DESIGN AND OPTIMIZATION OF CCHP SYSTEM IN KRAFT PROCESS USING PROCESS INTEGRATION

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By

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CANDIDATE'S DECLARATION

I hereby certify that the work is being presented in the dissertation entitled **"DESIGN AND OPTIMIZATION OF CCHP SYSTEM IN KRAFT PROCESS USING PROCESS INTEGRATION"** in the fulfillment of the requirements for the award of the degree of Master of Technology (CAPPD) and submitted in the Department of Chemical Engineering, Indian Institute of Technology Roorkee, Roorkee, is an authentic record of my own work carried out during a period from June, 2015 to May, 2016 under the supervision of **Dr. Bikash Mohanty**, Professor, Department of Chemical Engineering, Indian Institute of Technology Roorkee, Roorkee. The matter embodied in this work has not been submitted for the award of any other degree.

Place: IIT Roorkee

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CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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ABSTRACT

Combined Cooling, Heating and Power (CCHP) system is a cogeneration technology (CHP) that integrates an absorption cycle to produce power, heating and cooling, simultaneously. In this research, the implementation of a CCHP system in a Indian Kraft pulp and paper industry is studied. This system has been considered as two parts in design and optimization steps. One is a CHP system, which consists of a gas turbine cycle, and a HRSG system and another part is an absorption heat pump (AHP) driven by the discharged steam coming out from a steam turbine.

Pinch analysis is applied to find the appropriate placement of the proposed CCHP system. Aspen plus software is used to simulate the basic design of this CCHP system considering both parts. Afterward, genetic algorithm is used for optimization of the proposed CCHP system with minimum total annual cost (TAC) and highest energy efficiency. Having implemented the proposed CCHP system, both power and heating requirements of the pulp and paper mill can be supplied and cooling requirements can be reduced with the payout period of 3.21 years.

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SHAHARE CHETANAND TEJRAM

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NOMENCLATURES

a	Constant in Equation (7.12)
A	Shell and Tube Heat Exchanger Surface Area (m^2)
ac	Exponent for Viscosity Correction in Equation (7.17)
AF	Annual Factor
AHP	Absorption Heat Pump
b	Constant in Equation (7.12)
C_1 , C_2	Constants in Equation (7.16)
C_3	Constant in Equation (7.22)
C_4	Constant in Equation (7.26)
C_5 ,C_6 ,C_7	Constants in Equation (7.31)
C_8 ,C_9	Constants in Equation (7.32)
C_{10}	Constant in Equation (7.33)
CCHP	Combined Cooling Heating and Power
C_p	Specific Heat Capacity (kJ/(kgK))
C_i	Component Investment Cost
C_f	Fuel Cost ($/sec)
C_t	Constant in Equation (7.30)
D_s	Diameter of Shell (m)
D	Inside Tube Diameter (m)
D_t	Outside Tube Diameter (m)
D_e	Equivalent Diameter (m)
F	Correction Factor for LMTD
G	Mass Flow Rate of Fluid Stream per Unit Cross Sectional Area (kg/(m^2sec))
h	Heat Transfer Coefficient for Fluid Stream (W/(m^2K))

H	Annual Operating Hour (hours)
k, k_s, k_t	Thermal Conductivity of The Tube Wall, Shell Side Fluid and Tube Side Fluid (W/(mK))
K_s	Constant in Equation (7.20)
K_t	Constant in Equation (7.17)
L_{bc}	Baffle Spacing (m)
LMTD	Logarithmic Mean Temperature Difference
L_{tp}	Tube Pitch (m)
L	Length of The Tube (m)
LHV	Lower Heating Value (kJ/kg)
m^0	Mass Flow Rate (kg/sec)
ms	Exponent for Reynolds Number in Equation (7.22)
mt	Exponent for Reynolds Number in Equation (7.16)
M	Mass Flow Rate of Fluid Stream (kg/sec)
n	Constant in Equation (7.12)
NS	Number of Shell Passes
NT	Number of Tube Passes
N_b	Number of Baffles
N_t	Number of Tubes per Shell
OC	Operating Cost
P	Pressure
P_t	Tube Pitch
P_c	Compressor Pressure Ratio
Pr	Prandtl Number
Q	Heat Transfer Rate
R_{bs}	Ratio of Baffle Spacing to Shell Diameter
R	Fouling Resistance (m^2K/W)

Re	Reynolds Number
T	Temperature (K)
TAC	Total Annual Cost ($/yr)
U	Overall Heat Transfer Coefficient ($W/(m^2K)$)
v_t	Tube Side Fluid Velocity (m/sec)
v_s	Shell Side Fluid Velocity (m/sec)
W	Power
ΔP	Pressure Drop

Greek Symbols

H	Isentropic Efficiency
$Ø_r$	Maintenance Factor
µ	Viscosity
P	Density

Subscripts

COMP	Compressor
COMCHAM	Combustion Chamber
GASTUR	Gas Turbine
DUCTBUR	Duct Burner
SUPHEAT	Super Heater
ECONO	Economiser
EVAPOR	Evaporator
STEAMTUR	Steam Turbine
CONDENS	Condenser
GENERAT	Generator
SHX	Solution Heat Exchanger
ABSORB	Absorber
max	Maximum Value

min	Minimum Value
s	Shell Side
t	Tube Side
w	at Wall Temperature

CHAPTER 1

INTRODUCTION

Now a days, the interest has been increased in improving the energy efficiency and energy conversion. Many researchers are working in the field of applied energy for energy conversion and transfer of energy from one form to the other in an industry. Interest is growing due to concern for environmental issues and several reasons including rational utilization of resources, and profitability. Processes in the chemical industries are energy intense, such as the Kraft pulp and paper industry utilizes only about 5% of the total energy supplied, therefore the focus has turned into maximizing the internal energy recovery, recycling the wastes, the efficiencies increasing of processes and components recycling waste streams and simultaneously expanding product chain with new and advanced branches that can be easily integrated from material as well as energy point of view. Considering this, the Kraft pulp and paper mill can be transformed into a bi-refinery which can be seen as natural evolution of the present same site as both industries use same raw material and similar feed stock. These modifications can be resulted in innovative and more complicated process configurations, which requires optimization techniques and more advanced design for material and energy integration analysis to be really effective.

The goal behind this work is developing and designing a more robust simulation model of a Kraft pulp and paper mill and investigating the design parameters and configuration of the complete industrial and specific plant sites by considering techniques used in process integration. It is necessary to provide the basic designing module with basic framework in which various industries can be integrated, modelled and analysed. We can define CCHP system as a cogeneration technology which can reduce the use of an external source of electricity from the grid by using fuel which has low emission capacity such as natural gas. CCHP system drives the thermally activated components by using the recovered heat of fuel in a better way. The thermally-activated components used by CCHP system are gas turbine and steam turbine which can produce cooling and heating simultaneously resulting in high overall energy efficiency. As earlier mentioned chemical industries are energy intensive, Pulp and paper industry is also an energy intensive industry that requires electricity and heat for drying pulp related materials, concentration of black liquor (BL) in evaporator train and other similar operations like maintaining hot critical streams below the specific temperature limits by cooling. Most recently, various advanced energy conversion technologies such as absorption heat pumps with refrigeration and cogeneration are being utilized in the pulp and paper industry. In this work the possibility to combine a cogeneration technology and AHP producing heating, cooling and power generation in a Kraft pulp and paper mill has been investigated. The integration of a proposed CCHP system in Kraft pulp and paper mill must follow process integration practices which includes pinch analysis to get maximum benefits and to maximize the internal heat recovery which has to be followed by pinch analysis. The CCHP system which consist two parts CHP system and AHP system, is considered for the optimization using Matlab software. Cogeneration is one of the best technologies which makes a best use of low emission fuels by using recovered heat and produces power and heat simultaneously. The integration of cogeneration system with the existing Kraft pulp and paper mill has been studied in this work. Optimization considered the thermodynamic and thermo-economic viewpoints and has done with single objective optimization function. It has done by using evolutionary algorithm i.e. using genetic algorithm (GA) in a cogeneration energy system. Also optimization of a CHP system which consists gas turbine power plant has been performed by using genetic algorithm (GA). In the case of AHP, modelling of absorption heat pump using Aspen plus software has studied, also design and construction of a Lithium Bromide-Water absorption refrigeration system has been investigated. Genetic algorithm (GA) has used for optimal design of CHP system, and feasible region method is used to optimize the AHP system with shell and tube heat exchangers that are widely used in any chemical industry. The geometry of shell and tube heat exchangers have been optimized to minimize their total cost by feasible region method which uses the plot of tube side pressure drop vs. the shell side pressure drop. In this work, CCHP system is implemented with the existing Kraft pulp and paper mill. This task of implementing CCHP system is carried out by design and optimization of an integrated CCHP system to the existing process according to energy demands in this work. CCHP system is divided into two separate parts to carry out design and optimization procedures separately. First, designing of these two separate parts consisting of CHP system and AHP system which is an absorption heat pump is done, in order to maximize internal heat recovery within the process pinch analysis is used. Then the CHP system is optimized with an objective function, which considers minimum total annual cost (TAC) and then, the AHP system is optimized to get the optimum heat exchanger geometry minimizing the total annual cost (TAC).

Objectives

- Integration of CHP system in Indian Kraft pulp and paper mill.
- Design and optimization of CCHP system in same Kraft pulp and paper mill.
- Optimization of shell and tube heat exchanger geometry used in AHP system in order to minimize the total annual cost.
- Minimizing overall the total annual cost (TAC) of CCHP system.

CHAPTER 2

LITERATURE REVIEW

A thorough literature review on different aspects of CCHP system has been reported in this chapter. The research on combined cooling heating and power system started in 1989. Since then many investigators have published on different aspects of it such as implantation of gas turbine cycle, cogeneration techniques, implementing of absorption heat pump with the existing process. Also researchers have published various articles on conversion of energy from one form to the other, improving the efficiency of the process. As all design and simulation work utilizes the physical properties of fluids, which is black liquor in this case, literature related estimating the physical and thermal properties of black liquor has also investigated. Various Solution techniques for the designing and optimization are also investigated.

2.1 Combined Heat and Power Design

Kraft pulp and paper mill requires heat as well as power to heat process streams and drive electrical machines. All processing sites import power from grid. In most cases, power is generated from heat engines, a device which converts heat into the power. The high temperature heat required for this purpose is produced by burning natural gas, biomass, coal, oil or other fossil fuels. This high temperature heat is used to convert water into high pressure steam by evaporating it and then passing it through the turbine generating the shaft work. The exhaust steam comes out as low pressure steam is often recycled to the boilers for reuse or condensed (losing latent heat). The thermal efficiency of these heat engine is at the most 40%. Other heat engines like, the internal combustion engine burns natural gas, petrol or diesel oil and produces power and releases heat to atmosphere in terms of exhaust gas. Similarly, in gas turbine, fuel is mixed with compressed air and burnt to produce gas at a high temperature and pressure. This hot gas is then passed through a gas turbine to generate power. The low efficiency of heat engines is due to the fact that it rejects a large amount of heat to atmosphere unutilized. If it can somehow be used, in process plants then the overall efficiency of heat engine will improve. Thus, it will be an excellent idea to use heat engines as an integrated with the plant to produce power and to use the available heat as hot utility for the process heating, thus the efficiency of the system can be improved. This is the concept of combined heat and power (CHP). Thus, CHP (also Cogeneration) is the use of a heat engine or a power station to simultaneously generate both useful heat for process and electricity. The efficiency of the CHP system can be increased up to 80%.

Banafsheh Jabbari, Nassim Tahouni, et al. (2013) Studied the design and optimization of combined cooling heating and power system implemented to the existing Canadian Kraft pulp and paper mill. This study followed the process integration criterion. The pinch analysis has been done on the concentration section. Pinch analysis i.e. the structured process to find out the minimum heating utility and minimum cooling utility. For the mentioned study, they have considered the Canadian Kraft pulp and paper mill with five effect evaporator train and backward feed type. For the purpose of pinch analysis, they used pilot software with optimum minimum temperature difference of 5^0 C based on total annual cost. For finding the heating and cooling requirement, GCC has been used which shows the pinch point at 97.1^0 C and minimum heating requirement and cooling requirement are 15.2MW and 17.2MW respectively. Cold water and medium pressure steam (MP) are used supplying the minimum cooling and heating requirements. The CCHP system has been designed by considering two different parts, CHP cycle and AHP system. Designing of both the parts are done separately. The reference Kraft process has steam turbine which not able to produce 144t/h steam at 12 bar and 35 MW power need to run whole plant. By implementing the CCHP system, 144t/h steam at 12 bar and 35 MW of power has been produced. Optimization has been done by using genetic algorithm and multi-objective function are solved considering the total annual cost. To minimize the total annual cost of AHP system, the shell and tube heat exchangers used are optimized with optimum geometry. The economic analysis has been performed and confirmed that the CCHP system is economically feasible with 2.6 years of reasonable payout period.

Mariya Marinova, Enrique et al. (2007) Proposed the methods for positioning of the cogeneration units in the process. They have provided the guidelines for the selection of heat source and sink in order to maximize the energy conversion and to increase the efficiency of the cogeneration unit. The cogeneration unit includes steam turbine, gas turbine and heat pump. This methodology has implemented in the Kraft process. Cogeneration consists gas turbine and an absorption cycle is driven by the exhaust heat from the gas turbine. Integration has been done by implementing the absorption heat pump driven by steam turbine discharge. Process integration practice has been followed. This work presented a systematic methodology for best combination of gas turbine and absorption heat pump as an optimum positioning of both. Combined utility analysis of process is done to enhance the production efficiency and supply of energy by the utilities. Here the exhaust heat is produced and made available. This heat is generated by producing the high pressure steam (HP) in the existing recovery boiler. This energy is sent to the equipment as middle pressure (MP) and low pressure (LP) obtained by expanding high pressure (HP) steam. At the end the heat is transferred in plant to various process streams which can be heated or vaporised. GCC is used to find out the required heating and cooling utilities. The positioning of a vapour re-compression heat pump has been studied well by **Linnhoff et al. (1993)** in order to get maximum gains. For this purpose, evaporator and condenser must be place at across the pinch point. AHP and process limitations are considered as whole by using the phase equilibrium diagram of the Lithium Bromide-Water working fluid pair. **Bakhtiari et al. (2007)** have shown the proper way to generalize AHP. The GCC is used to integrate the evaporator and condenser with the process. The first step is to select the hot stream below the pinch point as receiver of the generator heat and condenser heat pair. A generator is driven by the heat from hot utility. The coefficient of performance (COP) can be estimated by using the empirical correlation. These correlations are proposed by **Alefeld (1983)** and it is used to determine the heat duties.

Nassim Tahouni, B. Jabbari, M. Hassan Panjeshahi (2012) Studied the integration of cogeneration system (CHP) with the Kraft pulp and paper mill which has implemented with the mill. The cogeneration system consists of an combustion chamber, air compressor, a gas turbine with a heat recovery steam generator (HRSG) system with supplementary firing fuel as natural gas which are integrated with a back pressure steam turbine in the existing Kraft pulp and paper mill. This CHP system has been designed to produce 35 MW of power required to run the whole plant and 192 t/h of high pressure superheated steam at 61 bar required to drive the back pressure steam turbine. For simulating the proposed CHP system Aspen plus software is used. Genetic algorithm (GA) is used to optimize this CHP cycle using thermodynamic model to minimize the total annual cost. The objective function is considered which is Total Annual Cost (TAC) of the implemented cogeneration system (CHP) to be minimized and five decision variables are taken in the consideration while carrying optimization. Also, it is shown that by using GA method, total annual cost of the CHP system is decreased by 18.5 % compared to one resulted from general simulation.

S.C. Kamate, P.B. Gangavati (2007) In this study the exergy analysis of bagasse based cogeneration plant to match heat using condensing and back pressure steam turbine has been done. The cogeneration system has been implemented to the 2500 tpd sugar factory. In this study exergy analysis and related methods in addition to the conventional energy analysis which are employed to component efficiencies and identifying the thermodynamic losses. This study has been carried out considering the various ranges of steam inlet conditions. The results show that, the cogeneration steam turbine plant has performed the exergy analysis with efficiency of 0.863 and 0.307 at the optimum steam inlet condition of 475^0C and 61 bar. Study showed that the boiler is the least efficient component where as turbine is the most efficient component of the plant.

