MINIMIZING COMPRESSION WORK IN A MULTI-PRESSURE LEVEL HEAT SUPPLY NETWORK

A B.Tech Project Report

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by

Abhijeet Singh

under the guidance of

Dr. Nitin Dutt Chaturvedi

to the

Department ofChemistry

INDIAN INSTITUTE OF TECHNOLOGY PATNA

May, 2017

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Certificate

This is to certify that the work contained in this thesis entitled "Minimizing compression work in multi-pressure level heat supply network" is a bonafide research work of Abhijeet Singh (1301CH01), carried out in the Department of Chemical and Biochemical Engineering, Indian Institute of Technology Patna, under my supervision and that it has not been submitted elsewhere for a degree.

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Declaration

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This is to certify that Abhijeet Singh

1. has sincerely worked on their project,
2. has contacted me regularly to update on the progress of the assigned project,
3. has received my comments on the preliminary version of the report and presentation and will address those prior to final submission/presentation,
4. may be allowed to present/defend the project before the department.

Remarks (if any):

Name of the Project Guide   Signature of the Project Guide

Dr. Nitin Dutt Chaturvedi

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Abstract

In a process industry, one of the efficient ways of becoming cost competitive is to employ the most efficient techniques and methodologies to utilize the available energy. One such area of energy targeting is compression work in heat supply networks. (HSNs). This paper deals in the most rigorous and robust algebraic methodology which takes into consideration pressures of the available steam streams, their temperatures and flow rates and use the previously derived methodologies of breaking multiple pressure systems into various subproblems and solving each set of two pressure level subproblem at a time. The overall cross flows between all the pressure levels determine the compression work required. In addition to that, an alternative graphical methodology is proposed having its basis on the pinch analysis and Problem Table Algorithm (PTA) to calculate the cross flows between the pressure levels. All of these methodologies and algorithms are supported with well defined illustrative examples for each case and further verified by GAMS analysis using CPLEX solver for the same.

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Acronyms

HU	≡	Hot Utility
CU	≡	Cold Utility
GCC	≡	Grand composite Curve
PTA	≡	Problem Table Algorithm
CCHP	≡	Combined cooling heat and Power
CHP	≡	Combined Heat and Power
HSN	≡	Heat Supply Network
HEN	≡	Heat Exchange Network

Notations

Fsi	≡	Flow rate of the i^{th} source(Sm^3)
Fdj	≡	Flow rate of the j^{th} demand(Sm^3)
σ_i	≡	isothermal pressure index of the i^{th} pressure level (kPa)
T	≡	Temperature (^oC)
Pi.	≡	Pressure level i (kPa)

Chapter 1

Introduction

1.1 Introduction

Running an industry always has everything to do with business and making profits, but this context of making profits has taken a center stage with companies becoming more and more responsible in their choice of resources, and their optimization, not just for enhancing profit shares but also caring for sustainability and saving the most for the generations to come , to make them realise their full potential. It is this urge for saving capitals and resources that industries are spending more and more on their RnD sector, to look for new methodologies of optimising these resources. And one such area that we are targeting by our work in this report is compression work or shaft-works in industries. Let’s briefly revisit the basic concepts

1.2 Energy Targeting

Simplistically speaking, Energy targeting is the process of optimizing energy supplied to the system in the form of hot utility or cold utility while satisfying all the available demands with the supplied sources. In industrial terms it deals with removing heat from hot streams that are needed to be cooled to specific temperatures, and just for the record part use this extracted heat to raise the temperatures of the cold streams to specific temperatures so that they can be used elsewhere.

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1.3 Principle of Energy Targeting

The basic principle of energy targeting as already proposed in many specialized chemical engineering techniques like pinch analysis, Problem Table Algorithm and Modified Problem Table Algorithm is to find a pinch temperature and segregating our process streams into two zones one above the pinch and the other below the pinch and to minimize the heat supplied to the system from the external utilities, there should be no transfer from heat across the pinch

1.4 Shaft work

Shaft-work is basically the work done on a stream apart from its flow work. This in process plant terminology stands for the compression work done on the system It has some of the very unique properties which have been later explained in the depth but have been cleverly used in the context of the current problem to solve this problem.

1.5 Onion Diagram of Process Integration

To put this thing in perspective is to look for the procedure how various processes are integrated in the industry, at the core of the industry lies reactor systems which forms the crux of all that is happening in the industry. Once the reactor system has been designed, the compositions of the outlet streams from the reactors are known, and one has to proceed to the design of the separation system. This is followed by the design of the heat recovery systems which is finally wrapped around by the utility systems

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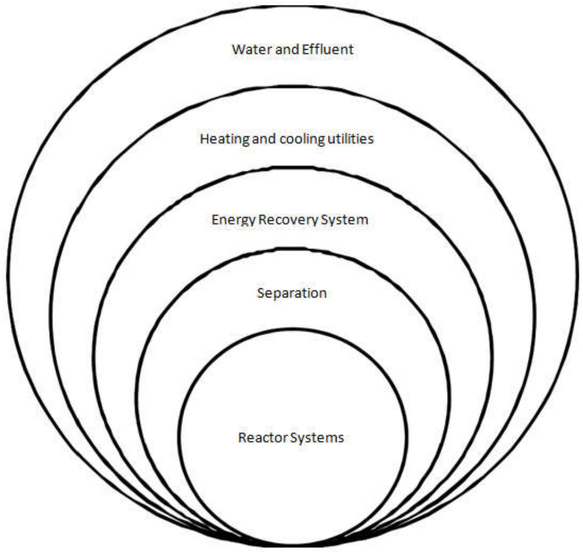
Fig 1.5.1 Onion diagram of process integration



1.6 Motivation

This compression work which involves multiple pressure levels has always intrigued chemical engineers and researchers to foray for the best optimizing solutions and methodologies for the reductions. Even a tiny bit of the reduction in the shaft-work will lead to the hefty savings for the industry as a whole. The whole world is looking to optimise energy expenditure as the energy is going to be expensive day by day and this means a lot to industries who are spending a good amount of their investment in energy expenditures in the compression work. The absence of any clear and coherent methodology for the optimization of the compression works in the process industries with multi-pressure level heat supply network have led to this problem.

1.7 Objective

Our main objective lies in the third layer of this onion model which is basically a form of energy conservation. The energy requirements and the capital costs are closely linked to each other, as energy costs form a significant portion of the total capital costs. Therefore, Our objective is to develop a concrete and robust methodology for minimizing compression-work in the multi pressure level heat supply networks. Though sounding trivial, this kind of work has till now not been reported in any of the journals or research publications dealing in this subject, which was the most prominent source of motivation for developing such an algorithm.

1.8 Past work

Energy requirements are increasing every day and there is an imminent need for the adoption of novel methods of energy conservation and optimization. Process industry plants being one of the core areas for the application of energy targeting [1]; require optimization techniques to cut the costs. In this regard, shaft work targeting has gained immense importance in the recent past with industries realizing its major role in cost depreciation and sustainable use of resources. Integration of the process plants is important in the energy targeting, which is evidenced by the decrease in a number of utility requirements resulting in the complex power and Heat Supply Networks (HSNs).

Compression work targeting takes the pressures of the streams involved into consideration, which forms an important alternative parameter to be further added in the process integration design[32].Lower cost designs have already been obtained by utilizing the temperature interval method to judiciously use the heat deficits supplemented by a nonlinear programming strategy for the same[8].A methodology has been developed for simultaneous optimization and heat integration of chemical processes based on non-linear optimization process involving a set of constraints with an aim to ensure minimum utility targets for the heat recovery networks [12]. Simultaneous optimization of the utility requirement and the shaft work is one key area which has been dealt in great detail in this paper and which has been left largely untouched, despite having wide range of potential applications. Pinch technology has been a successful methodology in the past for utility targeting. Additionally, the utilities targeted are independent of the network and thus, serve as a useful comparison parameter with the optimized network [11].Pinch location is considered detrimental to any integrated process design. A formulation which automatically accounts for their relocation in an integrated system has been developed which aims at selecting the best final design topology[13]. Previous analysis have been done on the

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compression works under various pressure ratios and evaporative rates, comparing the dry compression works with the wet compression works have shown a considerable advantage of the later over the former[37].

