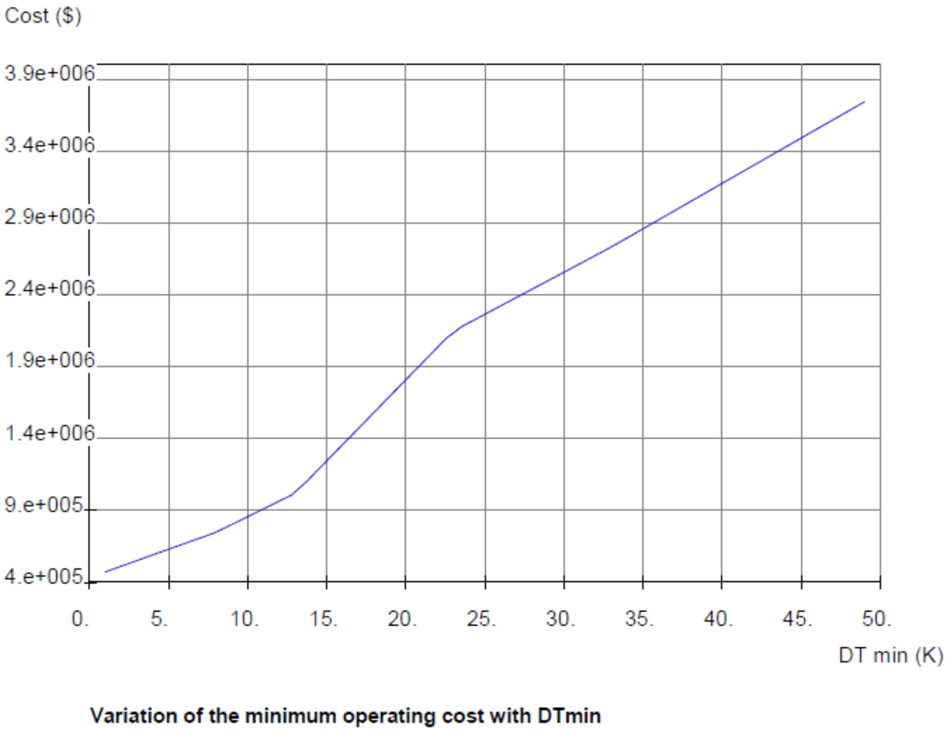


Figure 7.9 Variation of the Minimum Operating Cost with DTmin

Total Cost Targeting:

The cost targeting is divided into two parts: -

a) Capital cost Targeting and

b) Operating cost targeting.

With change in driving force or ΔTmin, these two costs vary opposite to each other. For example, with increase in ΔTmin, the utility costs increase as the utility consumption increases. However, capital cost decreases as the area of the heat exchanger network reduces with increase in driving force. Thus, it is better to consider both the costs during targeting a heat exchanger network and for further determination of optimum ΔTmin using Super-targeting.