2.2 Absorption Heat Pump

B. Jabbari, N. Tahouni et al. (2012) have studied an absorption heat pump (AHP) integrated with the evaporator train i.e. concentration section of Kraft pulp and paper process using pinch analysis. The proposed Water-Lithium Bromide AHP is optimized by minimizing the total annual cost. Genetic algorithm has been used to optimize the design of AHP system. It has been found out that by applying genetic algorithm (GA), the total annual cost of the proposed AHP is decreased by 18% compared to one resulted from simulation. The optimum minimum design of an absorption heat pump (AHP) which is implemented to the Kraft process is carried out by considering the optimum geometry of the shell and tube heat exchanger. The total annual cost has been decreased by 18%.

G. A. Florides, S.A. Kalogirou, S. A. Tassou et al. (2002) have represented the performance and characteristics of a single stage Lithium Bromide-Water absorption heat pump. Heat duties, mass transfer equations and the properties of working fluid pair are specified. Examination of LiBr inlet and outlet percentage ratio, the efficiency of the unit, performance relating to the temperature in the generator have been done. Designing of the shell and tube heat exchanger considering the Lithium Bromide–Water absorption unit is also presented. Single pass and vertical shell and tube heat exchangers have been used as an absorber and an evaporator. A single pass annular heat exchanger was designed as a solution heat exchanger (SHX). The generator and condenser were designed using horizontal shell and tube heat exchangers. Theoretical values calculated and were compared with the experimental values derived for a small experimental unit with a capacity of 1 kW. Finally, for a domestic size absorber cooler, a cost analysis is presented.

2.3 Optimum Shell and Tube Heat Exchanger Geometry

Antonio C. Caputo, Pacifico M. Pelagagge et al. (2007) Presented a novel approach to optimize the geometry of shell and tube heat exchanger. The method allowed to carry optimization of both the equipment design as well as the cleaning policy. The heat transfer area was defined by the given heat duty of the equipment as well as the fouling rate and the flow velocities are defined so that the pressure losses, cleaning interval and capital investment required reaching a maximum allowed fouling resistance are calculated. A genetic algorithm is used to determine the optimal values of both maximum allowable fouling resistance and geometric design parameters so that the minimization of total annual cost of heat exchanger including the maintenance cost, capital cost and operational cost are obtained. In this method the design phase of the heat exchanger geometry is optimized by neglecting maintenance expenditure, while during the carrying the operations, the heat exchanger geometry is initially finalized and then optimization were allowed to approach by only determining a minimum total annual cost based on the existing exchanger. In this work the problems of determination of equipment geometry and cleaning schedule are solved simultaneously so that the entire cost is minimized.

P. Choudhury, S. Chowdhury and B. Mohanty have given an equation based methodology which is proposed for the optimal geometry design of shell and tube heat exchangers. This method is based on tube vs. shell side pressure drop diagram. For this purpose they used well known Bell’s methods which accounts for bypassing of fluid streams, leakage, flow through window & end zones in the shell side of shell and tube heat exchanger. It produces a two-dimensional region of feasible designs based on the operating and geometrical constraints. Every point of this region shows a unique design. The design parameters variation can be represented as a two dimensional feasible curve. These parameters are heat transfer area, shell diameter, cost of exchanger tube spacing, baffle spacing and tube length. Cost and area values are compared to the Kern's method which shows optimization by Bell's method is feasible than the Kern's method.

K. Muralikrishna and U.V. Shenoy (2000) Proposed a methodology for determining the optimal feasible region for designing shell and tube heat exchanger by plotting pressure drop diagram. Feasible region has been drawn considering the operating as well as geometrical constraints during the designing. There is a optimal design in the feasible region for every point. This point represents the plot of tube side pressure drop vs. the shell side pressure drop which is unique design in terms of the shell and tube heat exchanger geometry. These constraints are shell diameter, tube length, baffle spacing etc. For getting the total annual cost corresponding to the specific design, various area curves can be plotted. These curves allows the screening of various design options for detailed rating and targeting the heat exchanger area for minimizing the total cost. The area targeting allows to choose heat exchanger with smaller area with smaller total cost. This minimum total cost yields the optimum pressure drop in tube side as well as shell side. These optimum pressures account the least power consumption and area. This methodology is based on the equations which can be implemented easily.

Marcel Taal, Igor Bulatov et al. (2012) Studied a cost estimation that can have a major impact on project profitability as well as on the technical solution. Various methods have provided different results. This can make a significant difference towards the selection of the right arrangements and real cost of a project. therefore, a proper estimation has to be used to generate enough confidence choosing the right alternative. This study gives an overview of the most common methods that can be used for cost estimation of shell and tube heat exchanger in the chemical process industry and an energy price projections. It has given the relevance of the choice of the most reliable source of energy price and a perfect method used to determine the validity of a project and when choosing between alternative projects.

M. R. Jafari and G. T. Polley (2000) Developed an algorithm for the comparison of cost for the shell and tube heat exchanger considering the tube inserts and tube plate. This algorithm shows the availability of heat transfer can enhanced by tube inserts resulted from the optimization of shell and tube heat exchanger. The relationship between area and pressure drop can be changed. This analysis also shows that there are some opportunities for power reduction. Heat exchanger has to be optimized in order to assess these opportunities. These optimization calculations are very straightforward and can be done using simple procedures. Previous studies have been done to develop few methodologies foe assessing heat transfer, surface area and pumping power (**Webb R. L. and Eckert E. (1972), Bergles et al. (1972)**). For this, friction factor and heat transfer data as a function of Reynolds number is necessary. According to the enhancement analysis, it is possible to optimize the system reducing the heat transfer area, resulting in increased heat capacity or power can be reduced for pumping the fluid.

2.4 Physico -Thermal Properties of Black Liquor

It is necessary knowing the physical and thermal properties of black liquor such as specific heat, density and viscosity at prior. These properties of black liquor are generally depend on the presence of the various organic and inorganic compounds and their concentration in the liquor at the specific temperature and pressure. The organic compounds presents are alkali lignin, iso-saccarinic acid, thioline, polysaccarides, fatty acids and some resins, while inorganic compounds are sodium hydroxide, sodium carbonate, sodium sulphate, sodium sulhide, sodium thiosulphate, elemental sulphur. These compounds are depend on the various papers as presented by **Ramrao et al. (2001)**, **Tamagawa (2005)**, **Slater(2001)**, **Patel and Thanawale (2006)** and thus brief review on the mentioned properties is presented below:

2.4.1 Specific Heat Capacity

Regested (1951) proposed a correlation for the specific heat capacity of the black liquor which is a function of total solid content present in the liquor. Assumption of temperature dependency of specific heat capacity is considered negligible. **Veeramani (1978)** has given the correlation which was proposed by **Regested (1951)**, developed a correlation for the specific heat of pine black liquor and bamboo as,

$$C_{PL} = [1.8 * 10^{-3} T_L - 0.54] * 10^{-2} [\%S] \quad (2.1)$$

Hultin (1968) proposed the correlation for specific heat capacity as

$$C_{PL} = 0.96 - 0.45 * 10^{-2} [\%S] \quad (2.2)$$

Grace and Malcolm (1989) proposed the following correlation as

$$C_{PL} = 1 - [1 - C_{PS}] * 10^{-2} * [\%S] \quad (2.3)$$

2.4.2 Density

Regested (1951) has proposed the correlation for the density of black liquor as a function of total solid concentration and observed temperature.

$$\rho = 1007 + 6 * T_s - 0.495 * T_L \tag{2.4}$$

Density vs. solid concentration of black liquor has been plotted by **Hultin (1968)** at temperature of 90^0 C and given two linear equations for two different case:

case1: for solid concentration of 10to 25%

$$T_S = 177(\rho - 963) \tag{2.5}$$

case2: for solid concentration of 50 to 65%

$$T_S = 146(\rho - 920) \tag{2.6}$$

2.4.3 Viscosity

Kobe and Mccormack (1949), Passinen (1968), Venkatesh and Nguyen (1985) presented viscosity data of black liquors of different concentrations an different black liquors as a function of temperature and solid concentration. The correlation viscosity of black liquor which were recommended by **Ray et al. (1985,1989)**, for various solid concentrations and temperature.

$$\mu = \exp\left[-8.3 * 10^{-3} - 6.55 * 10^{-3}\left(\frac{T_F}{100}\right) + 5.62 * 10^{-3}\left(\frac{T_F}{100}\right)(T_F - 660) + 5.7\left(\frac{T_F}{100}\right) - 1.307\right] \tag{2.7}$$

CHAPTER 3

PROBLEM STATEMENT

The present work has done on the data of Kraft pulp and paper mill which has taken from the literature of an Indian pulp and paper mill. The required data includes the data from concentration section which is used to concentrate the black liquor to make it combustible and the total annual cost of the plant. The detailed explanation about the existing Kraft pulp and paper mill is given below,

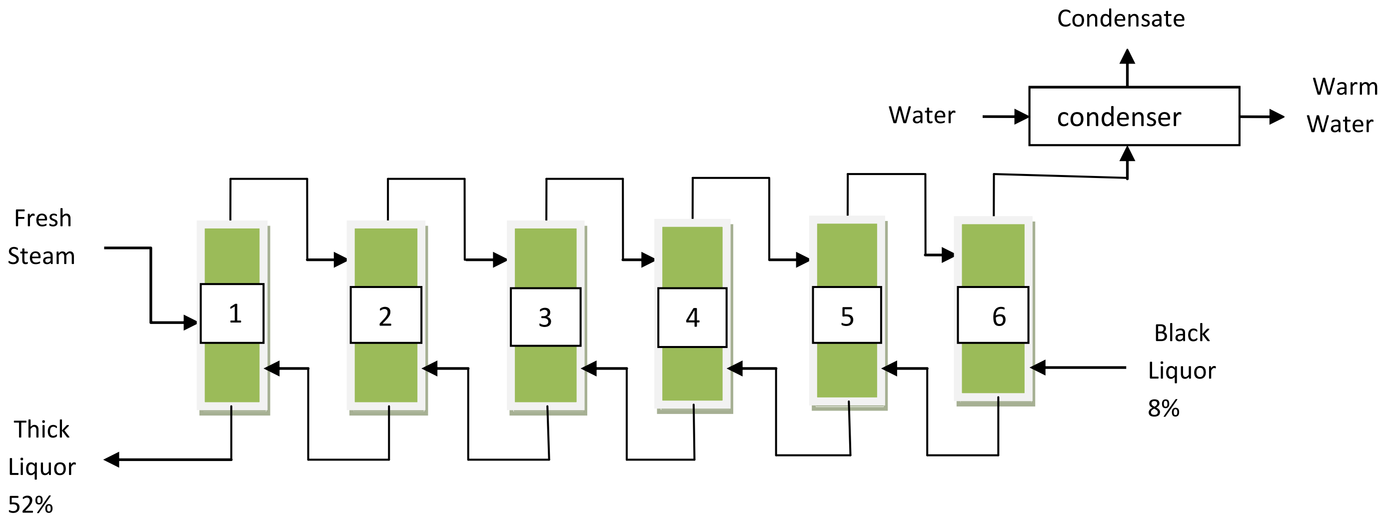

Figure 1.Concentration Section (Evaporator Train)

The plant uses the steam at 160^0 C and at 8 bar to concentrate thin black liquor with mass flow rate of 155 t/h. Plant uses six effect evaporator train for concentration purpose. The black liquor flows at 40 t/h at 54^0 C and at 1.1 bar. The evaporator train is backward feed type, where black liquor is fed to the last i.e. sixth effect and the live steam is fed to the first effect.

The vapours coming out of each effect is used as the heating medium for the other. The decrease in pressure actually causes the evaporation in the evaporator. The vapour from last effect is sent to the condenser. Various temperature and pressure conditions are used in the train. Temperature and pressure decreases from first effect to the last effect.

Pumps are provided to feed the black liquor from one effect to other. The vapour from last effect is sent to the condenser where it get condensed and the thick liquor from the first effect is sent to the recovery boiler to generate the live steam and the power which is used to run the plant. The whole plant needs 38 MW power and 155t/h steam. The existing plant with the recovery boiler is not sufficient to produce 38 MW power and 155t/h steam. Therefore, the plant needs to depend on the external source of electricity from grid and the remaining steam supply. The recovery boiler is able to produce 17 MW power, for remaining requirement it has to take power from grid. Stream data of concentrating section in evaporator train is given below,

Table 1. Stream Data of Concentration Section

	Stream	T_{in}(°C)	T_{out}(°C)	Q (MW)
Heating demand	Effect1 BL BLev	117 120	120 120	0.24 15
	Effect2 BL BLev	96 117	117 117	0.5 14.5
	Effect3 BL BLev	71 96	96 96	1.4 13
	Effect4 BL BLev	63 71	71 71	2.4 10.6
	Effect 5 BL BLev	54 63	63 63	2.7 15
	Effect 6 BLev	54	54	15
Cooling demand	Vap1 to effect 2	120	120	15
	Vap2 to effect 3	117	117	14.5
	Vap3 to effect 4	96	96	13
	Vap4 to effect 5	71	71	10.6
	Vap5 to effect 6	63	63	15
	Vap 6 to Condenser	54	54	15

As existing Kraft pulp and paper mill, it has to depend on the external source of electricity and steam demand.

Therefore it is reasonable to implement and study a CCHP system supplying steam demand as well as the electricity demand. By implementing a CCHP system we can generate power of 38 MW and 155 t/h steam by decreasing the total annual cost with reasonable payout period. By implementing CCHP system, the required hot and cold utilities can be minimized. For implementing the CCHP system, it has to follow the process integration criterion. Black liquor enters the last effect with 8% solid. It has to concentrate up to 52% solid to make it combustible. This process is done in the six effect evaporator train and consumes the highest degree of energy in the Kraft process. Therefore, the concentration section has been considered for the improvement of efficiency.

CHAPTER 4
METHODOLOGY

4.1 Overview

The methodology is shown in the Figure 2 given below. In a primary stage, Pinch Analysis has been done to carry out basic thermal analysis, i.e. process utilities (cooling and heating requirements and maximum process heat recovery). The individual composite curves of hot and cold streams, utility level targeting (optimal use of hot and cold utility use) by using the grand composite curve(GCC) has done. The composite curves and the grand composite curve(GCC) of black liquor evaporating train(concentration section) shows the pinch point and minimum heating and cooling requirements, that have to be supplied by the external sources of heating and cooling energies.

In the existing process, intermediate pressure (MP) steam is used to supply the heating requirement and fresh water as cold utility is used to supply the cooling requirement. Two separate parts are considered for the designing and integration of CCHP system, first CHP system and AHP system. These two systems are designed according to the energy demands. The steam discharged from steam turbine relates these two parts with each other. Optimization of the proposed CCHP system with objective to minimize the total annual cost(TAC) has been done supplying energy requirements of the mill by considering the CCHP system into two mentioned parts i.e. CHP system and AHP system. To optimize proposed system, genetic algorithm(GA) is used. The optimization tool available in the Matlab software is used, in which the required equations are entered, solved and values of objectives are calculated according to the given decision variables. The objective optimization has been carried out in this work with different objective functions, first the minimization of total annual cost(TAC) of the CHP system and AHP system.

4.2 Concentration Section

Concentration section consists of six effect falling film evaporator train. The steam is fed to the first effect and the black liquor is fed to the last effect. The train is basically backward feed type. For the simulation purpose aspen plus software is used. For each evaporator, shell and tube heat exchanger is considered with the two phase flash. The pressure in first effect is considered as 1.5 bar and in last effect, it is 0.14 bar. Separate pumps are provided to feed the black liquor to individual effect. Zero pressure drop is taken in each flash, while the reduction in pressure and temperature are the actual driving forces for the evaporation.