One potential area where the shaft work minimization could find its application is Combined Heat and Power (CHP) plants and Combined Cooling, Heat and Power (CCHP) Plants, which recover energy from the hot steam streams used in turbines present at elevated pressures. CHPs and CCHPs serve as a preferential thermal power producing units within a district network because of their high fuel efficiency [15].Various analysis has been done and methodologies been proposed in the past concerning the performance improvements of the CHPs and CCHPs. Heat and power networks in process design [9,10] have contributed significantly to the reducing costs and optimizing the power distribution for the Energy distribution especially in the small power supply networks which include District heating and cooling networks[17].

Moreover, cogeneration and waste utilization are targeted via process integration employing the concept of the extractable energy to facilitate cogeneration potential calculation in the steam systems ahead of power generation network designing [28]. Thermodynamic imperfections in the heat exchangers model of irreversible power plants have been analyzed earlier [23]. CHP model of integration of power and heat has been extended to Synthetic Natural Gas (SNG) production by thermal integration of SNG production cycle and steam power cycle [20]. In relation to that, conversion of the fluid power whether it is in the form of steam or in liquid to thermal optimization is detrimental for thermal power conversion in any thermal power plant [22]. Mathematical analysis of the effect of changing steam levels on the total steam flow rate for the various configurations is done in the case of hot liquid reuse [31]. Decreased fuel consumption and an improved thermal cycle performance was observed for the steam power plants employing Combined Pinch and Exergy Analysis (CPEA)[33].

Conversion of low-grade heat into power using Organic Rankine cycles(ORC) has made its way into various industrially profitable sectors where steam Rankine cycles are finding their application in the transformation of large-scale thermal energy into power[25]. For the distributed generation of power on a small scale, mini and micro turbines are ideal for CHPs [14].Enhancement of power generation and cooling capacity through utilization of waste heat have suggested towards a combined cooling and power scheme [35].The study of the Combined Heating and Power Plants have been extended to Combined power and cooling cycles for the possible improvements in their energy conversion efficiency and decreasing the cost of energy produced [34]. Early studies by Linnhoff and Dhole on the shaft work targets for the low temperature process design have categorically highlighted the impact of this work in the refrigeration industry [6].

CHPs and CCHPs are subsets to a large problem set of plants which are grouped under the category of total sites which incorporate several processes and are linked and serviced via central utility system [27]. An iterative bottom to top model (IBTM) has been proposed on the shaft work targeting of the total sites without the need for the simulation for steam turbine [27]. The procedures of the pinch technology are extended from the single processes to total sites [29]. In this regard, there is a contrast between, employing the optimization procedures for an individual process to a bigger application in the overall site optimization, by introducing the concept of heat savings [30]. Compressed air energy storage (CAES) has been used with CCHP to maximize the exergy efficiency while meeting the supply demands [36]. This paper deals in the minimization of the compression work that is required in the combined heat and power network having more than one pressure level. The paper is organized into various sub sections which deal with the methodology development and targeting algorithm, mathematical formulation and a series of illustrated examples.

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Chapter 2

Project Outline and Problem Statement

2.1 Project Outline

The project has been simplistically divided into following proper objectives which had to be achieved sequentially:

- Framing of a well researched problem statement and case study which encompasses all the possible scenarios which can possibly occur in the industrial process, so as to generalize our solution to the maximum level.
- A literature review to know about the current level of the work which has been done relevant to the problem.
- Development of mathematical formulation and algorithms for the problem.
- Validating the answers obtained with an algebraic software like GAMS.
- Draw the possible heat supply networks for the illustrated examples.

2.2 Problem Statement

- This paper deals with the development of a methodology for targeting shaft work utility for the multi-pressure level systems in intermediate fluid stream networks.
- There are a set S sources where each source i{1,2,...,S}. They have a fixed flow Fsi and are available at pressure Pi.

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- There are another set of D demands where each demand j{1,2,...,D}. They have a fixed flow Fdi and are available at pressure Pi.
- An external hot utility and cold utility is available which has to be supplied to meet the required demands.
- The primary target is to minimize the amount of external utility both hot and cold, required to satisfy all the demands at all the given pressures.

- In addition to that the methodology should be able to minimize the amount of compression work needed in the conversion of a fluid stream from low pressure to high pressure.
- It is also assumed that the entire work done in the conversion of a stream from one pressure level to another is done as a shaft work and no amount of heat from the fluid streams and external utility is used to do this compression work.
- As there is a direct mixing of the streams, an important assumption is that the streams are non-reactive and no amount of heat is released or consumed during the process of their mixing.
- The entire conversion of fluid streams from one pressure level to another is assumed to be done isothermally.

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Chapter 3

Development of Methodology

The methodology adopted in the paper utilizes assumption stated above , so without the loss of generality, the available streams, also referred as the source streams S{i=1,2,...,S} are considered to be present at given pressures P_{si}{i=1,2,...,S}and the corresponding demands D{j=1,2,...,D} available at pressure $P_{i.}$ The minimum amount of utility required in any HSN in obtained mathematically by the PTA algorithm [13] and graphically by heat recovery Pinch diagram or Grand Composite Curve (GCC).

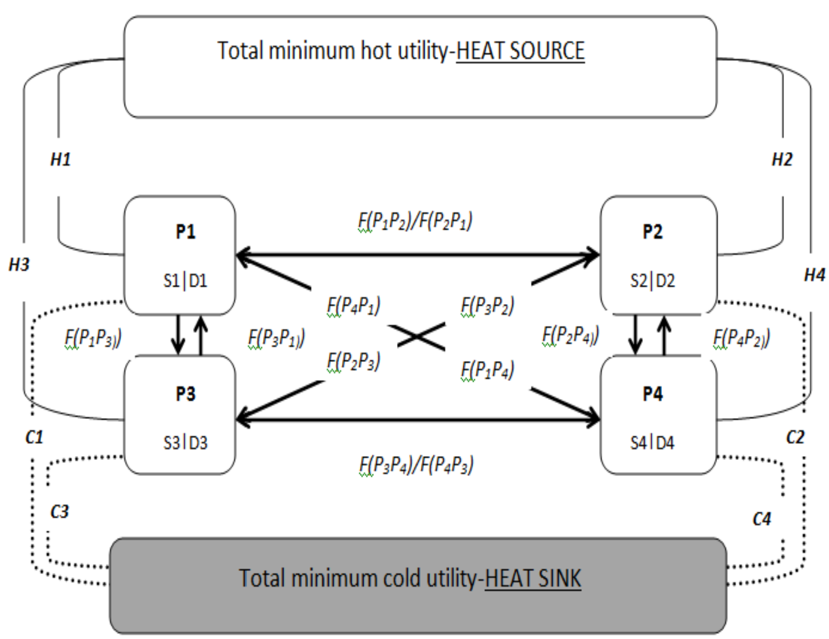
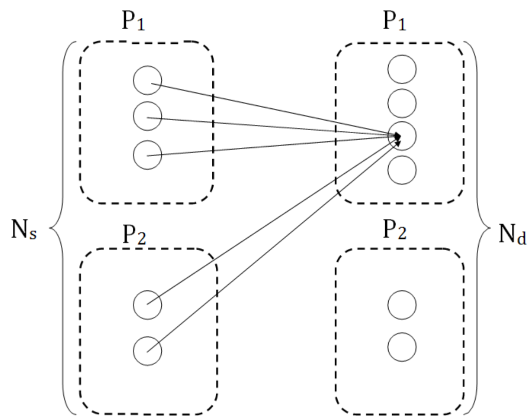


Fig 3.1 Schematic of the Problem definition

For every demand at any pressure level the amount of flow that is be supplied by all the sources is given as follows:

$$\sum_{k=1}^{N}\sum_{i=1}^{Sik} \mathbf{F_{ijk} = F_{Djk}} \ \forall\ \mathbf{k} \in \{1,2,3...N\} \ \text{ and } \ \mathbf{j} \in \{1,2,3...S_j\} \qquad (1)$$