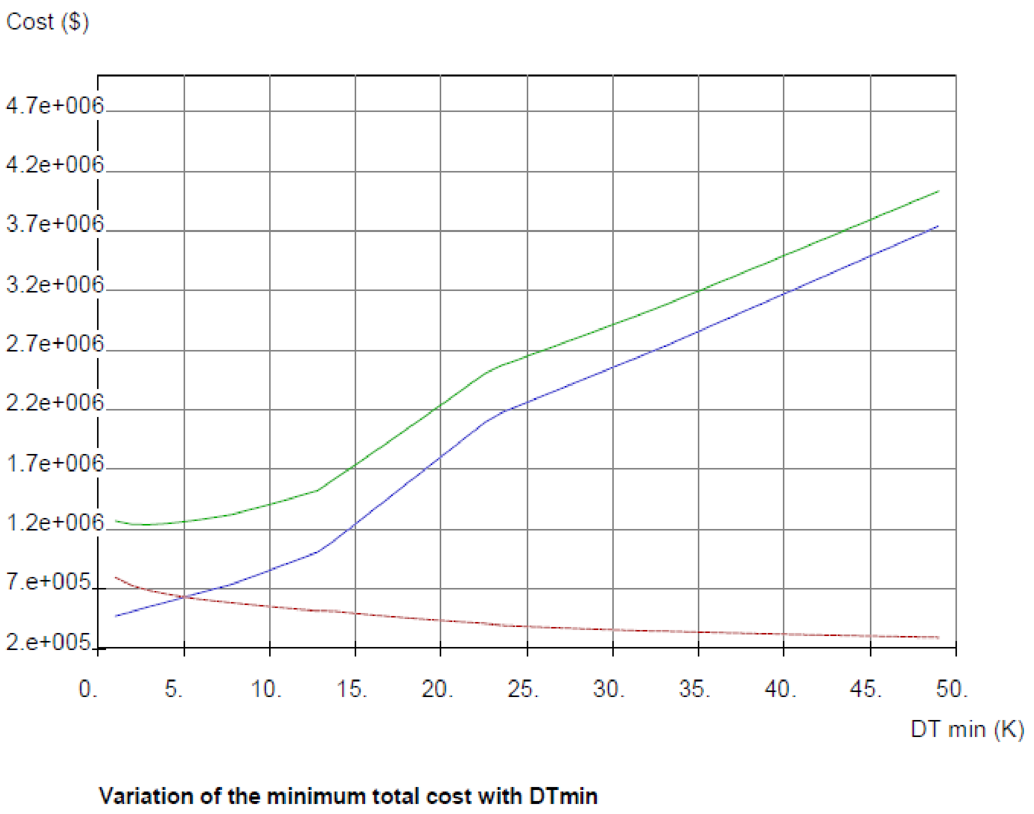


Figure 7.10 Variation of the Minimum Total Cost with DTmin

Estimation of Collector Area

Since requirement of Hot Utility = 3258 KW (*qprocess)*

Cp for water = 4.18 KJ/Kg-K, *Tavg* = 250 ºC, *Tin* =25 ºC

We get P = 3.46 kg/s

Since Iday = 5.5 kWh/m2/day, Efficiency of solar collector = 0.3125 (Paraboloid Dish)

Qc = Iday * ηdish = 5.5 *0.3125 = 1.718 kWh/m2/day

Hence the collector Area (Ac)

Ac = qc/Qc = 11378 m2

Total Capital Cost of the Project

Since the capital costs (in US $/m2) of Flat Plate Collector, Evacuated Tube Collector and Dish collectors are 178, 163 and 331, respectively.

Hence Total Capital Cost of the Project = US $ 11378 *331 = *US $ 37, 66,118*

Annual Fuel Oil Savings

Fuel oil savings (toe) = Qthermal / (kf× combustion), Annual Fuel Oil Savings

Fuel oil savings (toe) = 437 toe

(Considering ηcombustion = 0.15, total number of sunny days = 260, Qthermal = 3258 KW)

Carbon Savings

Annual CO2 Savings (kgCO2) = Cf × Fuel oil savings (toe).

*Annual CO2 Savings (kg CO2) = 3232.7*437 = 1412.7 kt*

Chapter 7

Conclusion

1. The minimum hot utility requirement, minimum cold utility requirement and the pinch point temperature were found to be 3258 kW, 46594 kW and 113 ˚C, respectively from both the temperature interval diagram, cascade diagram and composite curve diagram.

2. For a maximum energy recovery, the overlapped region indicates a total of 42316.6 kW of energy possibly can be recovered in the process. This shows a potential reduction of 62.9% in the utility requirement.

3. Refer graph Variation of min. number of Heat Exchanger with DTmin, The minimum no. of heat exchanger was found to be 12.

4. For getting the feasible solution the temp. difference is kept at 10°C, Pinch temperature was found to be 113 °C, Hot pinch is achieved at 118 °C and the Cold pinch is at 108 °C.

5. The Variation of energy targets vs ΔTmin shows that the possible range for the minimum temp. difference is from 0 to 89˚C.

6. As ΔTmin increases, there is a reduction in the heat transferred within the system which requires a lower heat transfer area and therefore resulting to a decrease in capital costs.

7. With change in driving force or ΔTmin, these two costs (Capital cost Targeting and Operating cost targeting (vary opposite to each other. For example, with increase in ΔTmin, the utility costs increase as the utility consumption increases. However, capital cost decreases as the area of the heat exchanger network reduces with increase in

driving force. Thus, it is better to consider both the costs during targeting a heat exchanger network and for further determination of optimum ΔTmin.

8. The total collector area was found to be 11378 m2 considering Paraboloid Dish Collector
9. The estimation of Annual fuel savings based on the amount of thermal energy (Qthermal in GJ) supplied by solar collectors is found to be 437 toe.
10. Annual CO2 Savings (in kg) was found to be 1412.7 kt.

Future scope

1. The same analysis can be extended to other industries aggressively and before commencement of any project the pinch analysis (Heat Integration) and Solar Heat Integration can be studied to make the project more energy efficient.

2. The Heat Exchange Network (HEN) can be designed based on the finding of the thesis, for minimising energy consumption of a heat network.

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