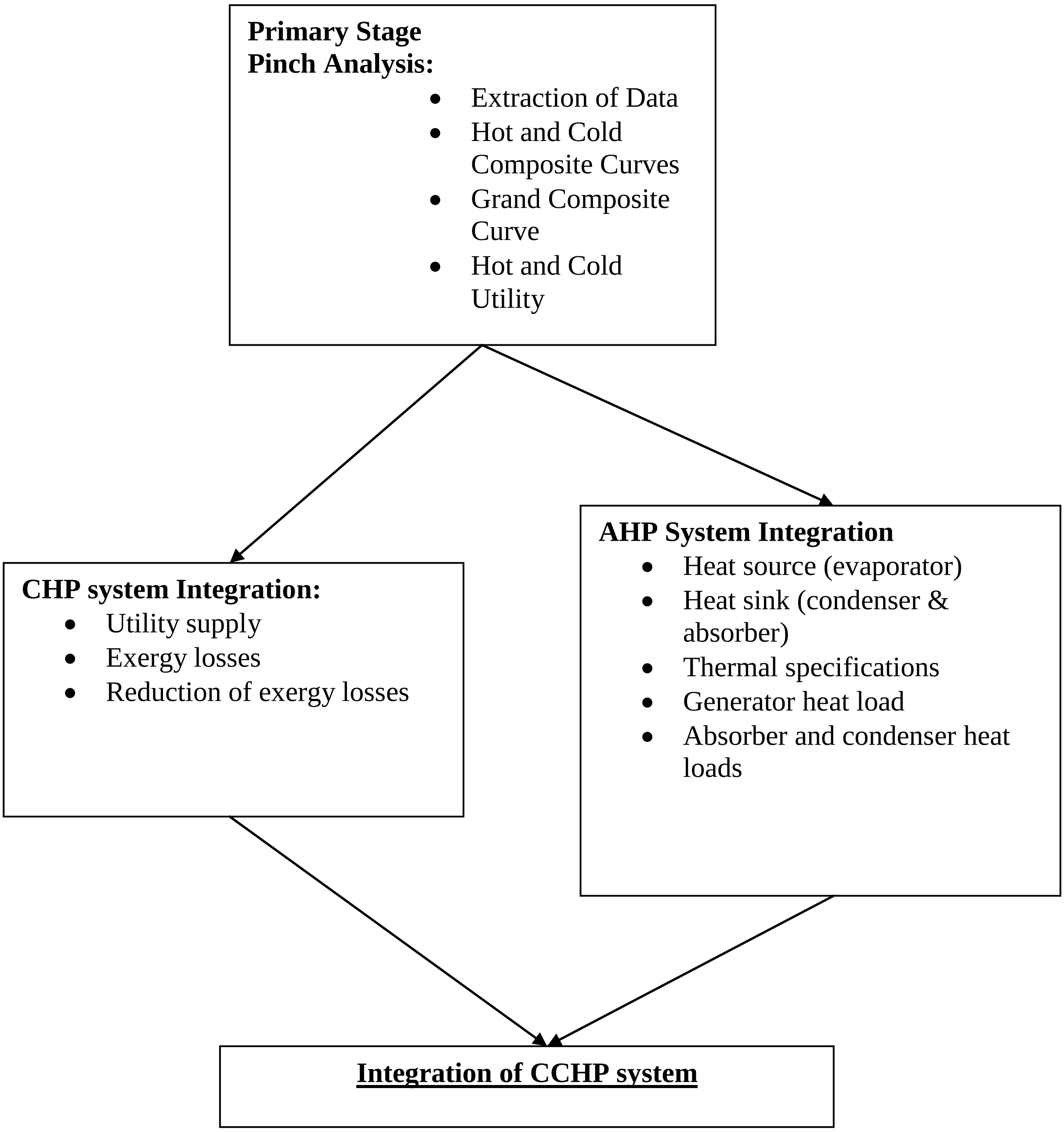

Figure 2. Integration of CCHP System Methodology

The simulated flow sheet is shown in figure 3. Middle pressure steam is used as a heating source at 160^0 C and 8 bar. While the black liquor is sent at 54^0 C and at 1.1 bar with 8% solid (wt %). The vapours from last effect are sent to the condenser. The concentrated black liquor has been come out at 120^0 C and with 52% solid (Wt%). The pressure decreases from1.5 bar in first effect to the 0.14 bar in the last effect.

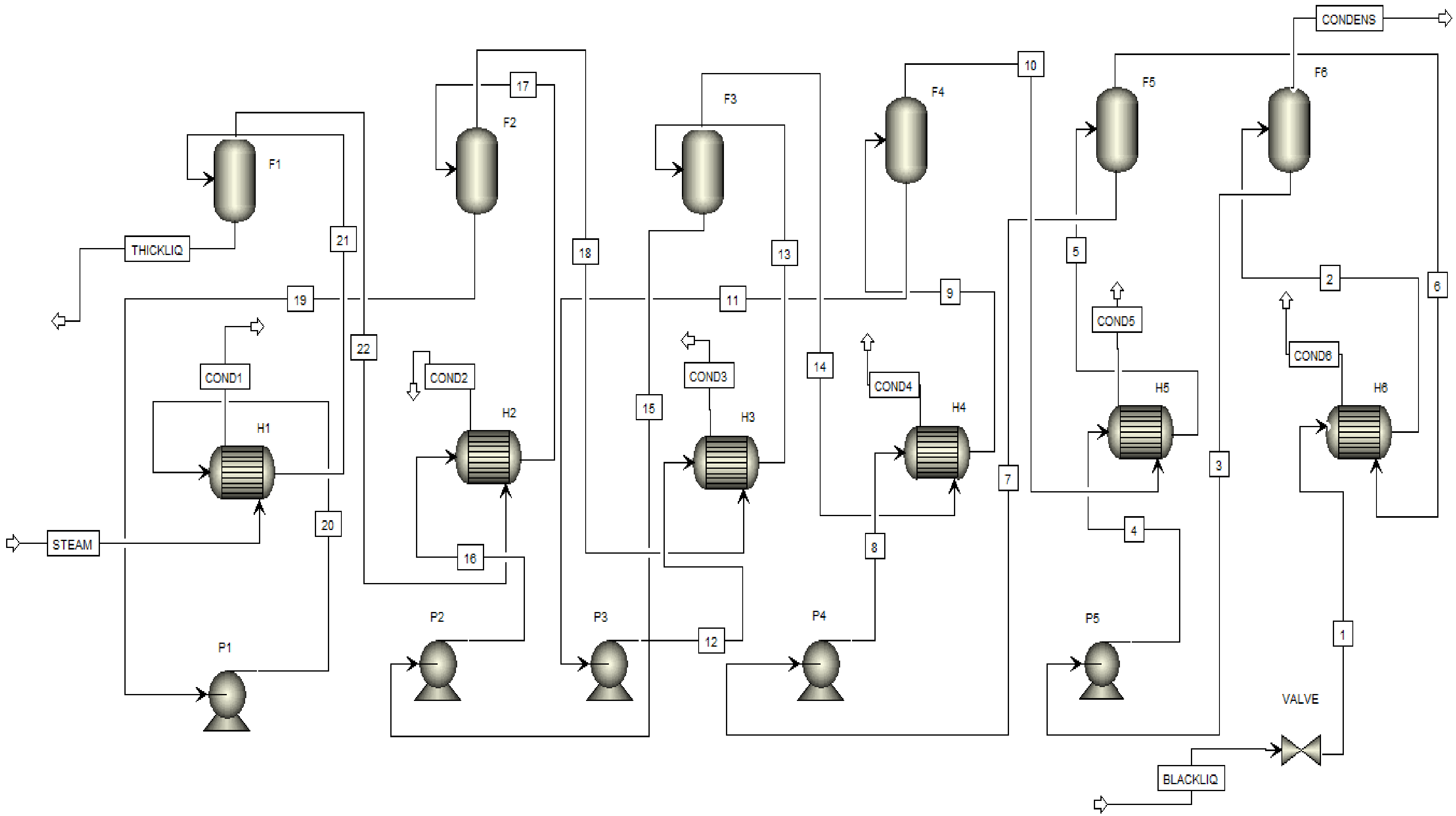

Figure 3. Simulation of Concentration Section (Evaporator Train)

4.3 Pinch Analysis

Definition of Pinch Analysis tells it is a structured approach used minimizing its need for heating and cooling energy supplied by hot and cold utilities and maximizing recovery of internal heat inside a process. **Douglas (1988), Linnhoff (1993), Smith (1995)** all have described the principles and application in a number of engineering manuals and reference works. It is well described that the pinch analysis must be done in a process to ensure real net energy savings. The central idea of Pinch Analysis is to represent a shifted temperature vs. enthalpy of streams diagram for all possible streams causing heat transfer inside the process; the heat which is available is shown by the Hot Composite Curve (HCC) and energy need in the process is shown by the Cold Composite Curve (CCC). Figure 4 shows the combined composite curves (CCC) diagram of the black liquor (BL) concentration section representing hot and cold streams.

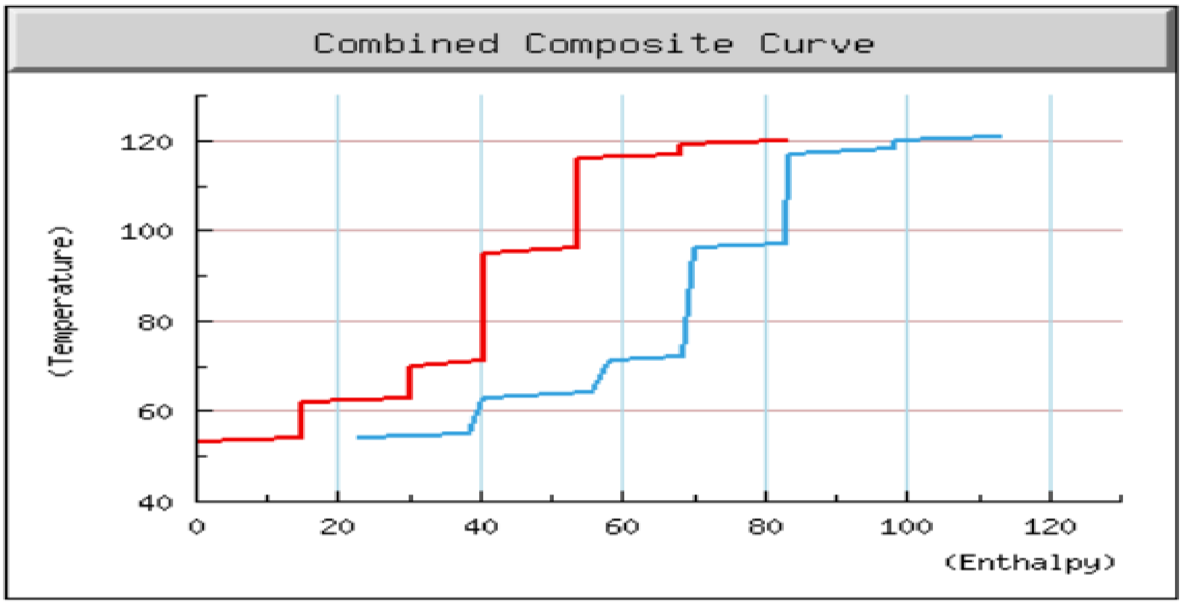

Figure 4. Combined Composite Curve

The optimum minimum temperature difference (ΔT_m) for this process which can be characterized by very low temperature approach and no heat transfer within the process has been varied and can be fixed considering the minimum heat utilities. the GCC shows the pinch point, minimum heating and cooling requirements which have to be supplied by the process. The Grand Composite Curve shown in figure 5 allows to satisfy the needed heating and cooling demands by making utilities available to utilize.

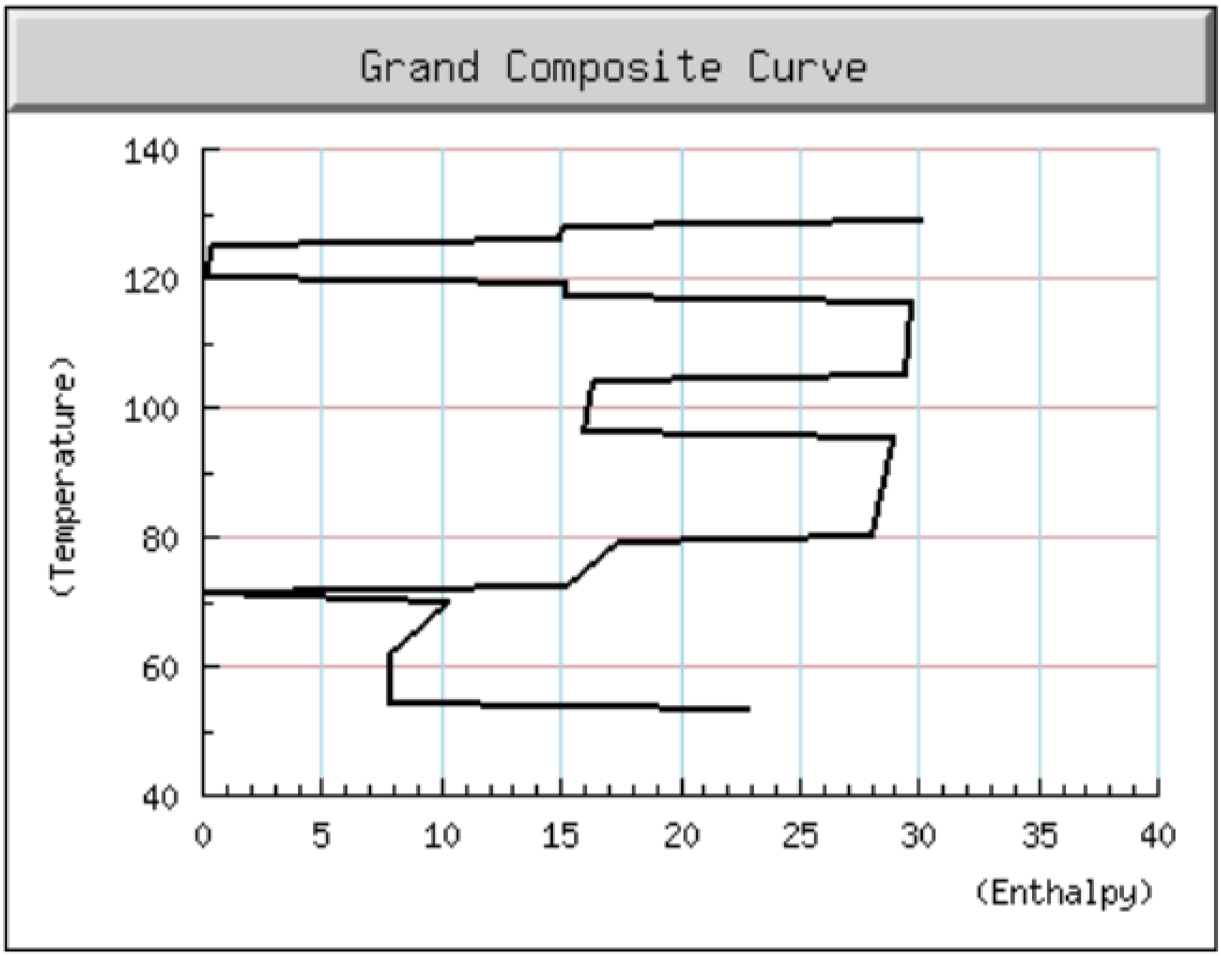

Figure 5. Grand Composite Curve

Specific set of hot and cold streams and the net thermal requirements in successive temperature zones has been provided by the grand composite curve (GCC). The GCC can be generated graphically from the hot and cold composite curves shifted with respect to the optimum minimum temperature difference. The GCC is a plot of the shifted temperature and the enthalpy.

CHAPTER 5

CCHP SYSTEM : SCHEME PROPOSAL

As mentioned earlier the Kraft pulp and paper mill requires 155 t/h steam at 8 bar and 38MW power to run whole plant. The back pressure steam turbine present in the exiting Kraft pulp and paper mill requires high pressure steam at superheated condition. However, the recovery boiler present in existing mill is not able to produce steam and power to satisfy the steam and power demand of the mill. Therefore, the rest must be supplied by external source of electricity i.e. from grid. hence, it would be reasonable implementing a gas turbine system with a heat recovery steam generator system (HRSG) to supply the power demand, as well as to produce the required superheated steam at mentioned conditions. The hot flue exhaust gases from the gas turbine enters to the heat recovery steam generator (HRSG) system producing the high pressure steam which drives the steam turbine generating the power and low pressure steam, which can be used for other process applications. In this work, some part approximately 11t/h steam at low pressure is used to drive the generator of an AHP system upgrading low temperature heat of the vapors coming from the last effect in the concentration section of the mill. The CCHP system, in actual consists of a CHP system integrated to an absorption cycle (AHP system) to generate heating, cooling and power demand.