Similarly, Fig 3.2 Schematic of demand satisfaction be supplied to the demands present at all the pressure level is given as follows:

$$\sum_{k=1}^{N}\sum_{j=1}^{Djk} \mathbf{F_{ijk} \leq F_{Sik}} \ \forall\ \mathbf{k} \in \{1,2,3...N\} \ \text{ and } \ \mathbf{i} \in \{1,2,3...D_i\} \qquad (2)$$

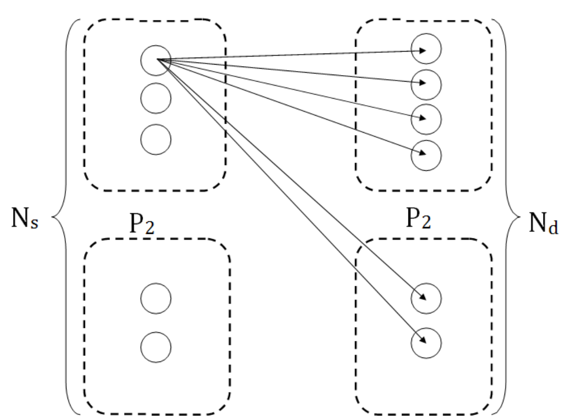


Fig 3.3 Schematic of the source satisfaction

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A part of the heat supplied to the demands will be given from the sources present at that level and the remaining is obtained from the hot utility present. The demands in the network must be strictly met while the sources in the system can be present in the quantities than the required. Thus a real balance needs to be struck between the hot and cold utilities required for the demands and sources respectively.

The demands for the system have to satisfied by the heat from the sources as well as from the external utilities.

$$\sum_{k=1}^{N} \sum_{i=1}^{Sik} F_{Sik}T_{Sik} + Q_{hjk} - Q_{cjk} = F_{Djk}T_{Djk}$$

$$\forall\ k \in \{1,2,3\ldots N\} \text{ and}$$

$$j \in \{1,2,3\ldots S_j\} \qquad (1)$$

\

An additional constraint has to labeled over equation (1) as follows

$$F_{ijk}\ Q_{hjk}\ ,\ Q_{cjk} \geq 0 \qquad (2)$$

It is to be noted that the heat supplied to the system is only in the form of thermal energy by the sources in the system and no form of heat is supplied by the conversion of work to heat, because of the constraint of the problem statement. Therefore the total hot external utility required by the system is given by:

$$\sum_{k=1}^{N} \sum_{j=1}^{Djk} Q_{hjk} = Q_h \qquad (3)$$

Similarly, the total amount of cold utility required in this case is given as follows:

$$\sum_{k=1}^{N} \sum_{j=1}^{Djk} Q_{cjk} = Q_c \qquad (5)$$

`

As previously assumed during the problem declaration, the entire compression work is isothermal in nature, which is calculated as follows:

$$\textbf{Objective}=\sum_{k=1}^{N}\sum_{j=1}^{Djk}\sum_{l=1}^{N}\sum_{i=1}^{Sik} F_{ijkl}\,(\sigma_i - \sigma_j)$$

$\forall\ k \in \{1,2,3...N\}$

$l \in \{1,2,3...N\}$

such that $k \neq l$

and $P_k < P_l$

$\forall\ i \in \{1,2,3...D_i\}$

and $\forall\ j$

$\in \{1,2,3...S_j\}$

Therefore the final equation for our two pressure level isothermal compression is as follows:

$W_{iso}= F_o((P_o\ln(P_{out}/P_o))-(P_o\ln(P_{in}/P_o)))$ (9)

The equation (10) is independent of the path traversed by the system to reach the final state, dependent on the initial and the final state of system. Using the characteristic expression for the isothermal process:

PF= constant (10)

This is a standardized equation, where F_o represents the flow rate of the stream being compressed and Po represents the standard pressure condition. The pressure conditions in the outlet and inlet are specified as Pout and Pin respectively.

Since, this is the generalized case for any two pressure levels, so for the brevity sake the quantity $P_o\ln(P_{out}/P_o))$ can be denoted as σ_{out}, referred as the isothermal pressure index of that pressure level.

Using this equation (9) becomes as follows:

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$Wij= |F_o (\sigma_1-\sigma_2)|$ **(11)**

The modulus operator is used to neglect the nature of the work obtained as a result of the order of precedence taken by a pressure level. The compression work calculated from the equation (11) is always positive. It is important to note that the P is directly proportional to σ, such that $P_1<P_2$ implying $\sigma_1< \sigma_2$. It is worth mentioning that all the objective function and all the constraints associated with the problem are linear in nature.

This study can be further extended to any number of pressure levels can be subject to certain considerations which are discussed later in great detail.

The objective for the study is therefore, the minimization of the equation (8). This can be further verified by GAMS analysis for the problem following a linear programming approach.

The mathematical analysis for the problem can be sub grouped into two cases studies which are defined as follows:

3.1 Case 1: Two pressure level :

At an individual pressure level, the sources and demands in any heat supply network can be considered as part of an independent network, the case is true for a small CCHP unit with at max two pressure levels and a linked district heating network [16 in the diary]. The total flows from the sources must match the total flow that the demands receive. It can be written in the form of following flow balance equation.

$$W=\sum_{k=1}^{2}\sum_{j=1}^{Djk}\sum_{l=1}^{2}\sum_{i=1}^{Sik} F_{ijkl}\,\sigma_{ij} \tag{12}$$

The interpressure level cross flow between HSN-1and HSN-2 is the cross flow of steam happening from the sources present at HSN-1 to the demands HSN-2, and is denoted as F_{12}. The additional flow that is transferred from the HSN-2 to HSN-1 can also be written as follows:

$F_{s1}-F_{d1}= \Delta_1$ **(13)**

`

Similarly for the transfer of flow from HSN-2 to HSN-1

$$F_{s2} - F_{d2} = \Delta_2 \tag{14}$$

The overall effective crossflow between the two pressure levels can be written from equation (5) and equation (6) as follows:

$$\Delta = F_{12} - F_{21} \tag{15}$$

From the equation (4),

$$\Delta = \Delta_1 = \Delta_2 \tag{16}$$

As the Δ remains constant for any two HSNs and hence, are dependent on each other. A change in the value of one is bound to be reflected in the value of the other entity, and hence :

Lemma 1: *The crossflow between any two HSNs can be minimized by minimizing the crossflow from any one of the HSN to the other*

The isothermal pressure index is function of the initial and final states of pressure, The above lemma serves as the premise for:

Theorem 1: *Overall compression work minimization is equivalent to the minimization of the overall effective cross flow between the two HSNs.*

Proof: Keeping the already declared nomenclature for the sources, demands and pressure variables, and without the loss of generality, we take the first p{1,2,...,p} sources in the S set as the sources belonging to HSN-1 and the remaining (S-p){p+1,p+2,...,S} sources belonging to the HSN-2. Similarly the first q demands{1,2...,q} belong to HSN-1 and the remaining (q+1,q+2,...,D) belong to HSN-2.Then, the work equation for the two pressure level can be written as follows:

$$W = \sum F_{11}\sigma_{11} + \sum F_{12}\sigma_{12} + \sum F_{22}\sigma_{22} + \sum F_{21}\sigma_{21} \tag{17}$$

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from equation(9) , the value of σ_{11} and σ_{22} is zero, as there is no compression work in case of transfer of fluid from the source to the demand in the same pressure level.Therefore the first and the third term in the RHS of the equation(17) become zero.

The compression work done in case of the transfer of fluid from the pressure at high level to the pressure at low level is zero, as it can be easily done without any expense of work or energy by simply employing the use of valves. The final work equation for the work equation becomes:

$$W = \sum F_{21}\sigma_{21} \tag{18}$$

Hence, the theorem 2 is proved .

The graphical energy integration between two power plants by determining the minimum amount of crossflow as proposed by Sahu and Bandyopadhyay[28] can be readily used in this case. However there is a slight modification in the GCC, the heat load is calculated by the taking the product of the flow (Sm^3) and the temperature (^oC). The GCC with the aforesaid variations for one plant and a reflected GCC for the other plant are used to find a common pinch point. At the pinch point, obtained from the shifting of the one curve towards the other, the transfer of heat across is infeasible. A piecewise linear curve, which is bounded by the two GCCs is drawn the value of the slope of the piecewise linear curve denotes the crossflow between each temperature interval.

3.2 Case 2: Multiple pressure level

The study of these systems is ideally suitable for the systems which employ smaller grid systems each having a mini and micro gas turbines for combined heat and power [14], a nearby located heat supply network. Extending from previous study of two pressure level HSNs, the generality of the study can be verified from a multiple pressure level HSNs. The pressure levels cascaded from the lower to the higher side in the magnitude and the biggest pressure level is denoted by the PH, and the subsequent n-1 pressure levels are denoted

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{Ph-1, Ph-2,.., P1}. The general expression for the work done as obtained from the Theorem 1 between the any two pressure levels is denoted as W_{ij} and which can be calculated from the equation(9). As the compression work is unidirectional in nature, having contributions only from the flow from the sources of the lower pressure to the demands of the higher pressure. Exploiting this unidirectional nature to reduce the complexicity of the problem. All the streams from P1 to Ph-1 are grouped as Ph-1 level streams and the compression work obtained using equation (9) between the two pressure levels is denoted as WHH-1. Flows from the pressure level PH-1 to PH can be considered as the demands for the PH-1 level and flows from the pressure level PH to PH-1 are considered as the sources for the PH-1 pressure level. Now, the modified pressure level PH-1 due to interpressurelevel crossflows from PH to PH-1, is considered as another HSN and all the streams $\{P_{H-2,}P_{H-3}$ .... P_1 } are grouped as another single HSN and the work is calculated between those pressure levels. This sub grouping of the pressure levels is continued until the last two levels. The overall effective compression work can be expressed as follows:

$$\mathbf{W= W_{12}+W_{23}+...+W_{H-2H-1}+W_{H-1H}} \qquad \textbf{(19)}$$

The graphical integration of energy for the multiple pressure levels can be carried out in the in the similar way as discussed for the two pressure level systems. The equation(19) denotes the maximum amount of the compression work that will be required in our final HSN. It can be shown that the compression work calculated is not the upper bound of the compression work, the minimum limit for the compression work. Method of mathematical induction is employed to hold the claim

Theorem 2: The minimum amount of compression work that is required for the Heat Supply network is calculated from the equation (19).

Proof:

Using method of mathematical induction,

The compression work between the first and the second pressure level is calculated from the equation (12) as follows:

$$\mathbf{W_{12}= F_{12}\sigma_{12}} \qquad \textbf{(20)}$$

`

Since, σ_{12} is constant and the flow from the HSN-1 to HSN-2 is dependent on the amount of the sources and demands present at the particular level, the heat duties of the demands have been already satisfied by the intrapressure level flows and inter pressurelevel flows and a minimum hot and cold utility requationuirement is maintained for the two pressure level verifying that the compression work done for the two pressure level HSN is minimum and maximum at the same time.

Now, assuming that the compression work for the i pressure level is minimum, The equation (10) becomes,

$$\mathbf{W_{min}= W_{12}+W_{23}+...+W_{i-2i-1}+W_{i-1i}} \qquad \textbf{(21)}$$

Using the previous stated hypothesis,

Adding a pressure level i+1, the equation(11), becomes

$$\mathbf{W= W_{12}+W_{23}+...+W_{i-2i-1}+W_{i-1i}+ W_{ii+1}} \qquad \textbf{(22)}$$

Rearranging equation (12),

$$\mathbf{W\text{-}W_{ii+1}= W_{12}+W_{23}+...+W_{i-2i-1}+W_{i-1i}} \qquad \textbf{(23)}$$

Since, it is already known that the RHS of equation (23) is minimum from the equation(21)

To get this the $W-W_{ii+1}$ should be minimum, as the value of the W_{ii+1} would be fixed for any two pressure system, which is derived in the base case of mathematical induction .

Therefore, we have our equation (23) representing the minimum compression work from the principle of mathematical induction. This proves our second theorem.

The following corollaries can be drawn from the theorem:

Corollary 1: The highest pressure level having only the sources can be neglected and the sources can subsequently be assumed to be the sources of the highest pressure level having at least one demand.

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Corollary 2: The lowest pressure level having only the demands can be neglected and the demands can subsequently be assumed to be the demands of the lowest pressure level having at least one source.

Corollary 3: The sources which are at the pressure level lower than the lowest pressure level having demand will contribute a constant amount of compression work to the HSN and subsequently can be assumed to be included in the sources of the minimum pressure level having at least one demand.

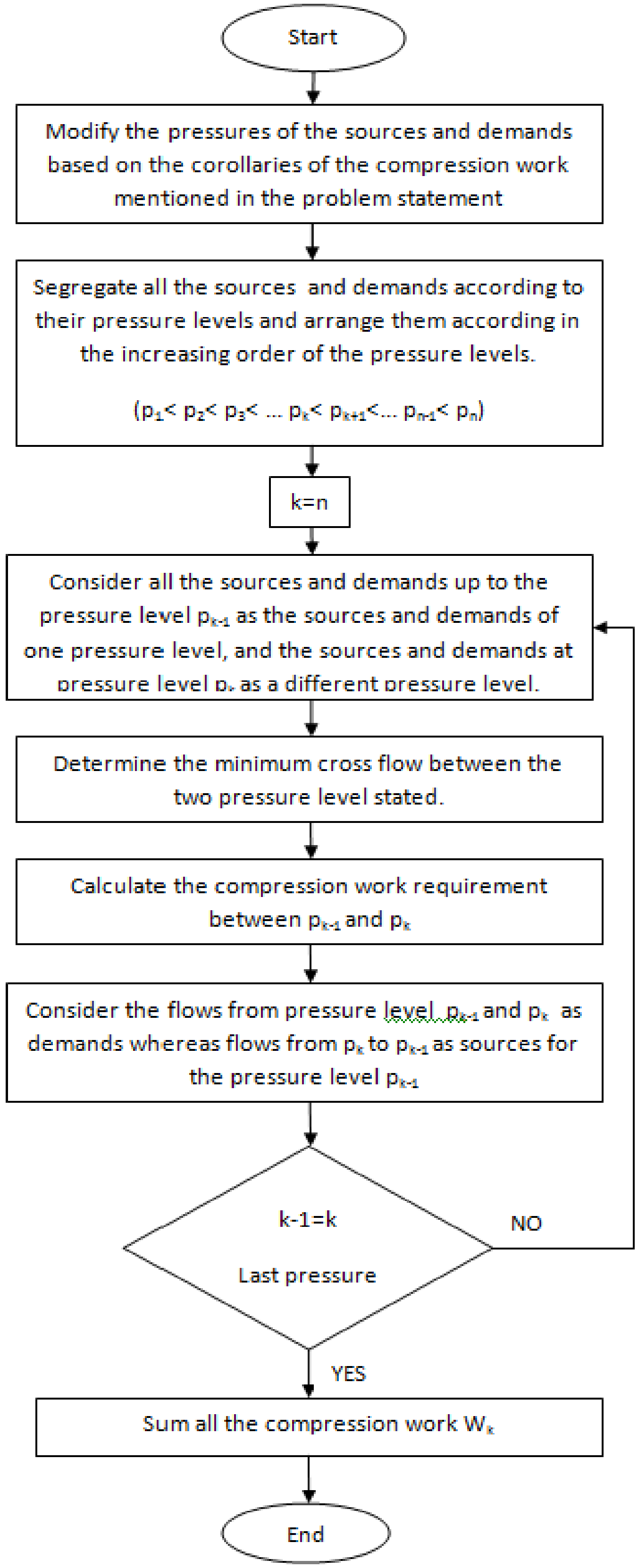
Corollary 4: The demands which are at the pressure level higher than the highest pressure level having source will contribute a constant amount of compression work to the HSN and subsequently can be assumed to be included in the demands of the highest pressure level having at least one source.