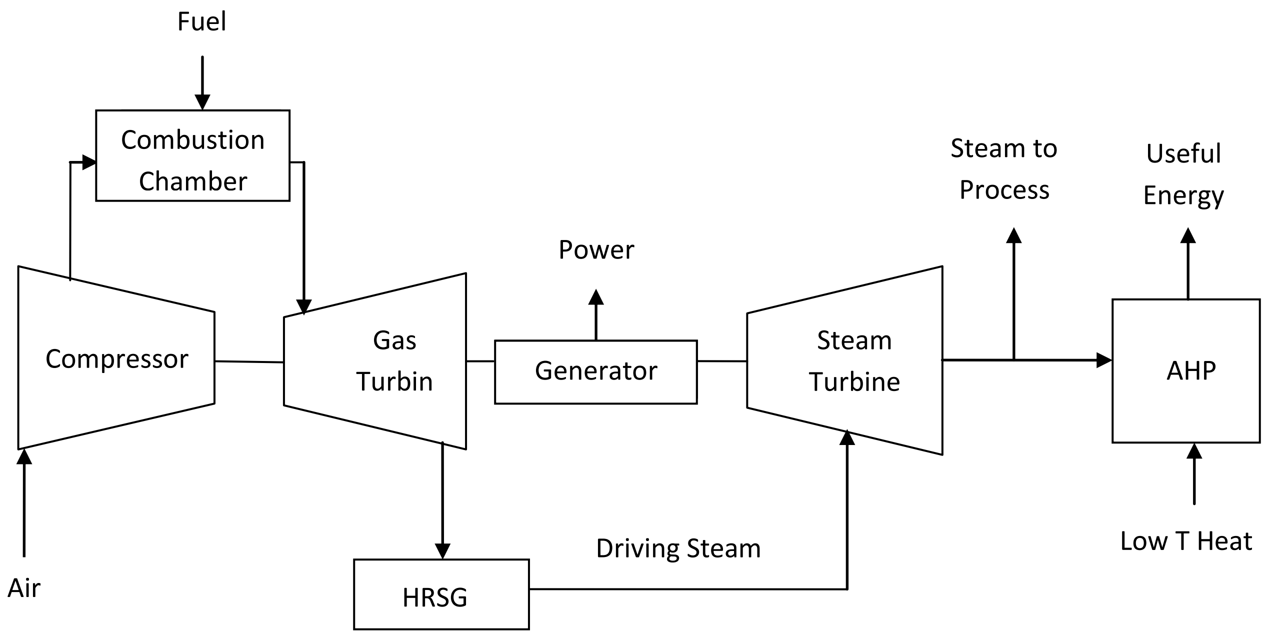

Figure 6. The Diagram of Proposed CCHP System

The CHP system consists of HRSG (heat recovery steam generator) system, gas turbine and combustion chamber for complementary firing. A proposed scheme is depicted in fig.

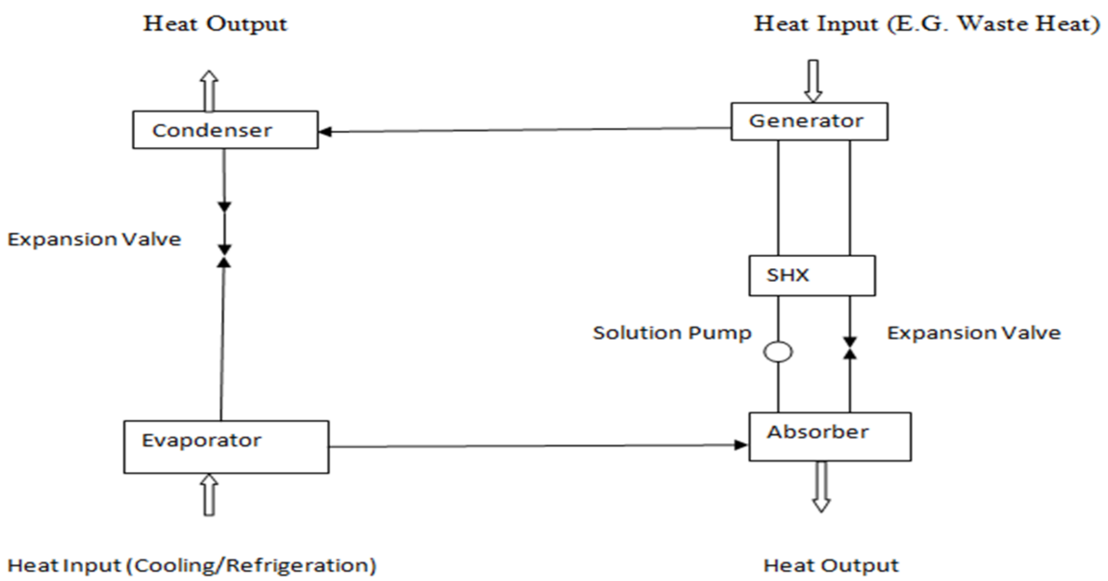

Figure 7. Absorption Heat Pump

Also, a schematic diagram representing the AHP system is given in figure 5. It consists five heat exchangers known as a condenser, a generator, an evaporator, an absorber and a solution heat exchanger (SHX).

Hence, by integrating the CCHP system, the electricity demand as well as steam demand of pulp and paper mill can be supplied as well as the heating and cooling requirements in the evaporator train is reduced.

CHAPTER 6
INTEGRATION OF PROPOSED CCHP SYSTEM

Integration of proposed CCHP system has been considered in two parts, the CHP system and the AHP system, which are designed and optimized according to specific energy and steam demands. By applying the CHP system, 38 MW power required to run the whole plant and 166 t/h of steam needed for steam turbine are supplied. Also, by implementing the AHP system, low temperature heat in black liquor (BL) concentration section has been upgraded by reducing the heating demand (30.14 MW) and cooling demand (22.9MW). These two parts are connected to each other by the medium pressure steam discharged from back pressure steam turbine.

6.1 Integration of CHP System

In this part a gas turbine (GASTUR) is integrated with the existing steam turbine as shown in simulation below. As already mentioned the back pressure steam turbine, it needs 166 t/h steam at 250^0 C and 40 bar to do shaft work. Hence the required medium pressure steam has produced and remaining of the power demand has been supplied by implementing the CHP system. Aspen plus software is used to simulate the CHP system. By simulating CHP system in aspen plus software, the flow rates, temperature and pressure conditions are found out. The flow sheet showing the simulation of CHP system is shown below in figure 8.

For supplementary firing natural gas is used in the combustion chamber. First air is compressed and then fed to the combustion chamber where combustion of natural gas takes place. Based on the basic design shown in simulation, 252 t/h normal air (stream 1) after compressing in the compressor (COMP) with 6 t/h natural gas (NATGAS1) fires in the combustion chamber (COMCHAM) follows the gas turbine (GASTUR). The flue exhaust gases (stream2) at 1100^0C are expanded by the gas turbine to 650^0C and 1.1 bar and produced 14.34MW electricity (WORK2). The HRSG system consisting of a super-heater (SUPHEAT), an evaporator (EVAPOR) and an economizer (ECONO), equipped with a duct burner (DUCTBUR) for supplementary firing which is considered to be single pressured. Flue exhaust gas coming out from gas turbine (stream 3) plus 4.9 t/h natural gas (NATGAS2) fed to the HRSG system which has produced 166 t/h steam at 250^0C and 40 bar (stream 10), which is supplied to the steam turbine (STEAMTUR). In this back pressure steam turbine hot high pressure steam at 40 bar is expanded to 8 bar and 188 ^{0}C and producing 23.56 MW power (WORK3). The medium pressure steam produced in the steam turbine can be used to fulfill the steam requirement of the whole mill.

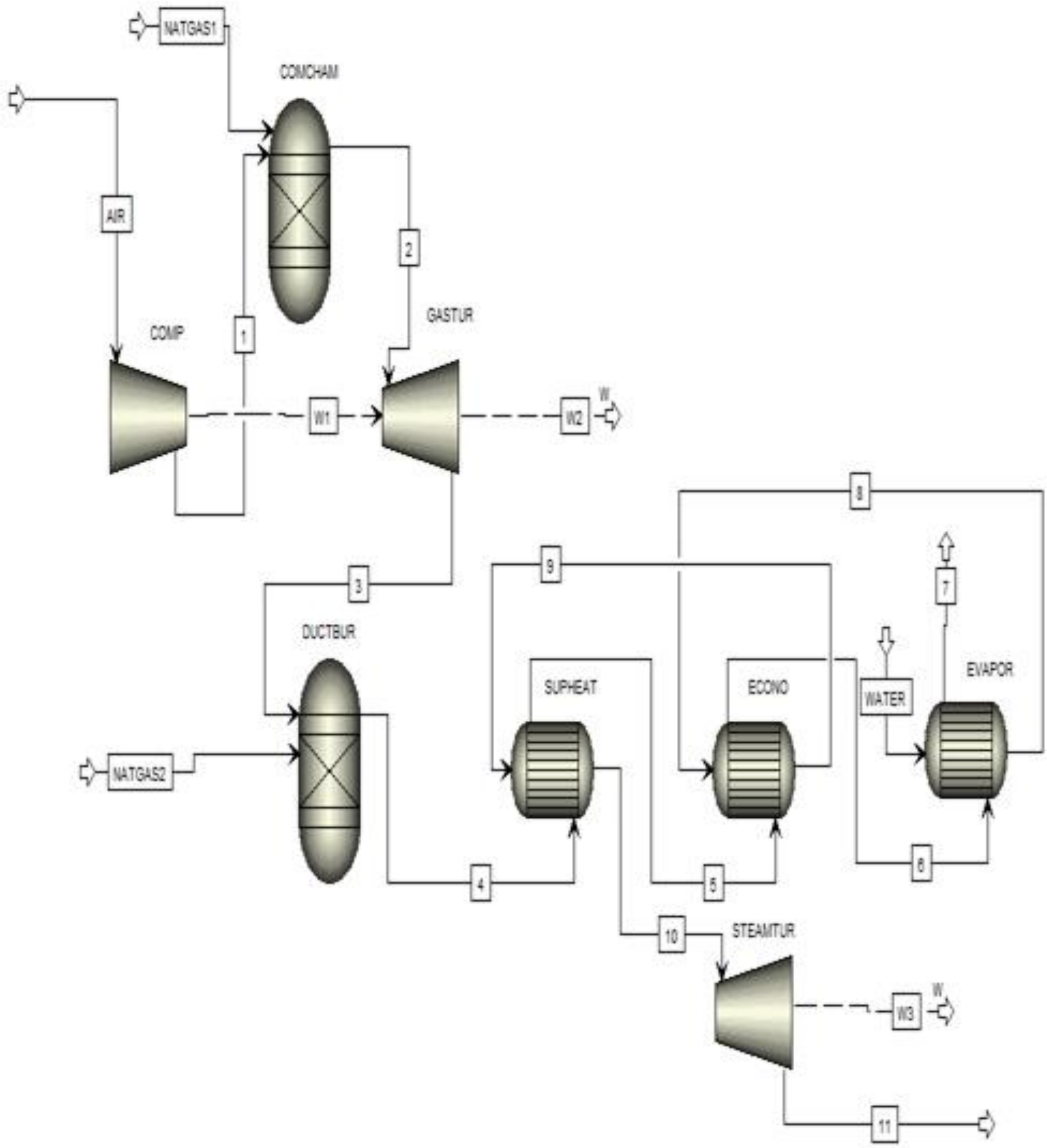

Figure 8. Simulation of CHP System

6.2 AHP Integration

The GCC plays a crucial role in the implementation of the AHP system. GCC is used to select a cold stream above the pinch and hot stream below the pinch to supply the energy requirement of evaporator and to receive the released heat from the absorber and condenser. Phase equilibrium diagram of Lithium Bromide-Water system is used to find the temperature of absorber, condenser, evaporator and generator of AHP system.

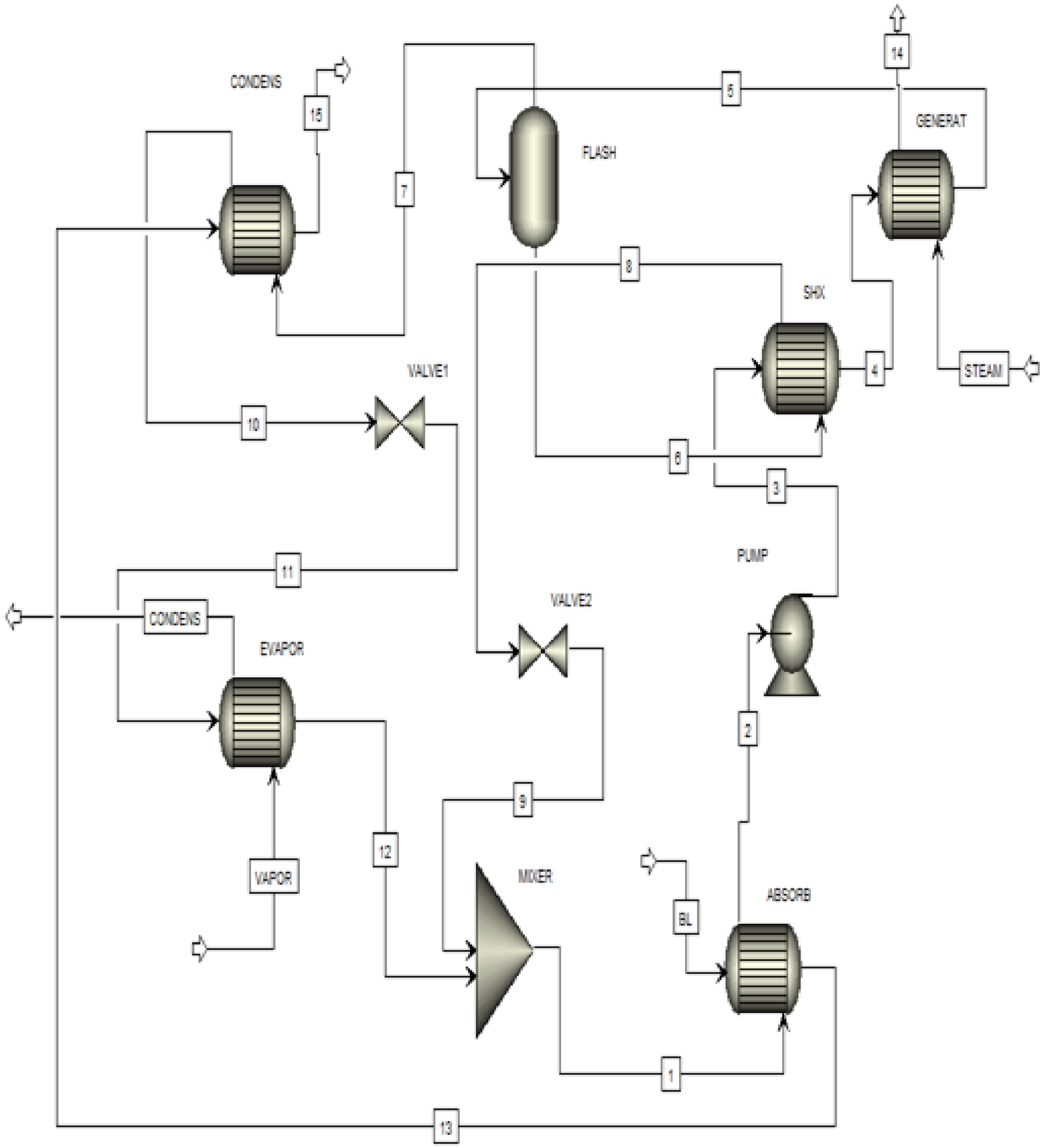

Figure 9. Simulation of AHP System

The vapors coming out from the last effect i.e. from effect six, which is sent to the condenser has selected as the source of heat at low temperature by heat load of 22.9MW at 54^0 C and the black liquor from the first effect has selected as low temperature heat sink with heat duty of 30.14MW at 120^0C. LiBr-water working fluid pair is used for heat upgrading. As driving heat source of generator ($Q_{GENERAT}$), medium pressure steam coming out of the steam turbine is used. The working fluid lithium bromide-water solution enters the generator with 66% lithium bromide weight fraction as weak solution and comes back to the absorber with 70% ammonia weight fraction as strong solution. For simulation purpose the aspen plus software is used. Simulation design is shown below in figure 9.

The performance of heat exchanger can be improved between strong solution and weak solution by using solution heat exchanger (SHX). Evaporator, absorber, condenser and generator are simulated by the heat exchanger model. The solution heat exchanger is simulated with heat exchanger model with two phase flash. The 11t/h steam discharged from the steam turbine at low pressure is used to supply the generator heat duty ($Q_{GENERAT}$) 17.44MW separating weak solution and gases refrigerant. From generator, the gases refrigerant is sent to the condenser, where it rejects heat and comes back to solution heat exchanger followed by the absorber. Useful cooling is produced in the condenser and absorber by expanding the refrigerant. The black liquor from first effect of evaporator train which has the total amount of useful heat, $Q_{CONDENS}$+Q_{ABSORB} with 30.14MW and Q_{EVAPOR} is 12.7MW.

CHAPTER 7
PROPOSED CCHP SYSTEM - OPTIMIZATION

The optimization of the designed CCHP system has been done to minimize the total annual cost and to fulfill energy requirements of the Kraft process. In the optimization procedure, again the CCHP system has been considered into two mentioned parts i.e. CHP system and AHP system. To optimize the proposed integrated CCHP system genetic algorithm (GA) and feasible region method are used, so for finding the best design the time taken by GA is relatively short. Optimization tool has used in which the required equations are entered and solved and the values of objective functions are calculated according to decision variables. Optimization tool is available in Matlab software. For optimization of AHP system, feasible region method is used.