The aforementioned corollaries are used in reducing the number of pressure levels, and minimizing the complexity of the problem. The proofs for each of them have been avoided for brevity, and can be easily derived from equation (19).

2.3 Targeting methodology

The methodology adopted for targeting the compression work is explained step by step in fig 3.4. We start by segregated our sources and demands into various pressure levels. This is followed by the grouping of the highest pressure level sources and demands into one group and the remaining sources and demands belonging to the pressure level just below the highest pressure level. The inter pressure level cross flow is calculated and the highest pressure level is removed. The flow from the higher pressure level to the lower pressure level is considered as source to the lower pressure level in the next step and the flow from the lower pressure level to the higher pressure level is considered as a demand for the lower pressure level in the next iteration. This process is repeated till there are only two sources left. The compression work calculated from the summation all the individual compression works calculated between any two pressure levels.

Fig 3.4 The targeting methodology for the multi pressure level HSN



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Chapter 4

Illustrative Examples

The proposed mathematical methodology is illustrated with the help of three pressure level case, five pressure level cases and a nine pressure level case. The results include hot and cold utilities supplied in the overall HSN. The illustrated examples are supported side by side with the graphical approach as shown by Bade and Bandypadhyay[28]. In addition to this, every illustration is verified with the help of a GAMS formulation solved for linear systems using CIPHER solver**.**

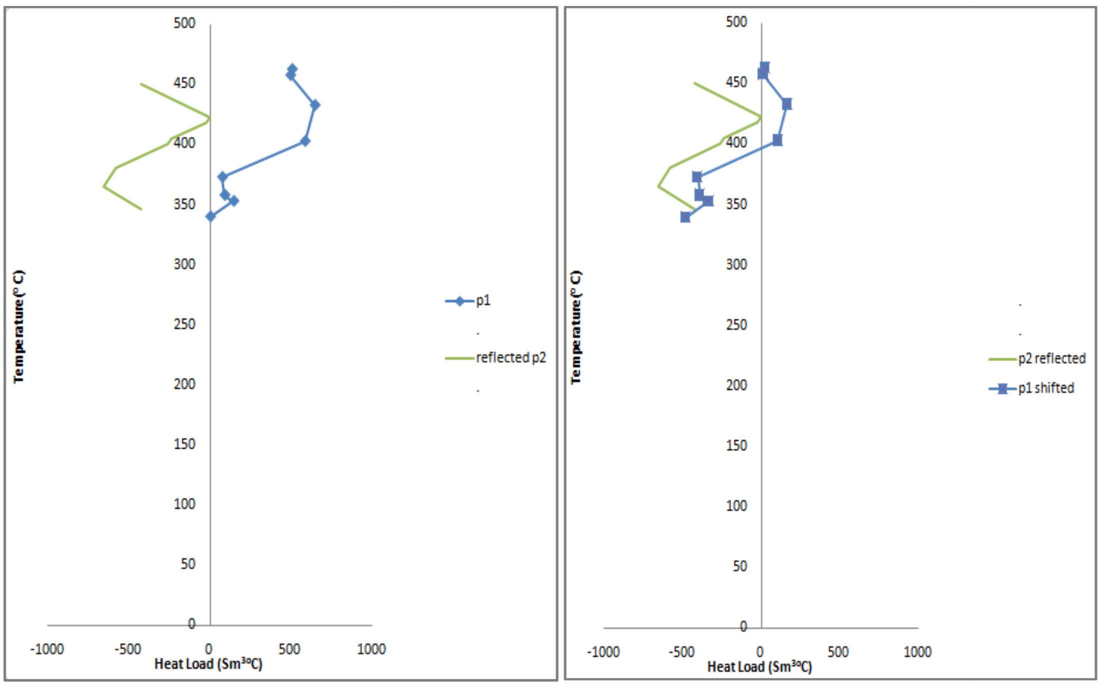
4.1 Illustrative example 1: Three pressure level

A steam data set for the process streams for the illustration is shown in table 3.1.1.

Table 4.1.1 : Dataset for the illustrative example 4.1

Sources				Demands			
Stream	Temperature(°C)	Flow(Sm³)	Pressure(kPa)	Stream	Temperature(°C)	Flow(Sm³)	Pressure(kPa)
s11	458	8	10400	d11	463	2	8600
s12	373	18	8600	d12	433	8	8600
s13	358	10	8600	d13	403	15	8600
s14	340	11	8600	d14	353	22	8600
s21	450	20	4200	d21	450	15	4200
s22	405	12	4200	d22	405	13.5	4200
s23	380	12.5	4200	d23	380	11	4200
s24	365	14.88	4200	d24	365	17	4200

The steam streams are segregated according to their pressures P_i. The pressure level P_3, containing only one source can be neglected for the compression work calculation in accordance with the corollary 1 stated before. The Two final pressure levels obtained P_k and P_{k-1} has their individual steam sources and demands.PTA is used to determine the hot and cold utilities. The hot utility comes out to be 503 Sm^3 ^oC while the cold utility comes out to be 0 Sm^3 ^oC with the pinch point at 340^oC for pressure level 1. Similarly, for the pressure level 2 the hot utility obtained was 420 Sm^3 ^oC hot utility and 425.50 Sm^3 ^oC cold utility with pinch at 422^oC. Plotting GCC for both of the pressure levels and using the methodology proposed by Bade and Bandyapadhyay[28] to integrate the two pressure levels (wherein one GCC curve is reflected about the temperature axis and the other is shifted to obtain a site pinch. The GCC Obtained for the illustrated example is shown in fig 3.1.1(a) and fig3.1.1(b).



(a) (b)

Fig 4.1.1(a)GCC for the two pressure levels with pressure 1 as unshifted

(b)GCC for the two pressure levels with pressure 1 shifted to obtain a site pinch

A piecewise linear curve is drawn between the two GCC curves which determines our total interpressure level crossflows. The values obtained for the crossflow are calculated from the slope of the piecewise linear curve which comes out to be 0.382 Sm^3 across temperatures 458^oC of 4200kPa pressure level to 400^oC of 8600kPa pressure level. For the two steam stream cross flows obtained between the two pressure levels the flow 0.382 Sm^3 contributes to compression work. The compression work calculated from the equation (9) comes out to be 27.73kJ with σ_{12} calculated to be 72.549 kPa respectively.