7.1 Optimization of CHP System

Optimization is carried out in this work by considering minimization of the total annual cost of CHP cycle. The objective function (given by **Tahaouni et al. (2012)**) is shown below,

$$TAC = \sum Ci * AF * \emptyset_r + C_{FUEL} * 3600 * H \tag{7.1}$$

TAC consists of the cost of each individual components (Ci), annual factor AF, the cost of fuel consumption (C_{FUEL}) and maintenance cost (Ør). These cost equations have expressed as functions of thermodynamic variables, which are the basic optimization parameters. The capital costs of combustion chamber ($C_{COMCHAM}$), compressor (C_{COMP}), gas turbine (C_{GASTUR}) and HRSG system (C_{HRSG}) are considered from literature.

$$C_{COMP} = \left(71.1 * \frac{m_{AIR}^{0}}{0.92} - \eta_{COMP}\right) * p_c * lnp_c \tag{7.2}$$

$$C_{COMCHAM} = \left(48.08 * \frac{m_{AIR}^{0}}{0.995} - \frac{P_2}{P_1}\right)(1 + \exp(0.018T_2 - 36.4)) \tag{7.3}$$

$$C_{GASTUR} = \left(479.34 * \frac{m^0_{NATGAS\,1}}{0.92} - \eta_{GASTUR}\right) * \log\left(\frac{P_2}{P_3}\right) * (1 + \exp(0.036T_2 - 54.4)) \tag{7.4}$$

$$C_{HRSG} = 6570 * \left(\left(\frac{Q_{ECONO}}{(\Delta T_{lm})_{ECONO}}\right)^{0.8} + \left(\frac{Q_{EVAPOR}}{(\Delta T_{lm})_{EVAPOR}}\right)^{0.8} + \left(\frac{Q_{SUPEH}}{(\Delta T_{lm})_{SUPEH}}\right)^{0.8}\right) + 2127m^0_{steam} + 1184.4{m^0_{NATGAS\,2}}^{1.2} \tag{7.5}$$

For determining the investment cost of duct burner ($C_{DUCTBUR}$) the following expression can be used,

$$C_{DUCTBUR} = \eta_{combustion} * 7000 * LHV * m^0_{NATGAS\,2} \tag{7.6}$$

Fuel cost can be determined by following relation,

$$C_{FUEL} = c_f * LHV * (m^0_{NATGAS\,1} + m^0_{NATGAS\,2}) \tag{7.7}$$

AF = 0.199, H = 8000 hours

Where c_f is the fuel cost per unit energy and has given by,

$$c_f = 0.003\$/MJ$$

Specific heat capacity of flue gases can be determined by the following relation,

$$C_p(T) = 0.991615 + \left(\frac{6.99703T}{10^5}\right) + \left(\frac{2.7129T^2}{10^7}\right) - \left(\frac{1.22442T^3}{10^{10}}\right) \tag{7.8}$$

Specific heat capacity of black liquor can be determined by the following relations given by literature,

By **Hultin (1968)**

$$C_{PL} = [1.8 * 10^{-3}T_L - 0.54] * 10^{-2}[\%S]$$

$$C_{PL} = 0.96 - 0.45 * 10^{-2}[\%S]$$

By **Grace and Malcolm (1989)**

$$C_{PL} = 1 - [1 - C_{PS}] * 10^{-2} * [\%S]$$

Where, s is the mass fraction of solid in black liquor.

By **Zaman and Fricke (1996)**

$$C_{PL} = 3.98 + 6.19 * 10^{-4}(T) + (c + dT)$$

Where, c and d are concentration dependent constants.

Some thermodynamic variables are given below,

Table 2. Thermodynamic Variables of CHP System

State	AIR,NATGAS1	1	2	3	4	5	6	7	Water	9	10	11	12
P(bar)	1.01	P_1	P_2	1.1	1.06	-	-	1.01	40	40	40	40	8
T(K)	298	T_1	T_2	T_3	T_4	T_5	T_6	T_7	298	439.8	453.9	562.3	328.4

Logarithmic mean temperature difference across each shell and tube heat exchanger in HRSG system is given below,

For super heater (SUPEH),

$$(\Delta T_{lm})_{SUPEH} = \frac{(T_4 - T_{11}) - (T_5 - T_{10})}{\ln\left(\frac{T_4 - T_{11}}{T_5 - T_{10}}\right)} \tag{7.9}$$

$$(\Delta T_{lm})_{SUPEH} = \frac{(T_4 - 562.3) - (T_5 - 453.9)}{\ln\left(\frac{T_5 - 562.3}{T_5 - 453.9}\right)}$$

For evaporator (EVAPOR),

$$(\Delta T_{lm})_{EVAPOR} = \frac{(T_5 - T_{10}) - (T_6 - T_9)}{\ln\left(\frac{T_5 - T_{10}}{T_6 - T_9}\right)} \tag{7.10}$$

$$(\Delta T_{lm})_{EVAPOR} = \frac{(T_5 - 453.9) - (T_6 - 439.8)}{\ln\left(\frac{T_5 - 453.9}{T_6 - 439.8}\right)}$$

For economizer (ECONO),

$$(\Delta T_{lm})_{ECONO} = \frac{(T_{WATER} - T_7) - (T_9 - T_6)}{\ln\left(\frac{T_{WATER} - T_7}{T_9 - T_6}\right)} \quad (7.11)$$

$$(\Delta T_{lm})_{ECONO} = \frac{(298 - T_7) - (439.8 - T_6)}{\ln\left(\frac{298 - T_7}{439.8 - T_6}\right)}$$

In the case of optimization of CHP system, five decision variables have been considered while carrying the optimization: pressure ratio in compressor (p_c); efficiency of compressor (isentropic) (η_c); efficiency of gas turbine (isentropic) (η_g); temperature of combustion gases entering the gas turbine (T_2); and the mass flow rate of fuel to the HRSG supplementary firing system ($m^0_{NATGAS2}$). The upper and lower bounds for decision variables are given below,

$8 < p_c < 18$; $0:65 < \eta_c < 0:92$; $0:65 < \eta_g < 0:92$; $900K < T_2 < 1250K$; $0 < m^0_{NATGAS2} < 6$

For heat exchange in HRSG system, some constraints have to be satisfied while carrying the optimization:

$\Delta T_p = T_6 - T_{10} > 0$; $T_5 > T_{10}$; $T_7 > T_{WATER}$; $T_4 > T_{11}$; $T_7 > 325$

7.2 Optimization of AHP System

For minimizing the total annual cost of the proposed AHP system, the heat exchanger geometry has been varied. Condenser and absorber have produced 30.14MW of heating energy and 12.7MW of cooling energy at the specific temperatures. Few heat duties and Unknown temperatures have found by the simulation carried out. Shell and tube heat exchangers are modeled as all heat exchangers. Phase change as well as single phase have been considered in the AHP heat exchangers while carrying the optimization.

Tube side and shell side pressure drop have been related with the shell and tube heat exchanger geometry which includes the tube length, shell diameter and the baffle spacing.

Shell diameter can be found out by equation given below,

$$D_s = a + bD_t(D_t)^{1/n} \tag{7.12}$$

Baffle spacing and shell diameter are related by equation,

$$R_{bs} = \frac{L_{bc}}{D_s} \tag{7.13}$$

Area of heat exchanger is given by,

$$A = \pi D_t L(NS)\left(\frac{D_s - a}{bD_t}\right)^n \tag{7.14}$$

Tube side pressure drop can be found out by following,

$$G_t = \rho_t v_t = \frac{4M_t(NT)}{\pi D^2 N_t} \tag{7.15}$$

$$\Delta P_t = C_1 \frac{L}{(D_s - a)^{n(2+mt)}} + C_2 \frac{1}{(D_s - a)^{2n}} \tag{7.16}$$

the constants C_1 and C_2 can be calculated as,

$$C_1 = \frac{2K_t(NT)^{3+mt}(NS)(4M_t)^{2+mt}(bD_t)^{n(2+mt)}}{\rho_t \mu_t^{mt}(\mu_t/\mu_{tw})^{ac}\pi^{2+mt}D^{5+mt}} \tag{7.17}$$

$$C_2 = \frac{20(NT)^{3+mt}(NS)M_t^2(bD_t)^{2n}}{\rho_t \pi^2 D^4} \tag{7.18}$$

shell side pressure drop can be found out by following relations,

$$\Delta P_s = \frac{2f_s G_s^2 D_s(N_b + 1)(NS)}{D_e \rho_s(\mu_s/\mu_{sw})^{0.14}} \tag{7.19}$$

$$f_s = K_s Re_s^{ms} \tag{7.20}$$

$$G_s = \rho_s v_s = \frac{M_s}{L_{bc} D_s (1 - D_t/L_{tp})} \tag{7.21}$$

$$\Delta P_s = C_3 \frac{L}{R_{bs}^{3+ms} D_s^{4+2ms}} \tag{7.22}$$

the constant C_3 can be calculated as,

$$C_3 = \frac{2K_s D_e^{ms-1} (NS) M_s^{2+ms}}{\mu_s^{ms} \rho_s (\mu_s/\mu_{sw})^{0.14} (1 - D_t/L_{tp})^{2+ms}} \tag{7.23}$$

Equations for heat duty and heat transfer coefficients are given below,

Heat transfer coefficient(overall) is given by,

$$\frac{1}{U} = \frac{1}{h_S} + R_d + \frac{D_t \ln\left(\frac{D_t}{D}\right)}{2k} + \frac{D_t}{D}\left(\frac{1}{h_t}\right) \tag{7.24}$$

Individual shell side and tube side coefficients are given by,

$$\frac{h_s D_e}{k_s} = 0.36 Re_s^{0.55} Pr_s^{0.33} (\mu_s/\mu_{sw})^{0.14} \tag{7.25}$$

$$\frac{1}{h_s} = \frac{D_s^{1.1} R_{bs}^{0.55}}{C_4} \tag{7.26}$$

C_4 can be calculated by,

$$C_4 = \frac{0.36 k_s}{D_e} \left(\frac{C_{ps} \mu_s}{k_s}\right)^{0.33} \left(\frac{\mu_s}{\mu_{sw}}\right)^{0.14} \left(\frac{D_e}{\mu_s}\right)^{0.55} \frac{M_s^{0.55}}{(1 - D_t/L_{tp})^{0.55}} \tag{7.27}$$

$$\frac{h_t D}{k_t} = 1.86 (Re_t Pr_t D/L)^{0.33} (\mu_t/\mu_{tw})^{0.14} \qquad \text{for } Re_t \leq 2100 \tag{7.28}$$

$$\frac{h_t D}{k_t} = 0.116 (Re_t^{0.66} - 125) Pr_t^{0.33} (\mu_t/\mu_{tw})^{0.14} \qquad \text{for } 2100 \leq Re_t \leq 10000 \tag{7.29}$$

$$\frac{h_t D}{k_t} = C_t Re_t^{0.8} Pr_t^{0.33} (\mu_t/\mu_{tw})^{0.14} \qquad \text{for } Re_t > 10000 \tag{7.30}$$

combining above equations give the following relations,

$$L(D_s - a)^n = C_5 \left(\frac{D_s^{1.1} R_{bs}^{0.55}}{C_4} + \frac{L^{0.33} (D_s - a)^{\frac{n}{3}}}{C_6} + C_7 \right) \qquad \text{for } Re_t \ll 2100 \tag{7.31}$$

$$L(D_s - a)^n = C_5 \left(\frac{D_s^{1.1} R_{bs}^{0.55}}{C_4} + \frac{1}{C_8 (1 + (D/L)^{0.66}) \left(\frac{C_9}{(D_s - a)^{\frac{2n}{3}}} - 125 \right)} + C_7 \right) \tag{7.32}$$

$$\text{for } 2100 \leq Re_t \leq 10000$$

$$L(D_s - a)^n = C_5 \left(\frac{D_s^{1.1} R_{bs}^{0.55}}{C_4} + \frac{(D_s - a)^{0.8n}}{C_{10}} + C_7 \right) \qquad \text{for } Re_t > 10000 \tag{7.33}$$

C_5 ,C_6 ,C_7 ,C_8 ,C_9 and C_{10} can be calculated using following relations,

$$C_5 = \frac{Q(bD_t)^n}{\pi D_t (NS) F (LMTD)} \tag{7.34}$$

$$C_6 = \frac{1.86 k_t}{D_t} \left(\frac{\mu_t}{\mu_{tw}} \right)^{0.14} \left(\frac{C_{pt} \mu_t}{k_t} \right)^{0.33} \frac{(4M_t)^{0.33} (NT)^{0.33} (bD_t)^{n/3}}{(\pi \mu_t)^{0.33}} \tag{7.35}$$

$$C_7 = R_d + \frac{D_t}{2k} \ln \frac{D_t}{D} \tag{7.36}$$

$$C_8 = \frac{0.116 k_t}{D_t} \left(\frac{\mu_t}{\mu_{tw}} \right)^{0.14} \left(\frac{C_{pt} \mu_t}{k_t} \right)^{0.33} \tag{7.37}$$

$$C_9 = \frac{(4M_t)^{0.66} (NT)^{0.66} (bD_t)^{2n/3}}{(\pi D \mu_t)^{0.66}} \tag{7.38}$$

$$C_{10} = \frac{k_t C_t}{D_t} \left(\frac{C_{pt} \mu_t}{k_t} \right)^{0.33} \left(\frac{\mu_t}{\mu_{tw}} \right)^{0.14} \frac{(4M_t)^{0.8} (NT)^{0.8} (bD_t)^{0.8n}}{(\pi D \mu_t)^{0.8}} \tag{7.39}$$

To carry out the optimization of AHP system, feasible region method (**K.Muralikrishna and U V Shenoy (2000)**) has used. This methodology has been discussed for the **Kern's method** to design the heat exchangers. It considers the maximum and minimum allowable shell side pressure drop ,tube side pressure drop, tube length, shell diameter and the constraints considering the baffle spacing. This method uses basically three equations which relate five design variables, namely shell side pressure drop, tube side pressure drop, length of the tube, shell diameter and baffle spacing to shell diameter ratio. For finding the optimum feasible region, the plot of tube side pressure drop vs. shell side pressure drop has to be plotted. The procedure for plotting is given in the table below,

Table 3. Calculation Sequence for Plotting Constraints on Pressure Diagram

Constraints	Step 1	Step2	Step3	Step4	Step5
v_{tmin} and v_{tmax}	Calculate D_s From equation (7.12) (7.15)	Choose ΔP_t and vary it	Calculate L from equation (7.16)	Calculate R_{bs} from equation (7.31) (7.32) (7.33)	Calculate ΔP_s from equation (7.22)
v_{smin} and v_{smax}	Choose D_s and vary it	Calculate R_{bs} from equation (7.13) and (7.21)	Calculate L from equation (7.31) (7.32) (7.33)	Calculate ΔP_t from equation (7.16)	Calculate ΔP_s from equation (7.22)
D_{smax}	Choose ΔP_t and vary it	Calculate L from equation (7.16)	Calculate R_{bs} from equation (7.31) (7.32) (7.33)	Calculate ΔP_s from equation (7.22)	
L_{max}	Choose D_s and vary it	Calculate ΔP_t from equation (7.16)	Calculate R_{bs} from equation (7.31) (7.32) (7.33)	Calculate ΔP_s from equation (7.22)	
R_{bsmin} and R_{bsmax}	Choose D_s and vary it	Calculate L from equation (7.31) (7.32) (7.33)	Calculate ΔP_t from equation (7.16)	Calculate ΔP_s from equation (7.16)	

for optimization purpose some constraints have to be satisfied in order to get the optimum values.

baffle spacing = 0.2 to 1.0 times Ds

$$\Delta P_t \leq \Delta P_{tmax}$$

$$\Delta P_s \leq \Delta P_{smax}$$

$$v_{tmin} \leq v_t \leq v_{tmax}$$

$$v_{smin} \leq v_s \leq v_{smax}$$

$$D_s \leq D_{smax}$$

$$L \leq L_{max}$$

$$R_{bsmin} \leq R_{bs} \leq R_{bsmax} \quad \text{i.e.} \quad 0.15 \leq R_{bs} \leq 1.0$$

the maximum allowable shell side pressure drop and tube side pressure drop are taken as 20kPa and 70kPa. The capital cost of AHP system can be found out by the following correlations given below,

heat exchanger capital cost = $30000+750A^{0.81}$

pump capital cost = $2000 + 5\ (\Delta P/\rho)^{0.68}$

efficiency of pump = $\eta_p = 0.7$

operating hours for plant (H) = 8000 hrs

annual factor (/year) = AF = 0.199

total annual cost of heat exchanger can be calculated by following equation,

$$TAC = AF\left[3000 + 750A^{0.81} + 2000 + 5\left(\frac{M_t \Delta P_t}{\rho_t}\right)^{0.68} + 2000 + 5\left(\frac{M_s \Delta P_s}{\rho_t}\right)^{0.68}\right] + \frac{C_{pow}\, H}{\eta}\left[\frac{M_t \Delta P_t}{\rho_t} + \frac{M_s \Delta P_s}{\rho_t}\right] \qquad (7.40\ )$$

The thermal and physical properties with inlet and outlet conditions of the fluid in the each heat exchanger have been given in table 4.

Table 4. Heat Exchangers Data of AHP System

Parameters	Absorber		Evaporator		Condenser		Generator		SHX	
	Shell	Tube	Shell	Tube	Shell	Tube	Shell	Tube	Shell	Tube
Mass flow(m) (kg/sec)	172.4	35.8	9.09	5.7	5.7	35.8	4.2	172.4	166	172.4
Dirt factor(R) (k/m^2W)	0.00019	0.00019	0.00019	0.00019	0.00019	0.00019	0.00019	0.00019	0.00019	0.00019
Density(ρ) (kg/m^3)	1700	972	0.075	998.2	0.59	968.1	5.3	1562	1568	1689
Specific heat capacity Cp (J/kgK)	1605	4210	1897	4198	1955	4219	2039	1908	1975	1631
Viscosity μ (cP)	1	0.31	0.012	0.62	0.021	0.31	0.021	1	1	1
Conductivity k(W/mK)	0.38	0.69	0.024	0.67	0.034	0.69	0.041	0.4	0.39	0.38
Temperature in (oC)	152	108	54	42	165.3	138	186	162	165	92
Temperature out (oC)	135.63	138	53	41.46	123.84	131	130	165	104.75	162

CHAPTER 8
RESULTS AND DISCUSSION

The present chapter embodies the results from the simulation carried out in Aspen plus software and Matlab software. In this chapter, the optimum geometry found by the feasible region method has been discussed for all the shell and tube heat exchangers used in designing the AHP system. Simulation results of concentration section, CHP system and AHP system have been tabulated. The optimization of CHP system and AHP system in Matlab software as well as by using the feasible region method have been discussed.

The concentration section has been simulated in aspen plus software. As mentioned, six effect evaporator train is used, considering the shell and tube heat exchangers and two phase flash as the model for each evaporator. The black liquor is fed to the last effect and the medium pressure steam is sent to the first effect.

At very first ,the pinch analysis has been done on concentration section. The required stream data is given in the problem table 1 to find out the minimum requirement of hot and cold utilities. The GCC has been drawn, which shows the pinch temperature at 70^0C and minimum heating and cooling requirements of 30.14MW and 22.9MW respectively with the minimum optimum temperature difference of 8^0C. These heating and cooling requirements have to be supplied by the medium pressure steam (MP) and the fresh water. The GCC of concentration section is shown in figure 10.

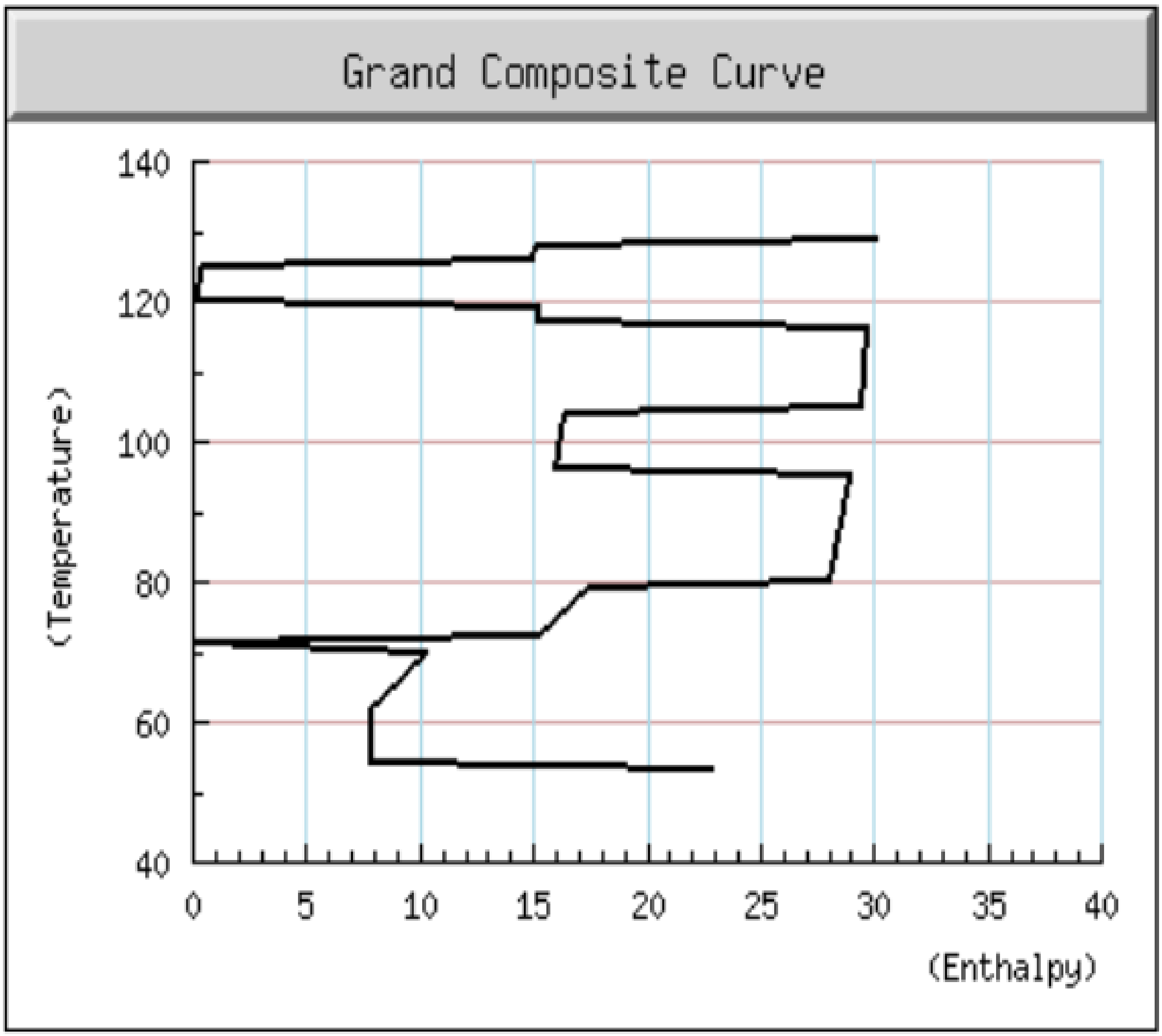

Figure 10. Grand Composite Curve

As the plant needs 38MW power to run and existing back pressure steam turbine is not able to produce the required power and the steam demand of the mill, the CCHP system has been designed. The designing method considers the CCHP system in two separate parts, CHP system and AHP system. The designing as well as the optimization has been carried out separately for each system and has discussed below. The simulation results are shown below in the table 1

Table 5. Simulation Results of Concentration Section (Evaporator Train)

	1	3	5	7	10	13	16	17	18	21	BLACK LIQ	COND ENS	STEAM	THIC KLIQ
Total Flow lbmol/hr	4586.78	615.709	615.709	326.312	153.64	172.672	153.727	153.727	12.1902	141.537	4586.78	3971.07	18965.7	133.67
Total Flow lb/hr	88890.3	16712.4	16712.4	11398.6	2888.60	8510	8147.3	8147.3	237.632	7909.66	88890.3	72177.9	34002.5	7755.2
Total Flow cuft/hr	1475.70	273.934	279.083	185.700	282004	141.266	134.580	134.638	4872.48	13299.2	1475.70	1.24E+ 07	6429.75	131.18
Temperature F	129.2	129.2	158	145.4	159.8	207.379	205.310	205.983	242.6	318.2	129.2	129.2	320	248
Pressure psi	14.5037 7	2.03052 8	14.5037 7	2.90075 5	3.62594 3	29.0075 5	36.2594 3	36.2594 3	18.8549 1	43.5113 2	14.6488 1	2.03052 8	116.030 2	20.305 28
Enthalpy Btu/lbmol	1.22E+ 05	1.25E+ 05	1.24E+ 05	1.27E+ 05	1.04E+ 05	1.29E+ 05	1.30E+ 05	1.30E+ 05	1.03E+ 05	1.20E+ 05	1.22E+ 05	1.04E+ 05	1.18E+ 05	1.30E+ 05
Enthalpy Btu/lb	6312.94	4593.19	4571.91	3625.97	5504.76	2622.73	2459.68	2459.31	5282.18	2140.06	6312.94	5698.97	6558.82	2248.3
Enthalpy Btu/hr	5.61E+ 08	7.68E+ 07	7.64E+ 07	4.13E+ 07	1.59E+ 07	2.23E+ 07	2.00E+ 07	2.00E+ 07	1.26E+ 06	1.69E+ 07	5.61E+ 08	4.11E+ 08	2.24E+ 09	1.74E+ 07
Entropy Btu/lbmol-R	-38.161	-43.394	42.4358	48.1726	7.14532	55.5082	58.0986	58.0694	9.79428	-44.635	-38.161	6.01447	31.8911	59.561
Entropy Btu/lb-R	1.96913	1.59869	1.56339	1.37906	0.38005	1.12629	1.09623	1.09568	0.50244	0.79871	1.96913	-0.3309	1.77023	1.0266

8.1 CHP System

8.1.1 Design Results for CHP System

For designing of CHP system aspen plus software is used. The gas turbine and the HRSG system is implemented to the existing steam turbine present in Kraft pulp and paper mill. The simulation flow sheet is shown in figure 8. 252 t/h air is compressed in a compressor, which is sent to the combustion chamber. In combustion chamber, 6 t/h natural gas is used for complementary firing. The flue gases from the combustion chamber at 1100^0C are passed through the gas turbine implemented and expanded to 1.1 bar at 516.11^0C, producing 14.34 MW power. The HRSG system is implemented with the steam turbine, which is modeled as the shell and tube heat exchanger to convert fresh water at various temperatures and pressures. The evaporator used in HRSG system convert water at low pressure steam (LP), while the economizer and the super heater are used to convert low pressure steam into the medium pressure steam (MP) and the high pressure steam (HP) respectively. For converting water into the steam, the flue gases from the duct burner and combustion chamber are used. For complementary firing in the duct burner, 4.9 t/h natural gas is used. The high pressure steam from the HRSG system is passed through the existing steam turbine and expanded to 8 bar and at 188 ^{0}C producing 23.56 MW power. Therefore, the CHP system has generated total 38 MW power to fulfill the power demand of whole mill. By generating the 38 MW power, the dependency of the mill on the external source of electricity from the grid has been decreased. The medium pressure steam is then supplied to the evaporator train i.e. in concentration section to supply the heating demand of the plant, while the part of the medium pressure steam is sent to the generator in the AHP system for heat up gradation of the vapors coming from the last effect of the evaporator train. In this way the CHP system and the AHP system are connected with each other by the medium pressure steam coming out from the back pressure steam turbine. The simulation results of the proposed CHP system are shown below in table 6.

Table 6. Simulation Results of CHP System

	1	2	3	8	9	10	11	AIR	NATGAS1	NATGAS2	WATER
Mole Flow lbmol/hr											
METHANE	0	0	0	0	0	0	0	0	821.2318	682.7108	0
WATER	0	1642.464	1642.464	20265.33	20265.33	20265.33	20265.33	0	0	0	20265.33
OXYGEN	4043.918	2401.454	2401.454	0	0	0	0	4043.918	0	0	0
NITROGEN	15212.83	15212.83	15212.83	0	0	0	0	15212.83	0	0	0
CARBO-01	0	821.2311	821.2311	0.00E+00	0	0	0	0	0	0	0
CARBO-02	0	0.000722	0.000722	0	0	0	0	0	0	0	0
Total Flow lbmol/hr	19256.75	20077.98	20077.98	20265.33	20265.33	20265.33	20265.33	19256.75	821.2318	682.7108	20265.33
Total Flow lb/hr	555564.9	568739.7	568739.7	365085.5	365085.5	365085.5	365085.5	555564.9	13174.82	10952.57	365085.5
Temperature F	962.0405	2012	1434.589	165.8004	322.6483	482.751	370.4	77	77	77	77
Pressure psi	2.55E+02	5.80E+01	1.60E+01	5.80E+02	5.80E+02	5.80E+02	1.16E+02	1.60E+01	1.60E+01	1.60E+01	5.80E+02
Enthalpy Btu/lbmol	6400.072	-53.9038	-4983.89	-121279	-118099	-111437	-107470	1.27E-12	-32037.8	-32037.8	-122822
Enthalpy Btu/lb	221.8365	-1.90294	-175.944	6.73E+03	-6555.49	-6185.72	-5965.48	4.39E-14	-1997.03	-1997.03	-6817.64
Enthalpy Btu/hr	1.23E+08	-1082280	-1E+08	2.46E+09	2.39E+09	2.26E+09	2.18E+09	2.44E-08	-2.6E+07	-2.2E+07	-2.49E+09
Entropy Btu/lbmol-R	2.345979	9.829351	10.12368	-36.2182	-31.8181	-24.749	-28.3505	0.857506	-19.4134	-19.4134	-38.8572
Entropy Btu/lb-R	0.081315	0.347002	0.357392	-2.01041	-1.76617	-1.37378	-1.57369	0.029723	-1.2101	-1.2101	-2.1569

8.1.2 Optimization Results for CHP System

Again for the optimization purpose, the CCHP system is separated in two parts. The optimization of CHP system is done in Matlab software using the optimization tool available in it. Genetic algorithm is used to optimize the CHP system which considered the five decision variables consuming very less time. Optimization is carried out by considering a single objective in the Matlab software, which is the minimization of total annual cost of the CHP system(equation). Five decision variables are considered for the optimization purpose. These decision variables included compressor pressure ratio, efficiency of gas and steam turbine, temperature of the combustion chamber and the fuel mass flow rate to the duct burner. For HRSG system, some constraints have been considered, those have to be satisfied while optimization. these constraints are,

$\Delta T_p = T_6 - T_{10} > 0$; $T_5 > T_{10}$; $T_7 > T_{WATER}$; $T_4 > T_{11}$; $T_7 > 325$

The lower and upper limit of the five decision variables are given below,

$8 < p_c < 18$; $0:65 < \eta_c < 0:92$; $0:65 < \eta_g < 0:92$; $900K < T_2 < 1250K$; $0 < m^0_{NATGAS2} < 6$

The results of optimal design and the economic evaluation of constraints for the proposed system found by the GA are presented in table below,

Table 7. Optimal Values of Variables and Objective Functions

Run no.	p_c	η_c	η_g	T_2 (K)	$m^0_{NATGAS2}$	T_4 (K)	T_5 (K)	T_6 (K)	T_7 (K)	TAC $/year
1	14.2	0.72	0.79	998.32	3.4	1504.35	1280.25	490.82	356.89	2.37E7
2	15.8	0.77	0.81	1052.68	3.7	1624.84	1320.18	627.39	402.35	2.53E7
3	16	0.7	0.88	1100.55	2.1	1302.70	1218.21	694.67	384.9	2.17E7
4	14.6	0.68	0.88	1257.34	2.8	1356.27	1289.57	706.38	368.27	2.19E7
5	16.5	0.64	0.84	1248.87	3.6	1421.28	1321.28	759.64	408.35	2.37E7
6	16.2	0.66	0.79	1109.58	4.1	1347.35	1345.67	654.28	368.25	3.21E7
7	18.01	0.81	0.76	1348.61	2.9	1368.71	1237.61	691.71	397.28	3.45E7
8	17.81	0.79	0.82	1400.94	1.7	1523.54	1257.29	764.38	428.67	3.12E7
9	16.06	0.81	0.83	1472.51	1.98	1432.64	1189.57	729.18	414.27	4.01E7
10	13.84	0.83	0.85	1245.63	1.37	1354.28	1224.63	657.68	358.01	2.21E7

as the GA produces new population every time, for every run, the different optimum solutions with the different values of decision variable are found. From the optimal results shown in above table, it is clear that the total annual cost of the CHP system is minimized with the respective values of decision variables. The total operating hours for the plant is taken as 8000 hrs with annual factor of 0.199.it can be concluded from the optimization that the minimum total annual cost of the CHP system is $2.17*10^{7}$\$/yr, with optimum values of five decision variables and the unknown temperatures. These values are shown in above table 7 in the third row. The optimum values of five decision variables and unknown temperatures are,

pressure ratio in compressor (p_c) = 16

outlet pressure of air from compressor (P_1) = 16.2bar

outlet pressure from the combustion chamber (P_3) = 15.4bar

efficiency of compressor(isentropic) (η_c) = 0.7

efficiency of gas turbine(isentropic) (η_g) = 0.88

gas turbine inlet gas temperature (T_2) = 1100.55K

mass flow rate fuel to the HRSG system ($m^0_{NATGAS2}$) = 2.1t/h

8.2 AHP system

8.2.1 Design Results for AHP System

The GCC is used selecting cold stream above the pinch receiving the heat loads from the condenser (Qcond) and the absorber (Qabsorb) and a hot stream below pinch point supplying the energy demand of the evaporator (Qevap). To determine the temperatures of heat exchangers consisting absorber, condenser, evaporator, generator and solution heat exchanger phase equilibrium diagram is used. The contaminated vapors from the last effect which is sent to the condenser is used as the heat source by heat load of 22.9MW at 54^0C and the black liquor coming from the first effect is selected as the heat sink by heat load of 30.14MW at 120^0C.