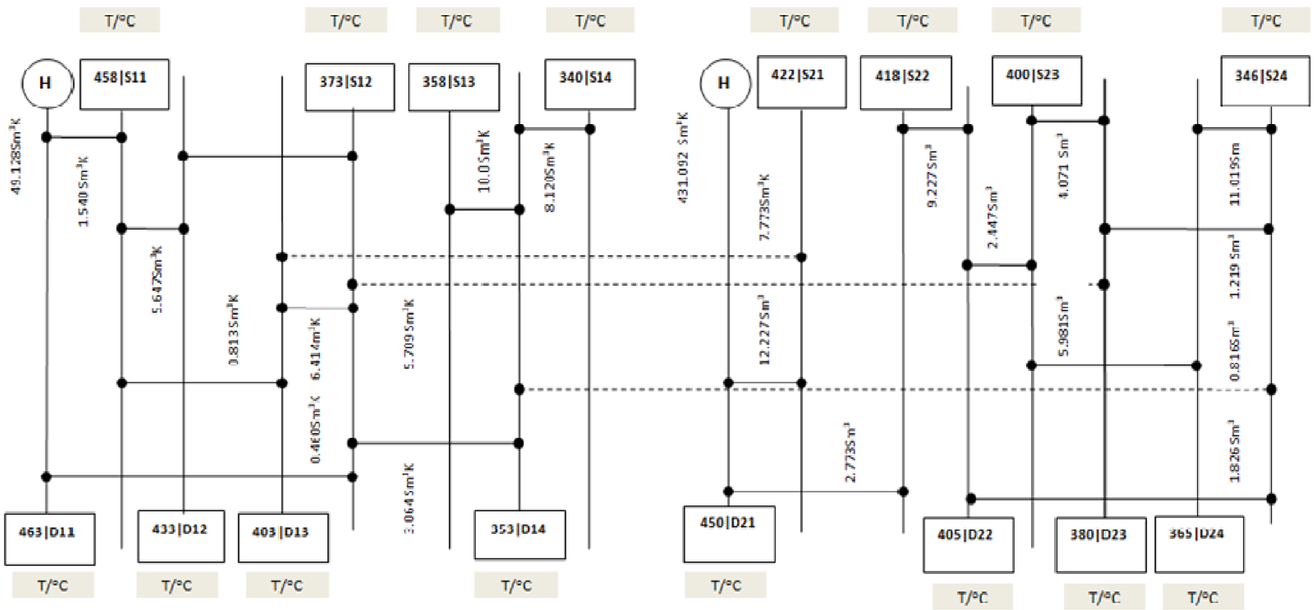


Fig 4.1.2 Heat supply network for the illustrated example 1

The heat supply network that is generated is shown in Fig 3.1.2, which comes out to be optimized and minimal. The answer is supported and validated by the GAMS analysis which was done using CPLEX solver for linear programming. The hot utility obtained was 480.22 Sm^3 ^oC the cold utility for the HSN was 0 Sm^3 ^oC as cold utility, which were less than the individual summations of the utilities of the two pressure levels and is consistent with the thermodynamic principles. The GAMS solution contained 9 blocks of equations and 9 blocks of variables with 20 single equations and 46 single variables and 144 non-zero elements.

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4.2 Illustrative example 2 : Five pressure level CCHP Plant

A CCHP plant network having five different types of turbines which are to be operated at their respective marked pressures to deliver optimum power. The different types of steam streams present in the CCHP plant are tabulated in table 4.2.1.

Table 4.2.1 Steam Pressures in a CCHP Plant

	STEAM STREAM	PRESSURE(kPa)
SPS	SUPER PRESSURISED STEAM	12000
VHPS	VERY HIGH PRESSURE STEAM	10050
HPS	HIGH PRESSURE STEAM	9000
MPS	MODERATE PRESSURE STEAM	4500
LPS	LOW PRESSURE STEAM	3000

The diagrammatic representation of a typical CCHP plant is as shown in figure 4.2.1.

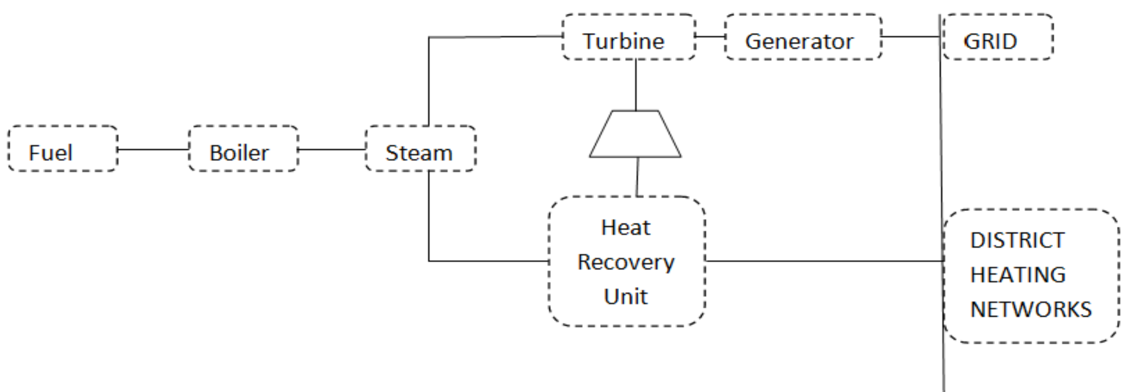

Fig 4.2.1 The basic schematic of the CCHP plant demonstrated in example 1

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The data set for the case study is given in table 4.2.2.

Table 4.2.2 : Dataset for the illustrative example 4.2							
Sources				Demands			
Stream	Temperature(°C)	Flow(Sm³)	Pressure(kPa)	Stream	Temperature(°C)	Flow(Sm³)	Pressure(kPa)
s11	511	15.248	12000	d11	488	9.144	10050
s12	444	2	10050	d12	456	12.66	10050
s13	388	15.104	10050	d13	411	10.548	10050
s21	567	1.15	9000	d21	588	7.296	9000
s22	510	3.073	9000	d21	390	11.86	9000
s23	478	10.548	9000	d31	552	8	4500
s24	353	13	9000	d32	450	15	3000
s31	530	14	4500				
s32	410	1.374	4500				
s33	380	2.219	4500				
s34	360	8	4500				

Super pressurised steam(SPS) is acting as the source of the entire CCHP plant and there is no steam equivalent of that pressure that acts as a demand at such high pressure. Such high pressure steams can be assumed to be present at the highest pressures which have the demands from the corollary 1. Similarly, the Low pressure steam(LPS) is the stream with the lowest pressure and acts as a demand. There is no source stream which is present at such low pressure level to supply the heat to that demand therefore, from the corollary 2 the pressure of the such a stream is assumed to be the pressure of a moderate pressure steam, as the moderate pressure steams(MPS) have both sources as well as demands. The remaining pressure streams VHPS, HPS, MPS have both sources and demands and have to solved using the targeted methodology.

The highest pressure level is considered as the one pressure level while all the pressure below the highest pressure level are grouped as one single pressure level. The hot and cold utilities of such two pressure level system are calculated from using the PTA and amount to be 45.628 Sm^3 ^oC while the cold utility comes out to be 0 Sm^3K with the pinch point at 388^oC for pressure level 1. Similarly, for the pressure level 2 the hot utility obtained was 601.874Sm^3 ^oC hot utility and 495.555 Sm^3 ^oC cold utility with pinch at 478^oC. The cross flow the pressure 1 to the pressure 2 which is 3.073 Sm^3 at 510 ^oC is taken as the source for the pressure level 2 in the next step and similarly, the cross flow from the pressure level 1 to the pressure level 2, which is 1.5996 Sm^3 at 478 ^oC is assumed to be the demand for the pressure level 2 .

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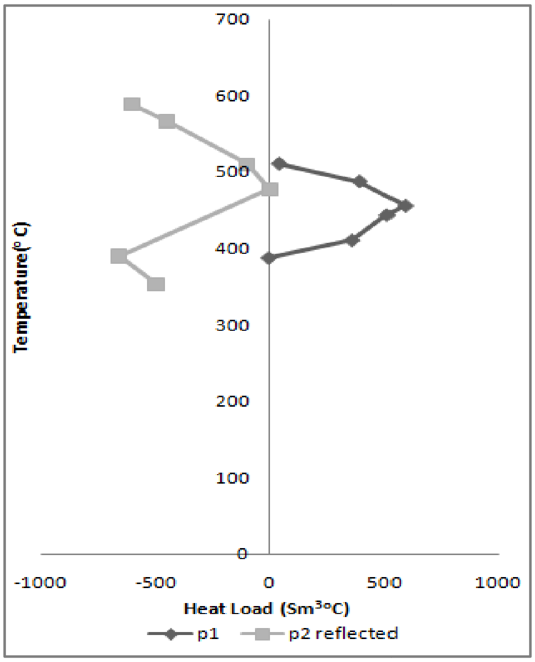