LiBr-Water pair is used as single working AHP to heat upgrade, while the medium pressure steam from the steam turbine is used as the driving heat source in the generator. Here the working fluid enters the generator with 66% LiBr weight fraction and comes back to the absorber with 70% LiBr weight fraction. Aspen Plus software is used to simulate the design of the AHP system. The shell and tube heat exchangers are modeled as evaporator, condenser, absorber, generator and the solution heat exchanger. The simulated flow sheet of AHP (absorption heat pump) system is shown in figure 9. The medium pressure steam from the steam turbine (11t/h) is sent to the generator, while the vapors from last effect and the black liquor from the first effect of concentration section are sent to the evaporator and absorber respectively. The simulation results of AHP system are given in table 8.

Table 8. Simulation Results of AHP System

Sub stream: MIXED	1	2	3	4	8	13	15	BL	CONDENS	STEAM	VAPOR
Total Flow lbmol/hr	98.14856	98.14856	98.14856	98.14856	17.21948	3493.769	3493.769	3493.769	4006.483	20260.58	4006.483
Total Flow lb/hr	1691.365	1691.365	1691.365	1691.365	308.6345	284578	284578	284578	72177.92	365000	72177.92
Temperature F	105.3887	105.3887	269.3438	269.3438	122	248	248	248	129.0829	428	129.2
Pressure psi	15.95415	15.95415	29.00755	29.00755	29.00755	21.75566	21.75566	21.75566	2.030528	116.0302	2.030528
Vapor Frac	0.839168	0.839168	0	0	0	0	0	0	1	1	1
Liquid Frac	0.160832	0.160832	1	1	1	1	1	1	0	0	0
Enthalpy Btu/lb	-2301.66	-2301.66	-2301.39	-2301.39	-6316.16	-1678.67	-1678.67	-1678.67	-5747.5	-5611.29	-5747.44
Enthalpy Btu/hr	3892951	3892951	3892494	3892494	1949385	-4.8E+08	-4.8E+08	-4.8E+08	-4.1E+08	-2.05E+09	-4.1E+08
Entropy Btu/lbmol-R	-24.5655	-24.5655	-31.0412	-31.0412	-37.3157	-75.1618	-75.1618	-75.1618	-5.91881	-10.5869	-5.91721
Entropy Btu/lb-R	-1.42552	-1.42552	-1.80129	-1.80129	-2.08194	-0.92276	-0.92276	-0.92276	-0.32854	-0.58766	-0.32845
Density lbmol/cuft	0.003135	0.003135	1.756135	1.756135	3.225012	0.731894	0.731894	0.731894	0.000321	0.01218	0.000321

8.2.2 Optimization Results for AHP System

The aim behind the optimization is to minimize the total cost of the proposed AHP system by finding the optimum shell and tube heat exchanger geometry (equation(7.40)). The proposed AHP system has produced the 12.7MW cooling and 30.14MW heating energy. Some temperatures and heat duties of heat exchangers are found out by the simulation carried out in Aspen plus software. All heat exchangers are considered as shell and tube heat exchangers. The optimization is done by using the feasible region method given by **K.Muralikrishna and U .V. Shenoy (2000)**. This methodology defines the region of all feasible designs graphically. This feasible region has been conveniently demonstrated on the two dimensional plot of tube side pressure drop and shell side pressure drop.

All five heat exchangers are considered for the optimization purpose. The shell side and tube side inlet and outlet temperatures with the physical properties of fluids and some basic data are given in the table 4. 1-2 shell and tube heat exchangers are considered with steel (k=36W/^{0}C) tubes of 0.0191m outside diameter and 0.0154m of inside diameter, laid out in 0.0254m square pitch. A 25% baffle cut has been assumed. Split ring floating head is assumed to avoid corrosion. The allowable maximum tube side (ΔPt) and shell side pressure drop (ΔPs) are considered as 70kPa and 20kPA respectively. A combined dirt factor of 0.00019 m^2 ^{0}CW^{-1} has been considered. The tube side and shell side velocity ranges have been considered as 1m/s to 1.8m/s and 0.3 m/s to 1m/s respectively. The maximum allowable shell diameter and the tube length are 2m and 10m, respectively. The baffle spacing has varied from 0.2 to 1 times the shell diameter.

Based on the assumed constraints, the feasible region has been identified on the pressure drop diagram. All constraints in the table 3 given are plotted in the form of tube side and shell side pressure drop one by one. The procedure is given in table 3. Individual Reynolds numbers have been calculated considering the minimum and maximum tube side and shell side velocities. The following plot is shown for the absorber with the shaded area as the feasible region. According to the linear programming the corner points in the plot are feasible points, which give the optimum tube side and shell side pressure drop. The calculations are done according to the table 3.

The respective plots of tube side vs. shell side pressure drop with shaded region as the feasible region for absorber, condenser, generator, evaporator and the solution heat exchanger are shown below. The feasible region consist many optimum points, but according to the linear programming, corner points are considered as most optimum points. These corner points on the feasible region have co-ordinates of tube side and shell side pressure drop. With these pressure drops, the optimum values of the tube length, shell diameter and the baffle space have been calculated by solving equations 7.16, 7.22, 7.30, 7.31 and 7.32 simultaneously. The area with respective length and shell diameter have been calculated by equation 7.14. The required heat duties, logarithmic mean temperature differences and logarithmic temperature difference correction factor have been calculated. The minimum area of the heat exchanger has been chosen for finding the total cost of the heat exchanger, which has calculated by equation 7.40. The summary of total cost calculation for each heat exchanger is given below,

8.2.2.1 Absorber

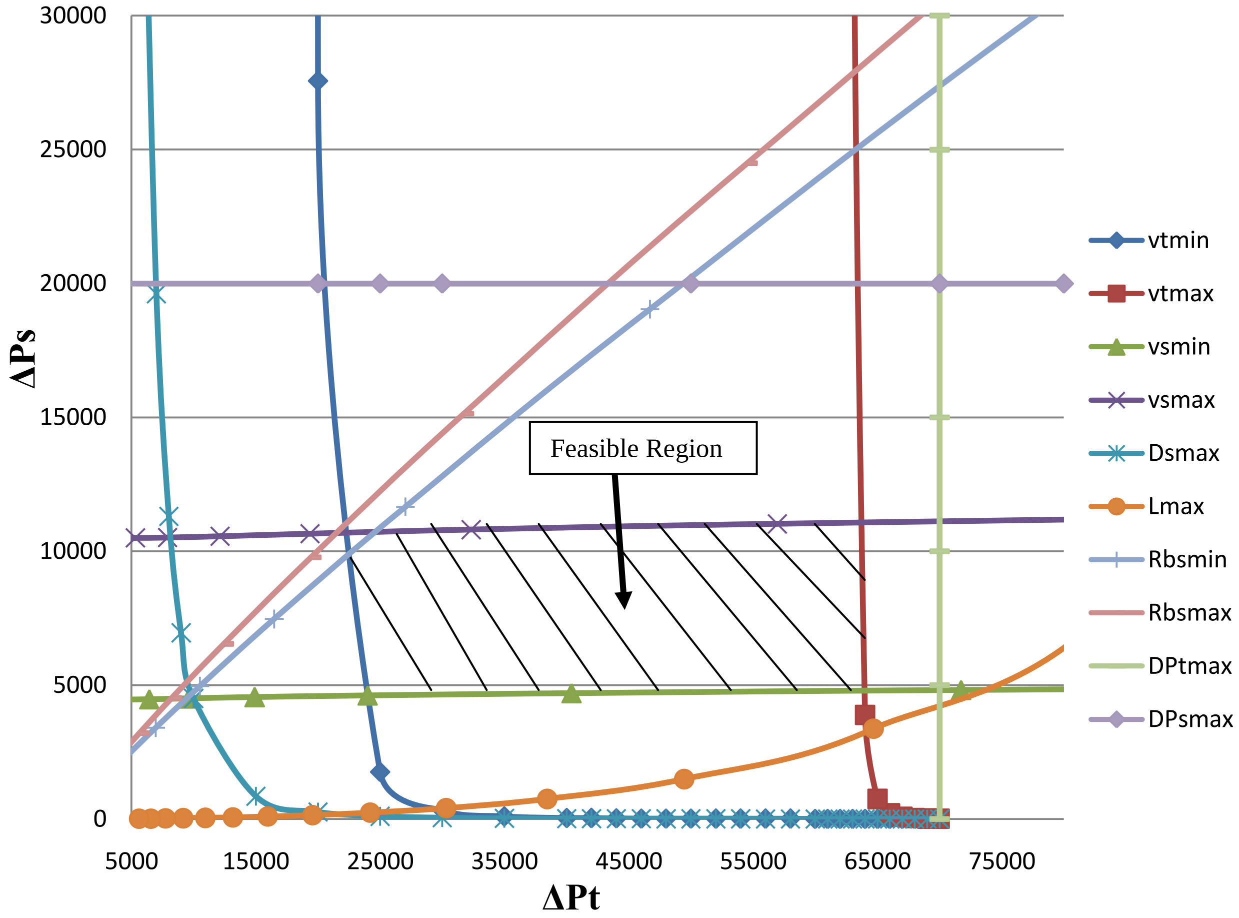

Figure 11. Absorber Tube Side Pressure Drop vs. Shell Side Pressure Drop

equations 7.16, 7.22, 7.30, 7.31 and 7.32 are solved in Matlab software using fsolve tool to get the optimum values of tube length, shell diameter and the baffle spacing. The area is calculated using the equation 7.14. The feasible corner points with optimum area is shown in table below,

Table 9. Optimal Geometry and Area of Absorber

Point	ΔPt (Pa)	ΔPs (Pa)	L (m)	Ds (m)	Rbs	Area (m^2)
1	24000	10000	6.98	0.6407	0.6322	156.9303
2	26000	10800	6.85	0.6322	0.7271	149.0243
3	24000	4000	7.08	0.6478	0.6888	163.5541
4	63000	4000	7.11	0.592	0.6	131.5076
5	63000	10000	6.952	0.598	0.6988	131.8358

8.2.2.2 Evaporator

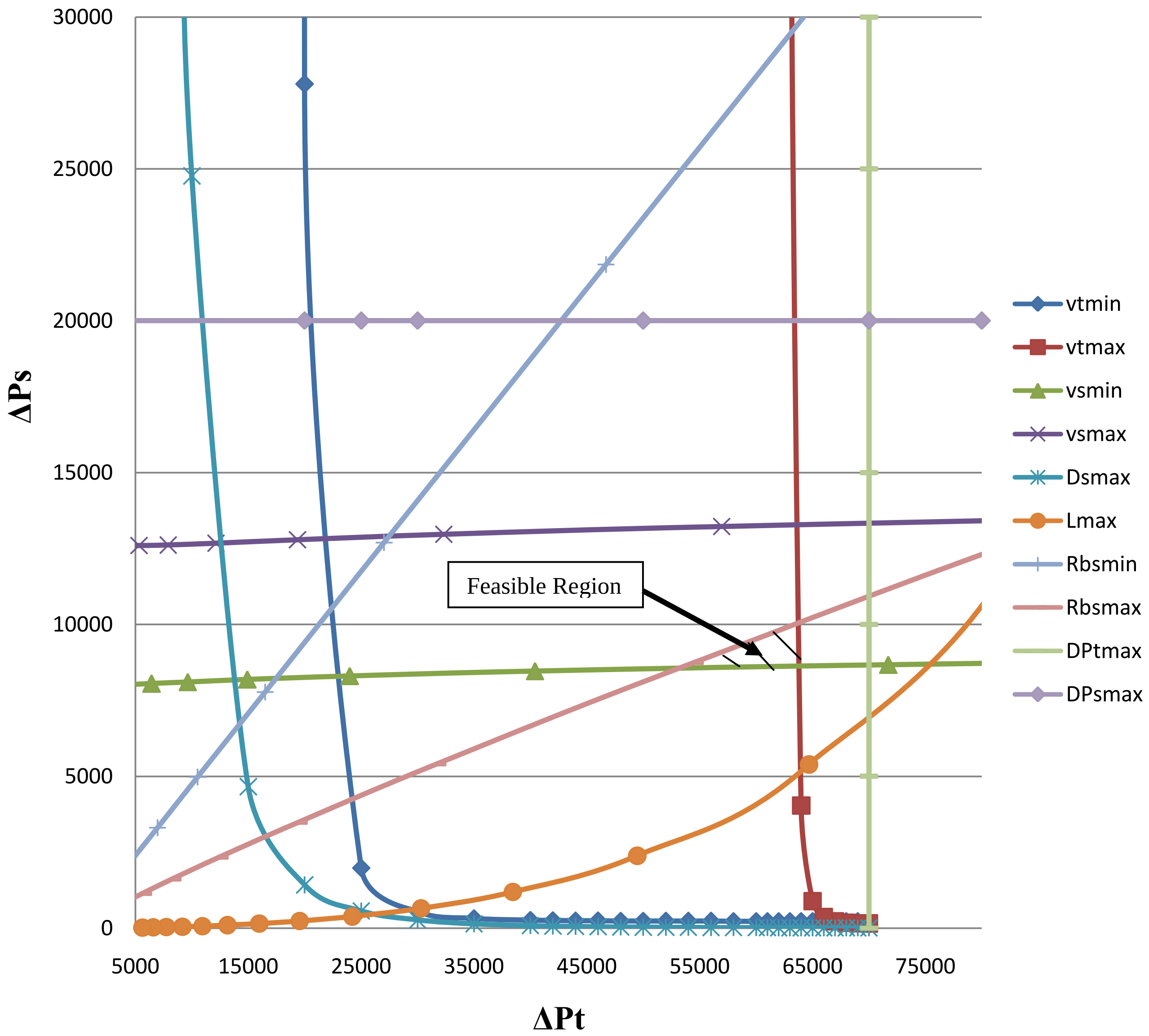

Figure 12. Evaporator Tube Side Pressure Drop vs. Shell Side Pressure Drop

The respective feasible points are shown below,

Table 10. Optimal Geometry and Area of Evaporator

Point	ΔPt (Pa)	ΔPs (Pa)	L (m)	Ds (m)	Rbs	Area (m^2)
1	52000	7600	5.4419	0.78	0.732	197.9194
2	64000	7800	5.7745	0.802	0.742	224.6844
3	64000	10000	5.27	0.821	0.748	217.0273

8.2.2.3 Condenser

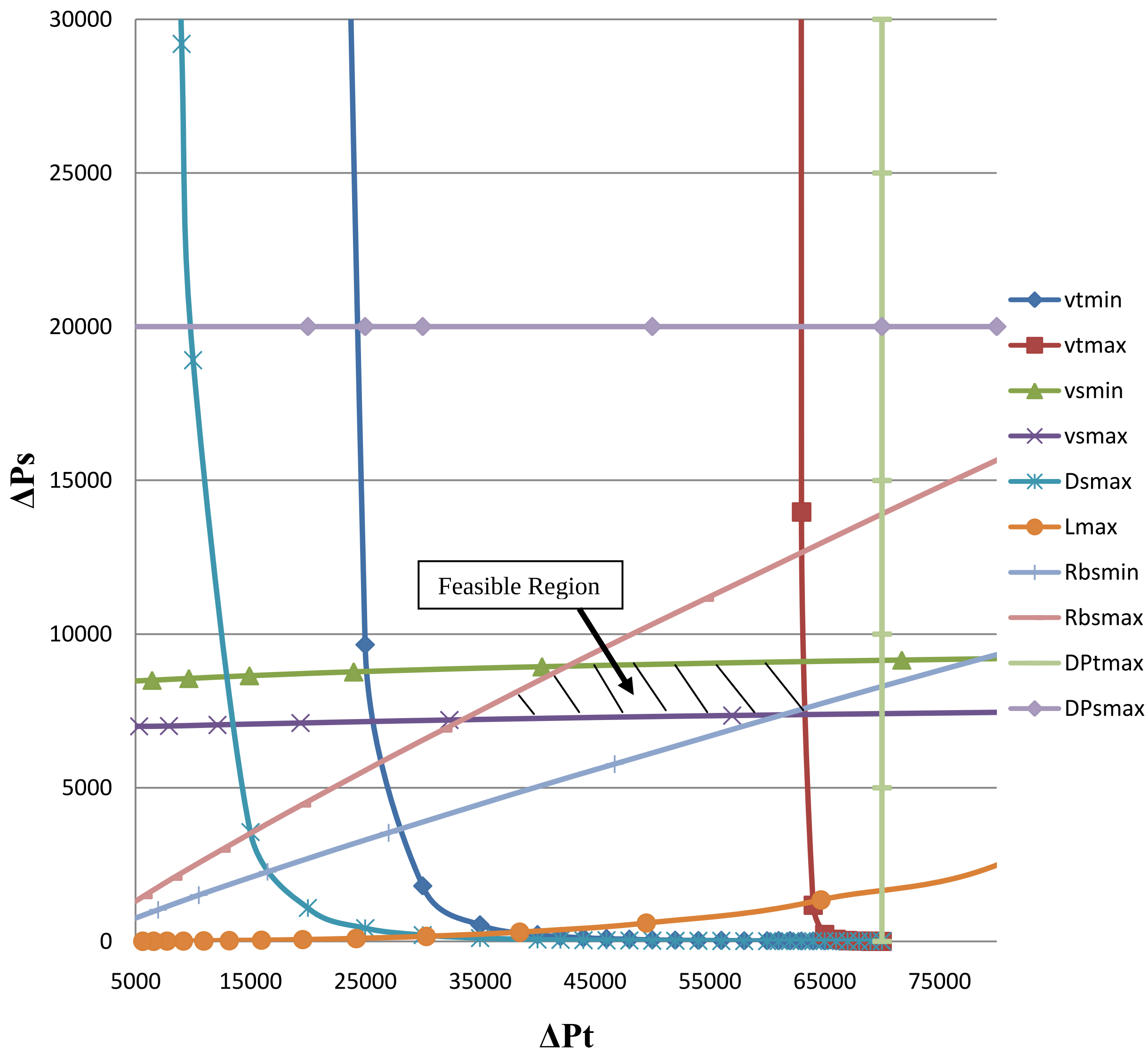

Figure 13. Condenser Tube Side Pressure Drop vs. Shell Side Pressure Drop

The respective feasible points are shown below,

Table 11. Optimal Geometry and Area of Condenser

Point	ΔPt (Pa)	ΔPs (Pa)	L (m)	Ds (m)	Rbs	Area (m^2)
1	33000	7300	7.345	0.901	0.58	378.6587
2	42000	8300	7.481	0.913	0.583	398.1599
3	63000	7250	7.527	0.919	0.591	406.9762
4	64500	7310	7.662	0.934	0.593	430.7338
5	64500	9400	7.684	0.956	0.596	456.8364

8.2.2.4 Generator

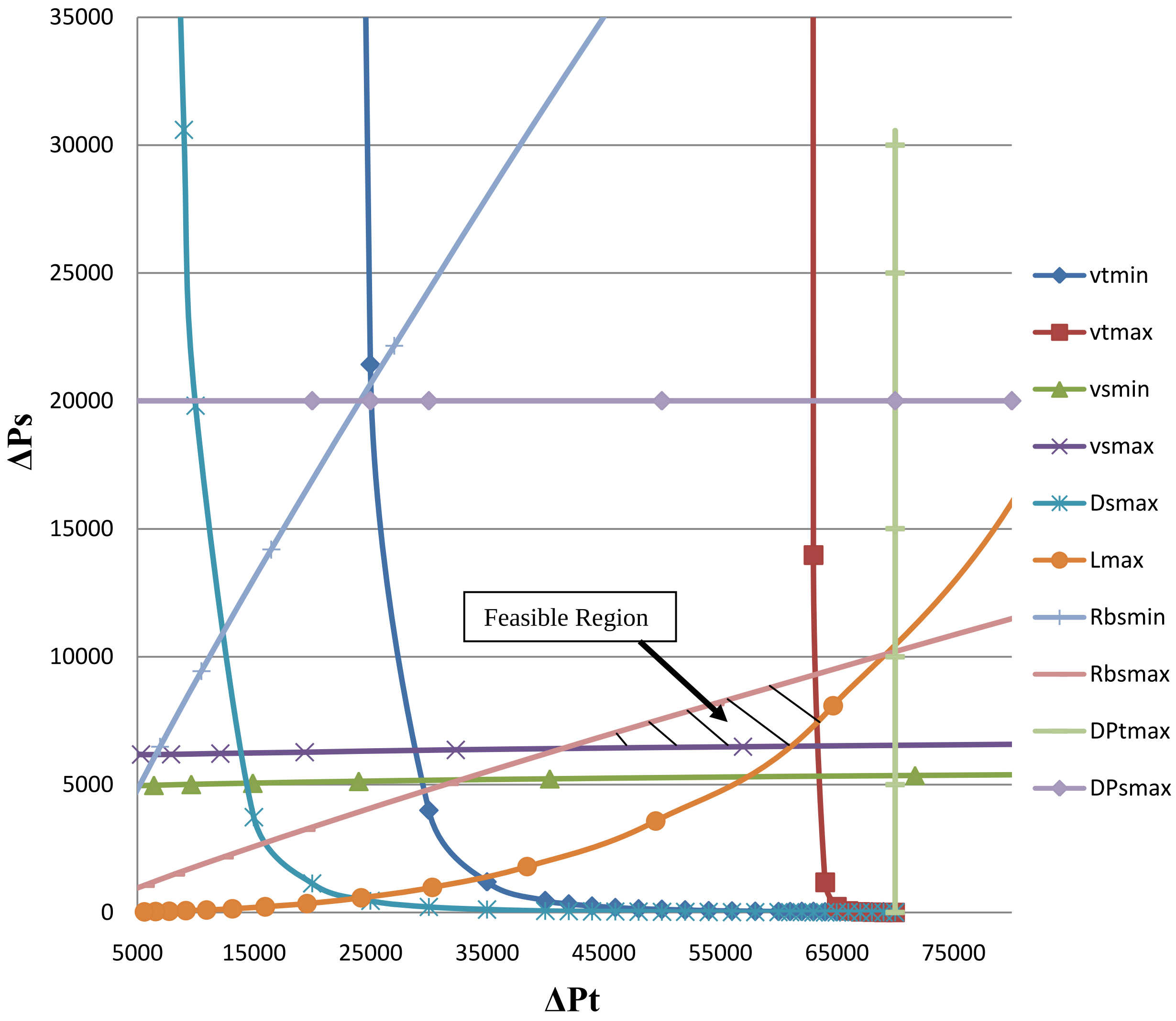

Figure 14. Generator Tube Side Pressure Drop vs. Shell Side Pressure Drop

The respective feasible points are shown below,

Table 12. Optimal Geometry and Area of Generator

Point	ΔPt (Pa)	ΔPs (Pa)	L (m)	Ds (m)	Rbs	Area (m^2)
1	32000	5700	4.571	0.986	0.724	292.6853
2	57000	5800	4.592	0.983	0.728	291.8881
3	62000	6300	4.521	0.991	0.737	293.0175
4	40300	6300	4.559	0.997	0.739	299.7887

8.2.2.5 Solution Heat Exchanger

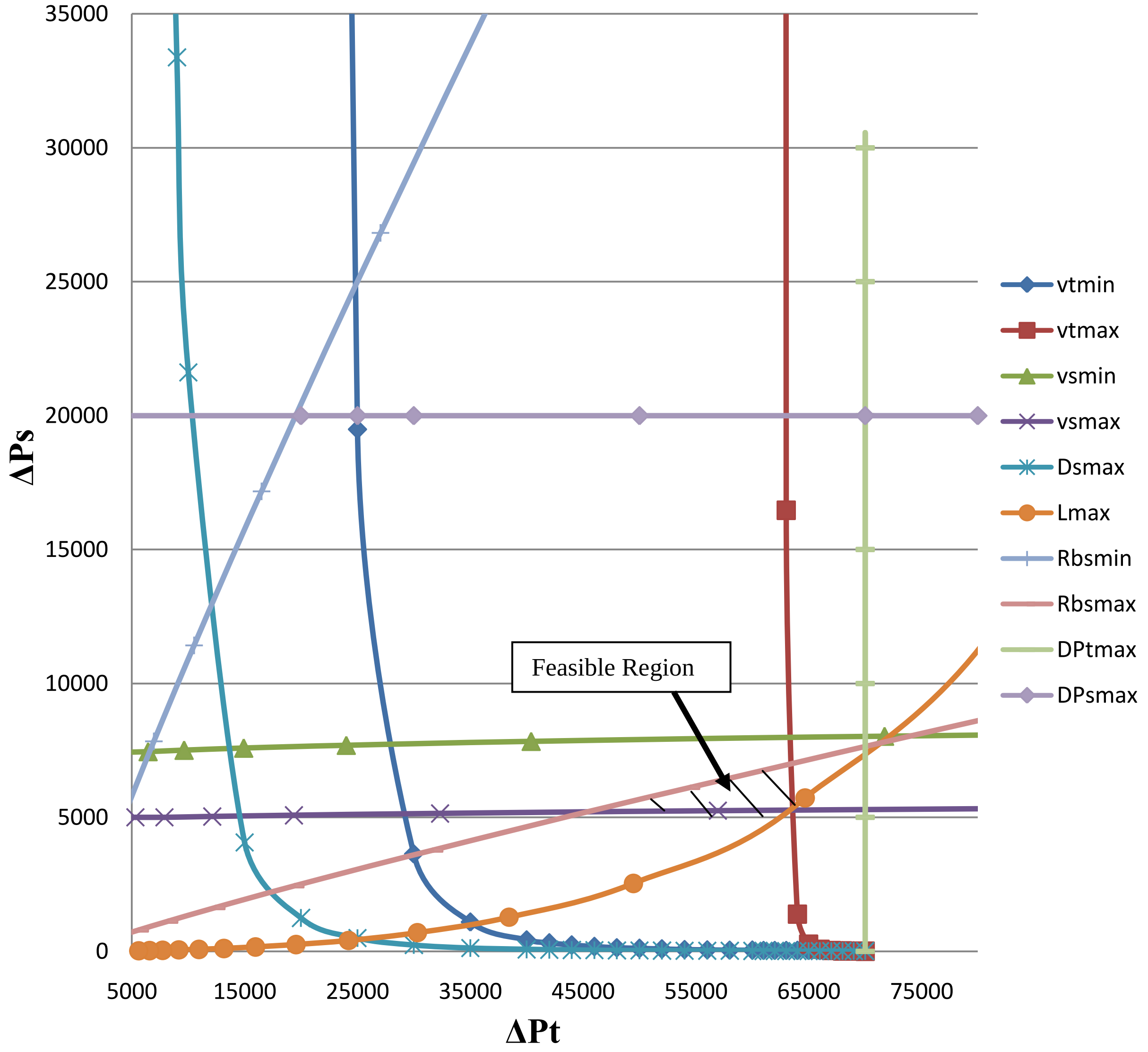

Figure15. Solution Heat Exchanger Tube Side Pressure Drop vs. Shell Side Pressure Drop

The respective feasible points are shown below,

Table 13. Optimal Geometry and Area of Solution Heat Exchanger

Point	ΔPt (Pa)	ΔPs (Pa)	L (m)	Ds (m)	Rbs	Area (m^2)
1	46000	5300	5.54	0.861	2.4322	255.9675
2	64500	5420	5.559	0.873	2.4271	265.5746
3	64210	7100	5.624	0.882	3.3888	275.4127

from the above results, five minimum areas have been selected to find out the total annual cost of the AHP system. The total cost has been found out by equation 7.40. The minimum areas and the optimal geometry of the heat exchangers are given in the table 14, the total annual cost (TAC) of heat exchanger is calculated by the equation 7.40 given by K. Muralikrishna and U.V. Shenoy(2000).

Table 14. Minimum Areas and Total Cost of Heat Exchangers

Heat exchanger	DPt(Pa)	DPs(Pa)	Tube length (m)	Diameter (m)	Baffle space	Area(m^2)	Cost of heat exchanger($)
Absorber	63000	4000	7.11	0.592	0.6	131.5076	16343.37035
Condenser	33000	7300	7.345	0.901	0.58	378.6587	26830.65778
Evaporator	52000	7600	5.4419	0.78	0.732	197.9194	19400.9185
Generator	57000	5800	4.592	0.983	0.728	291.8881	23396.72141
Solution heat exchanger	46000	5300	5.54	0.861	2.4322	255.9675	21875.34583
Total cost($) = 107847.0139							

therefore, the total cost of AHP system is sum of the total cost of all heat exchangers.
now, the total annual cost of the CCHP system is sum of total cost of CHP system and AHP system.

total cost of CCHP system = cost of CHP system + cost of AHP system

total cost of CCHP system ($) = 21700000+107847.0139=21807847.01

in this way, the CCHP system consisting CHP system and AHP system has been designed and optimized. By designing CCHP system, the total steam demand of the plant, reducing the required heating and cooling utilities and 38MW power has been generated.

8.3 Economic Analysis of CCHP System

By performing the economic analysis of CCHP system, it has confirmed that the system is economically feasible. Economical analysis is performed by considering the local cost equations of steam, power and cooling water cost. The costs of electricity and cooling water is taken as 37$/MWh and 0.9 $/m^3.the cost of steam is taken as 8$/t. The economic analysis for the total saving is shown in table 15 and table 16 respectively.

AF=0.199, H=8000 hrs

Table 15. Economic Analysis of Heat Exchangers - Part1

Utility	Quantity	Saving($/yr)
Electricity	38MW	38*37*8000=11248000
Steam	166t/h	166*8*8000=10624000
Cooling water	390t/h	390*0.9*8000=2808000
		Total saving = 24680000 $/yr

the economic analysis for the total expenditure is shown in table 16.

Table 16. Economic Analysis of Heat Exchangers - Part2

Operating cost ($/yr)	17890000
Fuel cost($/yr)	
Water cost($/yr)	
Installation cost($)	Cost of CHP system + Cost of AHP system 21700000 + 107847.0139 = 21807847.01
Net saving($/yr)	24680000 - 17890000 = 6790000

above economic evaluation shows that that the proposed CCHP system if economically feasible with net saving of 9190000$/yr. From the installation cost and the net saving, it is possible to find out the payout period. Therefore the payout period can be found out by the following equation,

Payout Period (Years) = [(Fixed Capital Cost or Installation Cost($))/Net Profit($/yr)]

Payout Period (Years) = 21807847.01 / 6790000 = 3.21

Therefore the simple payout period is 3.21years,which shows that the implementation of CCHP system is economically feasible and can be a cost attractive option for the Indian paper mill with simple payout period of 3.21years.

CHAPTER 9
CONCLUSION AND RECOMMENDATIONS

9.1 Conclusion

A CCHP system has been designed and optimized by producing 155t/h medium pressure steam to fulfill the heating demand of the concentration section and generating 38MW power to fulfill the power demand of whole mill. The proposed system has considered into two separate parts, first CHP system and AHP system for designing and optimization purpose. The proposed CCHP system has been successfully integrated with the existing Kraft pulp and paper mill. Pinch analysis has been performed successfully to find out the minimum requirements of heating and cooling utilities. One part of CCHP system, CHP system is designed using Aspen plus software and optimized using the Matlab software, by considering the five decision variables and unknown temperatures have been found out. Similarly, AHP system has been designed using Aspen plus software by considering all heat exchangers as shell and tube heat exchanger models and optimized using the feasible region method to find out the optimum geometry of the shell and tube heat exchangers. the methodology use to optimize the shell and tube heat exchanger is based on the Kern's method, which has provided the good model for tube side and shell side predictions. Both systems are optimized considering the minimum total annual cost (TAC).

Economic analysis has been successfully performed confirming that the proposed CCHP system is economically feasible. The economic evaluation proved that the CCHP system is cost effective and has reasonable payout period of 3.21years.

9.2 Recommendations

There is further scope to investigate the designing and optimization of CCHP system in Kraft pulp and paper mill. Some of the recommendations for carrying out the future work are:

1. The exergy analysis of the CCHP system can be done to increase the performance of each model used in designing.
2. Different cost functions can be used to calculate the total annual cost of the CCHP system.

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