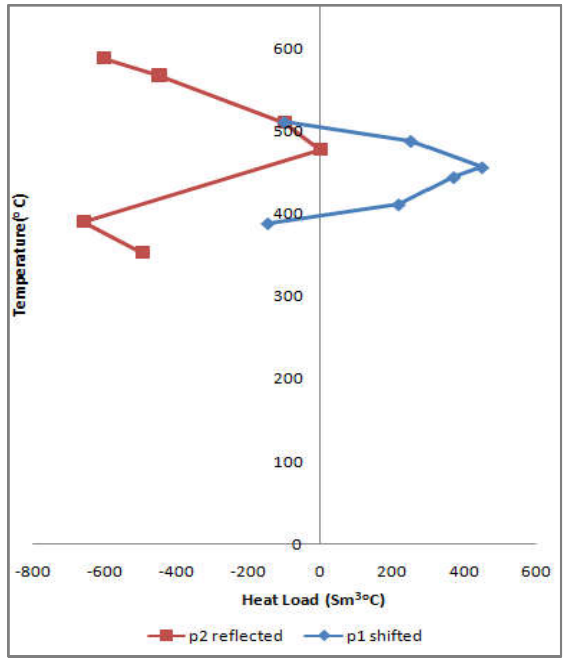

(a) (b)

Fig 4.2.2(a)Step 1:GCC for the two pressure levels with pressure 1 as unshifted

(b)Step 1:GCC for the two pressure levels with pressure 1 shifted to obtain a site pinch

In the next step of the methodology the similar approach is followed of the grouping of the pressure streams into the highest and rest subgroups. The hot utility of such respective two pressure level system is calculated using the PTA and amounts to be 503.538 Sm^3 °C while the cold utility comes out to be 679.68 Sm^3K with the pinch point at 510°C and 478°C for pressure level 1. Similarly, for the pressure level 2 the hot utility obtained was 226Sm^3 °C hot utility and 0 Sm^3 °C cold utility with pinch at 360°C. The cross flow the pressure 1 to the pressure 2 which is 0 Sm^3 and similarly, the cross flow from the pressure level 2 to the pressure level 1, which is 5.35 Sm^3 at 530 °C.

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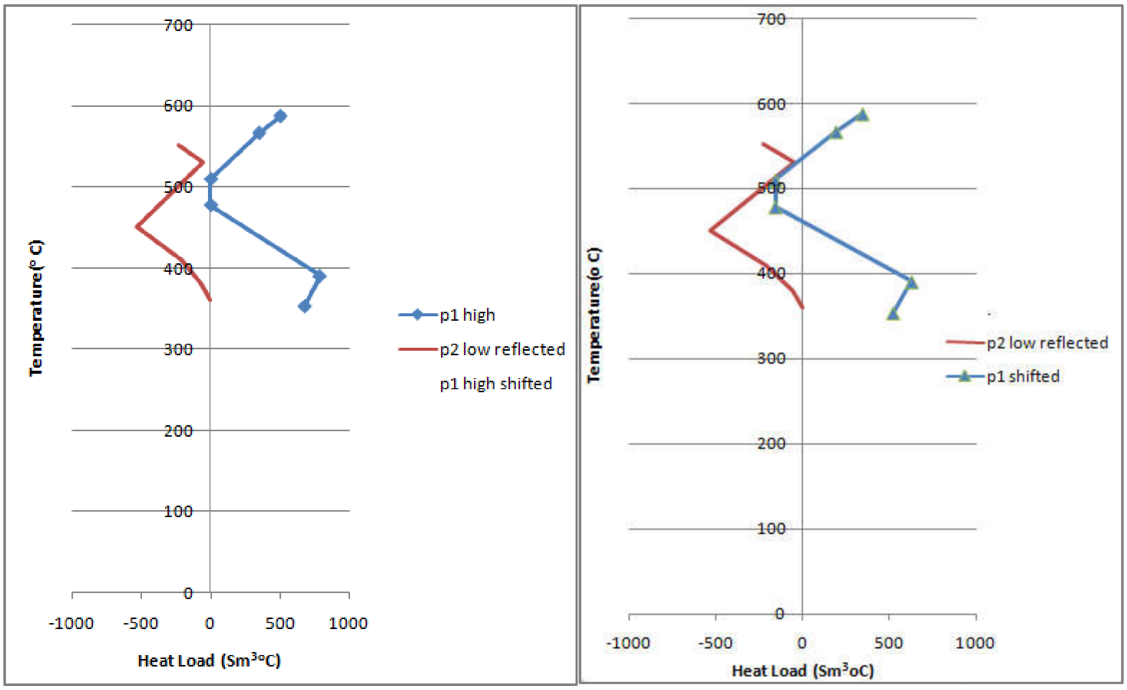

(b) (b)

Fig 4.2.3(a)Step 2:GCC for the two pressure levels with pressure 1 as unshifted

(b)Step 2:GCC for the two pressure levels with pressure 1 shifted to obtain a site pinch

The σ_1 calculated out to be 456.689Sm^3, σ_2 is 454.609 Sm^3 and σ_3 is 384.376 Sm^3 . The compression work comes out to be resultant of all of them and has the value 428.24kJ.

The answer is supported and validated by the GAMS analysis which was done using CPLEX solver for linear programming. The hot utility obtained was 559.538 Sm^3 ^{o}C the cold utility for the HSN was 0 Sm^3 ^{o}C as cold utility, which were less than the individual summations of the utilities of the two pressure levels and is consistent with the thermodynamic principles. The GAMS solution contained 11 blocks of equations and 27 blocks of variables with 24 single equations and 92 single variables and 197 non-zero elements.

The heat network for the example is shown as below:

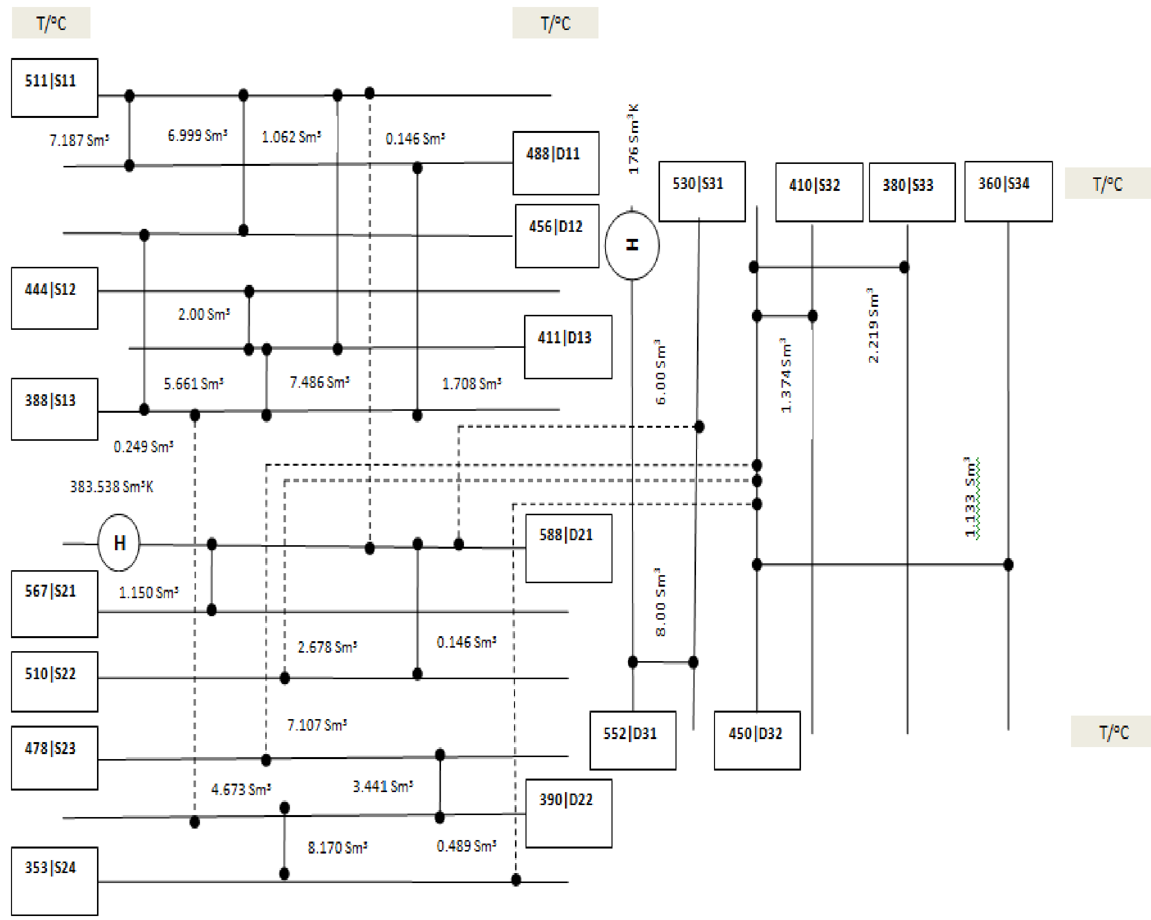

Fig 4.2.4 Heat supply network for the illustrated example 2

4.3 Illustrative example 1: Nine pressure level system

The data set used for the problem has been intentionally avoided for the brevity purposes, The GAMS analysis for the problem was done using CPLEX solver for linear programming. The hot utility obtained was 503.538 Sm^3K the cold utility for the HSN was 0 Sm^3K as cold utility, which were less than the individual summations of the utilities of the two pressure levels and is consistent with the thermodynamic principles. The compression work calculated out to be 54.09kJ The GAMS solution contained 29 blocks of equations and 23 blocks of variables with 187 single equations and 188 single variables and 324 non-zero elements.

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Chapter 5

Conclusions and Future Plan

The results obtained have proved the optimality of our methodology. The two level sub problem showed a 32.68% savings in the shaftwork which was compared by making a network which did not minimized the interplant cross but the consumed the similar amount of the utilities. Similarly, the shaftwork reduction was found to be 48.44% for our five pressure level CCHP case study. It was repeatedly found that the shaftwork reduction for the nine pressure level was found to be 51.65%. Not only did our shaftwork reduced considerably, But also the reduction was found to be increasing as the number of pressure level were increased.

This definitely would be limiting but the results have shown a successful attempt of our methodology in decreasing the amount of compression work required in the process plants and CCHP plants in specific.

This work can be extended to the cooling cycles in future which employ a great of shaftwork in their refrigeration processes, so the future scope for the study looks positive.

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References

1. Vacalavek V., Novotna A., Dedkova J. Pressure as a further parameter of composite curves in energy process integration. Applied Thermal Engineering 2003; 23:1785-1795, doi:10.1016/S1359-4311(03)00133-9
2. Colmenares,T. R. and Seider, W. D. Heat and power integration of chemical processes. AIChE J., 33: 898–915. doi:10.1002/aic.690330604
3. Duran, M. A. and Grossmann, I. E. (1986), Simultaneous optimization and heat integration of chemical processes. AIChE J., 32: 123–138. doi:10.1002/aic.690320114
4. Wood, R. M. and Hasan, M. (1987), Improved heat exchanger networks for energy conservation in palm oil refineries. International Journal of Food Science & Technology, 22: 209–218. doi:10.1111/j.1365-2621.1987.tb00480.x
5. Swaney, R. E Thermal integration of processes with heat engines and heat pumps. AIChE J.,1989 35: 1003–1016. doi:10.1002/aic.690350614
6. Zheng Q, Sun Y, Li S, Wang Y. Thermodynamic Analyses of Wet Compression Process in the Compressor of Gas Turbine. ASME. J. Turbomach. 2003;125(3):489-496. doi:10.1115/1.1575254.
7. Andreas C., Christoph K., Lothar P., George T. The contribution of heat storage to the profitable operation of combined heat and power plants in liberalized electricity markets, Energy 2012; 41(1): 75-82,https://doi.org/10.1016/j.energy.2011.06.048.
8. Townsend, D. W. and Linnhoff, B Heat and power networks in process design. Part I: Criteria for placement of heat engines and heat pumps in process networks. AIChE J.1983 29: 742–748. doi:10.1002/aic.690290508
9. Townsend, D. W. and Linnhoff, B. Heat and power networks in process design. Part II: Design procedure for equipment selection and process matching. AIChE J. 1983 29: 748–771. doi:10.1002/aic.690290509
10. Behnaz Rezaie, Marc A. Rosen, District heating and cooling: Review of technology and potential enhancements. Applied Energy 2012; 93: 2-10 https://doi.org/10.1016/j.apenergy.2011.04.020.
11. Mahmoud E., Dustin H., Dennis S. Targeting cogeneration and waste utilization through process integration. Applied Energy 2009; 86(6): 880-887 https://doi.org/10.1016/j.apenergy.2008.08.011.
12. Adrian B. Theory of heat transfer-irreversible refrigeration plants, International Journal of Heat and Mass Transfer 1989; 32(9): 1631-1639 http://dx.doi.org/10.1016/0017-9310(89)90045-8.
13. Heyne, S., Thunman, H. and Harvey, S. Extending existing combined heat and power plants for synthetic natural gas production. Int. J. Energy Res. 2012; 36: 670-681. doi:10.1002/er.1828
14. Adrian B. Maximum power from fluid flow, International Journal of Heat and Mass Transfer 1996; 39(6): 1175-1181.http://dx.doi.org/10.1016/0017-9310(95)00209-X.
15. Sheldon G. B., Thokozani M. Steam system network synthesis with hot liquid reuse: I. The mathematical model for steam level selection. Computers & Chemical Engineering, 2016; 85: 210-215 https://doi.org/10.1016/j.compchemeng.2015.10.014.

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16. Sheldon G. B., Thokozani M., Steam system network synthesis with hot liquid reuse: II. Incorporating shaft work and optimum steam levels, Computers & Chemical Engineering 2016; 85: 202-209 https://doi.org/10.1016/j.compchemeng.2015.10.016.
17. Abtin A., ChangKyoo Y. Combined pinch and exergy analysis for energy efficiency optimization in a steam power plant. International journal of physical sciences 2010; 5(7): 1110-1123
18. P.A Pilavachi, Power generation with gas turbine systems and combined heat andpower, Applied Thermal Engineering 2012 ;20(15-16): 1421-1429 https://doi.org/10.1016/S1359-4311(00)00016-8.
19. P.A. Pilavachi, Mini- and micro-gas turbines for combined heat and power, Applied Thermal Engineering 2002; 22(18): 2003-2014. https://doi.org/10.1016/S1359-4311(02)00132-1.
20. Eveloy V., Rodgers P. and Popli S. Power generation and cooling capacity enhancement of natural gas processing facilities in harsh environmental conditions through waste heat utilization, International Journal of Energy Research 2014; 38: 1921–1936, doi: 10.1002/er.3197
21. Demirkaya, G., Padilla, R. V. and Goswami, D. Y. A review of combined power and cooling cycles. WENE 2013; 2: 534–547. doi:10.1002/wene.75
22. Linhoff B., Dhole V.R. Shaftwork targets for low temperature process design. Chemical Engineering Science 1992; 47(2): 2081-2091 doi: 10.1016/0009-2509(92)80324-6
23. Ghannadzadeh A., Perry S., Smith R. A new shaftwork targetting model for total sites Chemical Engineering Transactions 2011; 25: 917-922
24. Dhole, V. R., & Linnhoff, B. Total site targets for fuel, co-generation, emissions, and cooling. Computers and chemical engineering 1993; 17: 101-109.
25. Linnhoff, B., & Eastwood, A. R. Overall site optimisation by Pinch Technology. Chemical Engineering Research and Design 1997; 75:138-144.
26. He, F., Xu, Y., Zhang, X., Liu, C., and Chen, H. Hybrid CCHP system combined with compressed air energy storage. Int. J. Energy Res. 2015; 39: 1807–1818. doi: 10.1002/er.3303.
27. Bandyopadhyay S., Chaturvedi N.D. Targetting compression work for hydrogen allocation networks Industrial and Engineering Chemistry Research 2014; 53(48): 18539-18548, doi: 10.1021/ie503429q
28. Mukund H. Bade and Santanu Bandyopadhyay Minimization of Thermal Oil Flow Rate for Indirect Integration of Multiple Plants Industrial and Engineering Chemistry Research 2014; 53(33):13146-13156 doi: 10.1021/ie502059f

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